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Accuracy of Abundance Indices Based on Stratified-Random Trawl Surveys

by

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I. Introduction

An intensive bottom trawl survey program was begun in 1963 by the Fisheries Laboratory in Woods Hole, and has been continued each year and expanded since that time. The Northeast Fisheries Center now conducts three surveys a year, two of which (spring and fall) extend from Cape Hatteras to Nova Scotia, covering an area about 75,000 square miles. The third survey, carried out in summer, does not include the Nova Scotia area but does include inshore areas north of Cape Cod in the western Gulf of Maine, areas which are not covered in the other two surveys. The major objective of these surveys is to provide annual estimates of the abundance and structure (age-length and species composition) of fish populations. This information is essential for helping assess the current status of stocks and particularly for predicting recruitment. The surveys also provide synoptic coverage necessary for relating fish distribution and abundance to large scale seasonal and annual changes in environmental factors, and they provide basic information on reproduction, growth, and feeding interrelationships.

Unique characteristics of the survey which eliminate major sources of bias inherent in commercial fishery statistics include the use of standardized trawl gear and fishing methods on calibrated research vessels, an unbiased method of station selection, and complete records of the weight and length frequency of all fish species in each trawl catch. In this paper we are primarily concerned with the accuracy of survey abundance indices for individual species which are expressed in terms of mean number (or weight) of fish per standard trawl haul. Evidence accumulated so far indicates that for many species the mean catch per tow is a valid index of abundance, particularly when it is combined with information on age-length composition and commercial statistics (Clark and Brown 1977; Halliday et al. 1971). However, the abundance indices by themselves can be biased and they do have fairly large random sampling errors. The sources and magnitude of bias as well as random sampling errors are discussed, and methods for improving precision and for detecting bias are reviewed.

II. Design of the Survey

The stratified-random design was chosen to optimize sampling from both biological and statistical considerations (Grosslein 1969). The survey region is subdivided into sampling strata whose geographic and depth boundaries are broadly related to fish distribution, and trawl stations are randomly located in each stratum (Figure 1). This results in a fairly uniform distribution of stations throughout the survey area (see Figures 2 and 3) and insures some trawling in each depth zone in all geographic subdivisions. At the same time, random sampling within each stratum provides valid estimates of sampling error (variance) and the catch per haul indices are unbiased in the sense that every (trawlable) habitat is sampled with probability proportional to the area covered by the habitat in each stratum. Further details on selection and allocation of stations, and operations and data collected at sea, are summarized by Grosslein (1974).

Standard Abundance Index

The standard abundance index is the stratified mean catch per haul for some set of strata which encompasses the population or stock of interest. The formulae for the stratified mean $\bar{y}_{st}$ and its variance $V(\bar{y}_{st})$ are:

$$\bar{y}_{st} = \frac{1}{A} \sum_h A_h \bar{y}_h$$

$$v(\bar{y}_{st}) = \frac{1}{A^2} \sum_h \frac{A_h^2 S_h^2}{n_h}$$

where

A_h = area of the h^{th} stratum

A = the total area

$\bar{y}_h$ = sample mean catch per tow in the h^{th} stratum

N_h = number of tows in the h^{th} stratum

S_h^2 = sample variance of the h^{th} stratum

The estimator $\bar{y}_{st}$ will be unbiased as long as the stratum means $(\bar{y}_h)$ are unbiased. Furthermore, variance of the stratified mean will be smaller as compared with simple random sampling given that abundance is sufficiently different among different strata (see Cochran 1976, for further details on the theory of stratified sampling).

III. The Distribution of Catch per Tow

Few fish species, if any, are randomly distributed in space. This lack of randomness is reflected by the variance of the distribution of catch per tow being much greater than the mean. The most obvious and troublesome implication of this large variance is that a large sample will be needed to obtain a high level of precision. Though this high haul to haul variability of catches cannot be wished away, a careful design of a survey will reduce its effects.

One would like to fit one of the available theoretical distributions to sample data for, amongst others, the following reasons: 1) to be able to choose a 'normalizing' transformation of the data so that the usual normal theory can be applied to detect trends, generate confidence intervals, etc., and 2) to be able to exploit the properties of the distribution so that the maximum level of precision is obtained for a fixed amount of sampling effort.

The distribution most often found useful for describing trawl data has been the negative bionomial distribution (Taylor 1953). There are several models which will generate a negative binomial distribution (Anscombe 1950) and in some situations contradictory hypotheses lead to the same distribution (Bliss and Fisher 1953). This multitude of possible generating mechanisms, probably accounts for the negative binomial being able to describe a large variety of overdispersed populations.

Transforming the data and confidence intervals

The mean and variance of the negative binomial distribution are related by

$$\sigma^2 = \mu + \frac{1}{k}\mu^2, \qquad (1)$$

which can be rewritten as

$$\sigma = \left(\frac{1}{\mu} + \frac{1}{k}\right)^{\frac{1}{2}} \mu. \qquad (2)$$

For a fixed value of k, and for relatively large (with respect to $\frac{1}{k}$) values of μ (2) is approximately linear. Hence the appropriate variance stabilizing transformation is

$$y = \ln (X) \qquad (3)$$

(see e.g. Snedecor 1967). Since in groundfish survey data, we quite often have 0 counts, X is replaced by X+1. It should be noted that the appropriateness of (3) depends on the degree of linearity between the standard deviation and the mean. If k is not stable or if μ is too small then (2) may be far from linear. Furthermore, it is not true that if a transformation stabilizes the variances it necessarily reduces nonnormality. Thus when applying a statistical procedure which assumes normality to the transformed data, care must be taken in interpreting the results to ascertain the robustness of the method to departures from normality. There are also problems with interpretation of results expressed in the transformed scale. For example, when testing for the equality of means in a one-way analysis of variance, the original means will be equal if and only if the ln transformed means are equal, but if the hypothesis of equality of the means is rejected, conclusions drawn from further analysis may be more meaningful in the original scale than in the transformed scale (see e. g. Scheffé 1959).

For the groundfish survey, the ln transformation does stabilize the variance, but in many cases the resulting distribution is still far from normal (Figure 4). Hence any analysis based on the assumption that ln (X+1) is normally distributed, may be significantly in error. In particular confidence intervals calculated under such circumstances could be misleading. It has been found, however, that the values ln (X) $X \neq 0$, are often nearly normally distributed (Figure 4). Similar results hold for other highly skewed distributions of counts. For example it has been observed that for mackerel egg counts, ln (X), $X \neq 0$ is normally distributed whereas ln (X+1) is not (Ulltang 1978). In the appendix we indicate how the near normality of ln (X), $X \neq 0$ may be exploited using what is called a Δ-distribution to generate confidence intervals that appear to be more realistic in practice than those generated by other methods.

IV. Distribution Properties Relative to the Design of the Survey

In this section we illustrate with experimental results and survey data how the distributional properties of the catch-per-tow can be used to maximize sampling efficiency. Other than the initial choice of the stratification which is mainly based on biological considerations, the major design factors that need to be considered are the sampling strategy within a stratum, the size and characteristics of the trawl, and the duration of the tows. Due to the lack of precise information on the overall distribution of fish in the survey area or whether the habitats change over long periods of time, a random sample within a stratum was deemed to be the safest strategy to follow even though systematic sampling may be slightly more efficient in terms of cruise time. For an example of the effects of different sizes of trawls on the survey indices see Grosslein and Sauskan (1969).

To illustrate the relationship between tow duration and sampling efficiency, we use the results of an experiment conducted on Georges Bank where tows of varying duration were made across a large area of the bank. The experiment also exemplifies other major distributional properties of the survey.

Catch vs. length of tow

Clearly, one would expect that the relation between the time towed and the catch would be linear. That indeed this is the case is shown in Figures 5 and 6 where the sample mean is plotted versus duration of haul. Of practical concern is the strength of the relation, since, as we will see below, it may sometimes be desirable to change the length of the standard survey tow periodically. As can be seen from the graphs the relation is quite good considering that each point is based only on 16 tows. It can also be inferred from these results that no gear saturation occurs over the time period considered. That is, fish are just as 'catchable' for 2-hour tows as they are for 15-minute tows.

Relation between the standard deviation and the mean

Figure 7 shows that for the experimental data the standard deviation is linearly related to the mean, with a small positive y-intercept. That the intercept is positive is consistent with the hypothesis that the distribution is negative binomial. For from equation (2) it can be seen that the graph should rise sharply from 0 before becoming nearly linear. Hence if one simply regressed σ on μ, the intercept would in general be positive. The same relationship between the standard deviation and the means holds for standard survey data (Figure 8), even though the herring stock declined greatly over this seven year period, $^{\sigma}/\mu$ remained virtually constant. Stratum standard deviations are also linear function of the stratum means whether measured in numbers (Hennemuth 1976) as above or weight (Figure 9).

The stability of the parameter k for different size sampling units and for varying population levels

It is of interest to ascertain whether k is constant for changing population sizes or if it is dependent on the choice of sampling unit. Bliss and Owen (1958) analyzed Taylor's (1953) trawl catches of haddock which were taken on Georges Bank over three summers in differing depth zones. They found no marked trends in k over time or depth. The value of k determined from the experimental data collected on Georges Bank 20 years after Taylor's data gives a value of k for haddock which lies within the confidence interval calculated by Bliss and Owen. In Figure 10 we plot estimates from the groundfish survey data of $\frac{1}{\hat{k}}$ versus $\bar{x}$ for herring. As was observed, during this period the stock declined drastically, but there appears to be no change in k. Since k is stable for many other species, it appears that k is a function only of the species and not of population levels or time.

In Figure 11 we plot $\frac{1}{\hat{k}}$ versus $\bar{x}$ for several demersal species caught in the 1965 experiment on Georges Bank; each point represents a sampling unit of a different size. Taking into account the small size of the sample (16 tows for each haul duration) and hence the relatively large variance of the estimator of $\frac{1}{\hat{k}}$, k does not appear to vary with sampling unit size. For details on estimating a common value of k see the paper by Bliss and Owen (1958).

The stability of k for a species over a wide range of population levels tends to imply that the broad distributional properties (e.g. the amount of schooling) are relatively independent of the size of the stock, while the constancy of k for varying sampling unit sizes reflects small scale distributional properties (e.g. the amount of clumping in the area covered by a single tow). The two most likely models for the distribution of fish which will generate a negative binomial distribution are (after Anscombe 1950):

1) Heterogeneous Poisson sampling. If the mean λ of a Poisson distribution varies from area to area and has a Gamma distribution (which approximates well a wide range of distributions) then the resulting distribution is negative binomial.

2) Randomly distributed clumps. If clumps or schools are distributed randomly over the bottom so that the number of clumps observed in a sample of fixed area has a Poisson distribution, and the number of individuals in the clumps are distributed independently in a logarithmic distribution, then the resulting distribution is negative binomial.

Now if the "clumps" of fish were of a scale such that the mean number of "clumps" obtained increased with increasing tow duration, then k should also increase. Since this is not the case for our experimental data (tow length varied from 15 min to 2 hours), it may be inferred that the fish are fairly randomly distributed locally. Thus model 1) may be more appropriate, in which case k would be approximately indpendent of sampling unit size, and areas of high density or schools would be represented by a large value of λ. This is not to say the fish are not clustered, but only that on a small scale they are randomly distributed.

Precision vs. duration of tow

When sampling a population, it is generally true that the larger the size of the sampling unit the greater the precision; but for a highly contagious population, little precision will be gained by taking large sampling units. Put precisely, the coefficient of variance, denoted by C which equals $\frac{\sigma}{\mu}$, decreases with increasing unit size sampling but does not go to 0. This may be contrasted to a randomly distributed population where C will tend to 0 when the size of the sampling is increased.

For the negative binomial distribution we have from (2) that

$$C = \left(\frac{1}{\mu} = \frac{1}{k}\right)^{\frac{1}{2}}. \qquad (4)$$

Figure 12 shows C plotted as a function of μ with an estimate of k for eel pout along with the sample estimates of C (i.e., $S/\bar{x}$). It is quite apparent from the graph that though C continuously decreases, little precision is gained for eel pout by towing longer than that sufficient to obtain a mean of about 4.

From the general shape of the graph of C it can also be seen that for species with similar values of k, those with small mean catches will have higher coefficients of variance than those with large mean catches. Furthermore from equation (4), the smaller k is the higher C will be. This phenomenon was observed by Hennemuth (1976). The coefficients of variation were largest for mackerel and herring both of which have low values of k and μ. It should be noted that the rate of decrease of C (Figure 12) will depend on k, from equation (4) it can be seen that the smaller k is the smaller the mean will need to be in order to detect an increase in C. This effect of the magnitude of k on the general sampling properties of the negative binomial distribution can be seen easily from equation (1); the smaller k is, the larger will be the range of population sizes for which σ^2 approximately equals $\frac{1}{k}\mu^2$.

<u>Selecting sample size and length of tow to maximize precision</u>

Taylor (1953) observed that when heterogeneity is present, a smaller sampling unit is more efficient (with respect to total area covered by the trawl) than larger units. This can be seen easily from Figure 12; the area sampled by the trawl to obtain a mean catch of 4 is one half the area needed to be sampled to obtain a mean catch of 8 though C is virtually the same for both. On the other hand, it is also apparent from Figure 12 that as the mean catch becomes small, the efficiency gained by taking more shorter tows will be small because C increases rapidly. This situation may again be contrasted to the case when the fish are distributed randomly, i.e., for a randomly distributed population all unit sizes are equally efficient.

Another way to depict this gain in efficiency is as follows. The coefficient of variation C for a single tow of length T with expected mean catch of m_o is by equation (4) equal to

$$C = (\frac{1}{m_o} + \frac{1}{k})^{\frac{1}{2}}$$

If instead of taking one long tow, n shorter tows of equal duration with total towing time equal to T were made, then the coefficient of variation for the sample mean will be

$$C_n = C/\sqrt{n} = (\frac{1}{m_o} + \frac{1}{nk})^{\frac{1}{2}}.$$

Hence as more tows are taken of proportionately shorter duration, the coefficient of variation will tend to $C_\infty = (\frac{1}{m_o})^{\frac{1}{2}}$, the maximum precision obtainable with total towing time T. We can thus measure the relative efficiency of taking one tow of total duration T versus taking n shorter tows of the same total duration by $\frac{C_\infty}{C_n}$. Figure 13 shows this measure of efficiency for eel pout where m_o = 25 which corresponds to a T of two hours and k = .64. Again it is apparent that one gains little by taking many very short tows. To reach 50% efficiency approximately 12 tows are required, whereas over 1000 tows are needed to approach 100% efficiency.

In practice one long tow is not equivalent, in terms of sampling effort, to many short tows; it takes a fixed amount of time to set and haul up the net regardless of the duration of the tow. The amount of ship time available to conduct a survey is usually fixed, hence it needs to be determined how many tows and the length of each tow which can be made in a fixed amount of time which will give the maximum precision. For our survey, stations are selected at random in each stratum and then a cruise track is selected which tends to minimize the amount of cruising time between stations (Figure 3). Thus since the total area to be surveyed is fixed (and stratified) the total transit time will, to a great extent, be relatively independent of the number of tows. After estimating the time required for transit, let T denote the total time left for sampling purposes at each station. Denote by c the amount of time needed to set and haul up the net, and let t be the duration of an individual tow. Then the number of tows n which can be made in time T will be:

$$\frac{T}{c+t} \tag{5}$$

and the mean catch per tow m of length t is given by (see e.g. Figures 5 and 6)

$$m = a\,t \tag{6}$$

Thus substituting (6) into equation (4) and using (5), the coefficient of variation C_n for the sample mean is given by

$$C_n = \left(\frac{1}{a\,t} + \frac{1}{k}\right)^{\frac{1}{2}} / \left(\frac{T}{c+t}\right)^{\frac{1}{2}}$$

which is equal to

$$\frac{1}{\sqrt{T}} \left(\frac{c+t}{a\,t} + \frac{c+t}{k}\right)^{\frac{1}{2}}$$

and which has a minimum at

$$t_o = \sqrt{\frac{ck}{a}} \qquad (7)$$

Thus other than the obvious restraint of $t_o \leq T$, the most efficient length of tow is independent of T. If it is deemed, for a particular survey, that the amount of transit time necessary will increase with sample size then this can be taken into account by increasing c.

To determine t_o, one needs to know c, k, and a. From experience with the gear, c is easily estimated, and k, which as we have seen appears to be independent of population levels and sampling unit size, can be estimated from catch per tow data (or preliminary estimates of between .1 and .9 can be used, in general the greater the level of schooling the lower the value of k). Since equation (6) has intercept zero, if the mean catch for any length of tow is known, then "a" can easily be estimated.

For our survey, c is equal to ½ hour. Values of t_o a for a few selected species are given in Table 1. As can be seen from Table 1, t_o varies considerably from species to species, hence since we are interested in many species a t_o must be chosen which is adequate for most. Furthermore since t_o is inversely proportional to m, the optimum tow length will increase as the stock declines. Thus it may be desirable to lengthen the towing time if the stocks decline drastically. Since catch is linearly related to time towed, the surveys will still be easily comparable. Taking into account these factors it appears that our present ½ hour tows are efficiently monitoring the multitude of species in which we are concerned.

V. Accuracy of the Survey Index

It has been found that for most species the 95% confidence intervals are of the order of ± 50% of the mean for areas such as Georges Bank (strata 13-25) where approximately 70 tows are taken in each survey (Table 2, Grosslein 1971). Though the precision of each survey index is not high, when looked at as a time series the survey indices do reflect population trends rather well (Clark and Brown 1977). For example, the recent survey abundance indices for yellowtail flounder in southern New England indicate a substantial decline in abundance which was corroborated by other population studies (Figure 14). However, the yellowtail indices also illustrate the problem of occasional anomalous indices - the 1972 index was clearly an outlier which represents a problem for predicting abundance for that one year although in the longer time series it did not obscure the basic downward trend. The 1972 index probably was biased because of a change in fish behavior or gear performance and this is discussed further in the last section.

Factors affecting the precision of the abundance indices

One obvious way to increase the precision would be to increase the sample size. But this would be prohibitively expensive. Grosslein (1971) has estimated that to reduce the confidence intervals of the mean to ± 10% the number of tows would need to be increased to a level more than eight times the present sampling intensity (Table 3). Another possible way to increase precision would be to post stratify the sample with respect to time of day to take into account the substantial diel differences in catchability observed for many species (e.g., yellowtail, Figure 14). Preliminary calculations indicate that such a stratification could reduce the standard error by about 10%. Another approach would be to control or at least monitor the performance of the trawl more closely, for example, it is likely that some of the observed variability may be generated by the actual variation in distance towed on standard hauls (Figure 15, Overholtz 1978). We now consider the possible contribution of this factor to the variability of survey abundance indices.

As we have seen, heterogeneous Poisson sampling is a likely model for explaining the fact that the distribution of catch per tow is negative binomial. That is, we assume the fish are distributed randomly in a particular small area with Poisson mean λ which varies from place to place. Further we assume that the distribution of λ is Gamma. Then the mean μ_λ and variance σ_λ^2 of λ, in terms of the parameters of the Gamma distribution, are $^k/\alpha$ and $^k/_{\alpha}{}^2$, respectively. The resulting distribution is negative binomial with parameter k, and $p = \frac{\alpha}{\alpha+1}$. Its mean is $^k/_\alpha$ which is μ_λ, i.e., the average density of fish, and its variance is $\frac{k\ (\alpha+1)}{\alpha 2}$ which can be rewritten as

$$\frac{k}{\alpha} + \frac{k}{\alpha^2}$$

Thus the variance σ^2 of catch per tow can be expressed as

$$\sigma^2 = \mu_\lambda + \sigma_\lambda^2 \qquad (8)$$

or σ^2 equals the mean number of fish per sampling unit (or recalling that the mean equals the variance for a Poisson distribution, μ_λ represents its 'average' variability caused by the fish being randomly distributed locally) plus the variance of λ, i.e., the variability of the density of fish from area to area.

The above decomposition of σ^2 assumes that the sampling unit is of fixed size. For our survey this is not the case. At present each tow lasts for 30 minutes at a speed of 3.5 knots through the water. However, the actual speed and hence distance over the bottom varies according to the effects of wind and currents (Overholtz 1978). Thus if the fish are stationary with respect to the bottom the effective value of λ will not only be a function of location but also of distance towed. Hence assuming that the mean catch λ and the distance towed d are linearly related, then we have

$$\lambda = ad \tag{9}$$

where a is the Poisson mean of a standard unit, say for d=1, and varies from place to place. If we further assume that the resulting distribution of λ is Gamma, which as we have noted closely approximates a wide range of distributions, then the distribution of catch per tow will be again negative binomial.

In order to estimate the added variability caused by d being a variable, we can approximate the mean and variance of λ, using a Taylor series expansion of (9), by

$$\mu_\lambda = \mu_a \mu_d$$

and

$$\sigma_\lambda^2 = (\mu_d)^2 \text{ var(a)} + (\mu_a)^2 \text{ var(d)}$$

where we have made the reasonable assumption that a and d are independent. Thus the variance of catch per tow will be from (8) equal to

$$\mu_a \mu_d + (\mu_d)^2 \text{ var(a)} + (\mu_a)^2 \text{ var(d)}$$

which may be rewritten as

$$\mu_a \quad \mu_d + \left(\frac{var(a)}{(\mu_a)^2} + \frac{var(d)}{(\mu_d)^2}\right) \quad (\mu_a \quad \mu_d)^2 \tag{10}$$

Comparing equation (1) to (10), it can be seen that the effect of distance towed being a variable is to increase $^1/_k$ which approximately equals for larger values of μ $\sigma^2/_{\mu}2$ or C^2. Thus we can estimate the percentage of C due to d by

$$100X \left(1 - \sqrt{1 - k \frac{var(d)}{\mu_d^2}}\right) \tag{11}$$

For example, for our spring survey $\frac{var(d)}{\mu_d^2}$ was estimated to be .13; then for k = .6, we would have from (11) that 6% of C is due to variable distance towed. This slight loss of precision due to variable distance towed, reflects the fact that our survey covers a very large area, and hence the major component of the variance of λ is due to marked difference in fish density across the region surveyed; for surveys of limited area, varying distance towed may have a much greater relative effect. Furthermore since our survey is stratified, the variance of λ will be smaller in each stratum than for the whole area and hence (11) can only be taken as a lower bound for the precision to be gained when stratified estimates are used.

Sources of Bias

Bias in trawl survey abundance indices may arise from changes in (1) fish behavior, (2) gear performance, or from (3) mismatch between timing and area of survey in relation to movements and distribution of the fish. Since our surveys usually encompass the entire range of populations in a synoptic way, we are usually most concerned about sources (1) and (2).

It is necessary here to distinguish between consistent and erratic differences in fish behavior and gear performance. Unadjusted survey indices have a consistent bias in the sense that they reflect only that proportion of fish in the path of the trawl which is actually caught. That is, the mean catch per haul is only a relative abundance index and must be adjusted by the average catchability coefficient to represent absolute abundance.

Each species has its own unique behavioral characteristics and hence catchability coefficient, which for most species exhibits consistent differences with time of day, season and bottom type. Normally we treat each season separately and differences related to bottom types generally are not a problem because we compare the same set of strata from one year to another. Time of day usually is not a problem because we combine a fairly large number of hauls spread rather uniformly throughout the 24-hour period over a large geographic area; therefore, significant imbalances between numbers of day vs. night hauls in stratified indices are uncommon. Another probable source of consistent bias may occur as a result of the greater tendency for our survey vessel to tow against the current as indicated by the fact that the average distance hauled is less than 1.75 knots (Figure 15). This consistent bias would have the effect of reducing the average catchability coefficient by a very small amount, and would be troublesome only if one were comparing two areas of widely different current speeds.

In this paper we have dealt primarily with relative indices and are more concerned with erratic changes in fish behavior or trawl performance. Gear malfunctions can be detected by haul by haul monitoring of trawl performance, but behavioral changes are more difficult to measure. For example, since the trawl samples only a few meters above the bottom, biological factors may change the vertical distribution of the fish from year to year, and hence the percentage of the population which is "catchable" may vary over time. This is more likely to be a problem for pelagic species such as herring or mackerel but it can also occur with demersal species as illustrated by the yellowtail flounder index for 1977. In this case we examined day and night catches separately and noted that the day catches did not show the anomaly in 1972 (Figure 14). It was further observed that the ratio of night to day catches were relatively stable over the rather large reduction in stock size from 1970-1975, except for 1972 (Table 4). The implication here is that there was an increase in catchability of yellowtail in 1972, perhaps due to an unusual level of activity off the bottom after dark. In general, it is possible that ratios may be useful in detecting anomalies in catchability or gear efficiency (a stability index, say). We will continue to search for new indices, which will be sensitive to changes in availability of fish to the sampling gear. In any case, a closer monitoring of trawl performance with acoustical devices and perhaps also photographic studies of fish behavior in front of the trawl, may hold significant promise of improving accuracy, by distinguishing between variability induced by standard trawling operations and that generated by the actual spatial distribution and behavior of the fish.

APPENDIX

THE Δ-DISTRIBUTION

If a population is such that there is a proportion q of zeros, and the distribution of nonzero values is lognormal, then the resulting distribution is called a Δ-distribution [see Aitchison and Brown (1957) for a detailed description of the properties of this distribution]. If X is a variable so distributed, then its mean is:

$$\mu_x = (1 - q)e^{\mu + \frac{1}{2}\sigma^2}$$

where μ and σ^2 are the mean and variance, respectively, of lnX, $X \neq 0$, and the variance of X is:

$$\sigma_x^2 = (1 - q)e^{2\mu + \sigma^2}\left\{e^{\sigma^2} - 1 + q\right\}.$$

The following estimators for μ_x and σ_x^2 are unbiased and efficient:

$$m = \begin{cases} \frac{n_1}{n} e^{\bar{y}} g_n(\frac{1}{2}s_y^2) & n_1 > 1 \\ \frac{x_1}{n} & n_1 = 1 \\ 0 & n_1 = 0 \end{cases}$$

$$r^2 = \begin{cases} \frac{n_1}{n} e^{2\bar{y}} \left\{ g_{n_1}(2s_y^2) - \frac{n_1 - 1}{n - 1} g_{n_1}\left(\frac{n_1 - 2}{n_1 - 1} s_y^2\right) \right\} & n_1 > 1 \\ \frac{x_1^2}{n} & n_1 = 1 \\ 0 & n_1 = 0 \end{cases}$$

where n_1 is the number of nonzero sample values, $y = \ln X$, and g_n is the usual adjustment function for the retransformation of the lognormal distribution which can be approximated by e^x for larger values of n.

It may be noted that there is no assumption made about the relationship between the zero counts and the nonzero counts other than that a fixed proportion is zero. This may be contrasted to another model often used for the description counts, the truncated or censored lognormal distribution (Thompson 1951). For this distribution the frequency of x counts per sampling unit is given by:

$$\int_{\ln x}^{\ln(x+1)} dN(\mu,\sigma^2)$$

In particular, the frequency of zeros is:

$$\int_{-\infty}^{0} dN(\mu,\sigma^2),$$

and hence the zero and nonzero counts are part of a unified distribution.

<u>A simple method for deriving approximate confidence intervals for the Δ-distribution.</u>

From a perusal of the literature, no method has been found for calculating confidence intervals for the Δ-distribution. The major difficulty is that one would like a confidence interval for the product of the parameter p, the proportion of nonzeros and μ, the mean of X, $X \neq 0$, i, e, a confidence interval for pμ, the mean of X.

An approximate confidence interval may be obtained as follows:

(1) Calculate separately confidence intervals for P (which has a binomial distribution) and μ, say:

$$p' \leq p \leq p''$$

and

$$\mu' \leq \mu \leq \mu''$$

are 95% confidence intervals (where the fact that lnX, $X \neq 0$ is normal is used to calculate the interval for μ).

(2) Let the confidence interval for $p\mu$ be defined by the minimum and the maximum of $p\mu$ on the above rectangular region. Hence the confidence interval will be:

$$p' \mu' \leq p\mu \leq p''\mu''$$

The level of confidence will clearly be greater than 90%, and probably at least 95%. [See Halperin and Mantel (1963), and Halperin (1964) for an elaboration of the problems involved in determining confidence intervals for nonlinear functions of parameters.]

For our data, the confidence intervals generated by this method seem much more realistic than those derived under the assumption that ln(X+1) is normal; in the latter case the confidence intervals derived sometimes do not even contain the arithmetic mean, whereas for the former, the retransformed means are consistently close to the arithmetic mean.

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Table 1. Optimum towing time (t_o) for selected species on Georges Bank corresponding to population levels in 1965.

Species	Yellowtail	Eel pout	Cod	Haddock
t_o (min.)	12	18	45	2

Table 2. Stratified mean catch per haul (pounds, linear) of yellowtail on Georges Bank, and estimates of precision. *Albatross IV* fall surveys.

Year	Mean	Variance	S.D.	S.D./Mean	Mean ± 2 S.D.	No. hauls
	Strata 13-25 (15,300 sq. mi.)					
1963	18.00	11.56	3.40	.19	11.2-24.8	57
1964	18.58	53.27	7.30	.39	4.0-33.2	63
1965	12.36	15.73	3.97	.32	4.4-20.3	66
1966	5.38	3.07	1.75	.32	2.1-8.6	67
1967	9.71	6.91	2.63	.27	4.4-15.0	65
1968	14.73	11.33	3.37	.23	8.0-21.5	62
1969	12.02	9.73	3.12	.26	5.8-18.3	66
1970	6.37	3.49	1.87	.29	2.6-10.1	70
	Strata 13, 16, 19 (7,800 sq. mi.)					
1963	23.10	33.19	5.76	.25	11.6-34.6	16
1964	32.10	194.97	13.96	.43	4.2-60.0	18
1965	18.48	56.99	7.55	.41	3.4-33.6	19
1966	8.71	11.35	3.37	.39	2.0-15.4	19
1967	16.58	25.96	5.10	.31	6.4-26.8	25
1968	24.50	40.78	6.38	.26	11.7-37.3	25
1969	21.44	36.96	6.08	.28	9.3-33.6	30
1970	10.69	12.44	3.53	.33	3.6-17.8	24

Table 3. Sample sizes (total number hauls) required for specified precision of stratified mean abundance indices ($\log_e$ catch/haul in pounds) from ALBATROSS IV surveys on Georges Bank.

LEVEL OF PRECISION		Total number hauls required, approximately proportional allocation	
Percentage change linear scale	2 standard deviations linear scale	Haddock (strata 13-25)	Yellowtail (strata 13, 16, 19)
± 10%	± .10	>500	>500
± 20%	± .18	338	253
± 30%	± .26	164	120
± 50%	± .40	70	51
±100%	± .69	23	17

Table 4. Ratio of mean night catch/mean day catch for yellowtail.

Year	1970	1971	1972	1973	1974	1975
Ratio	1.4	1.8	5.2	1.4	1.0	1.3

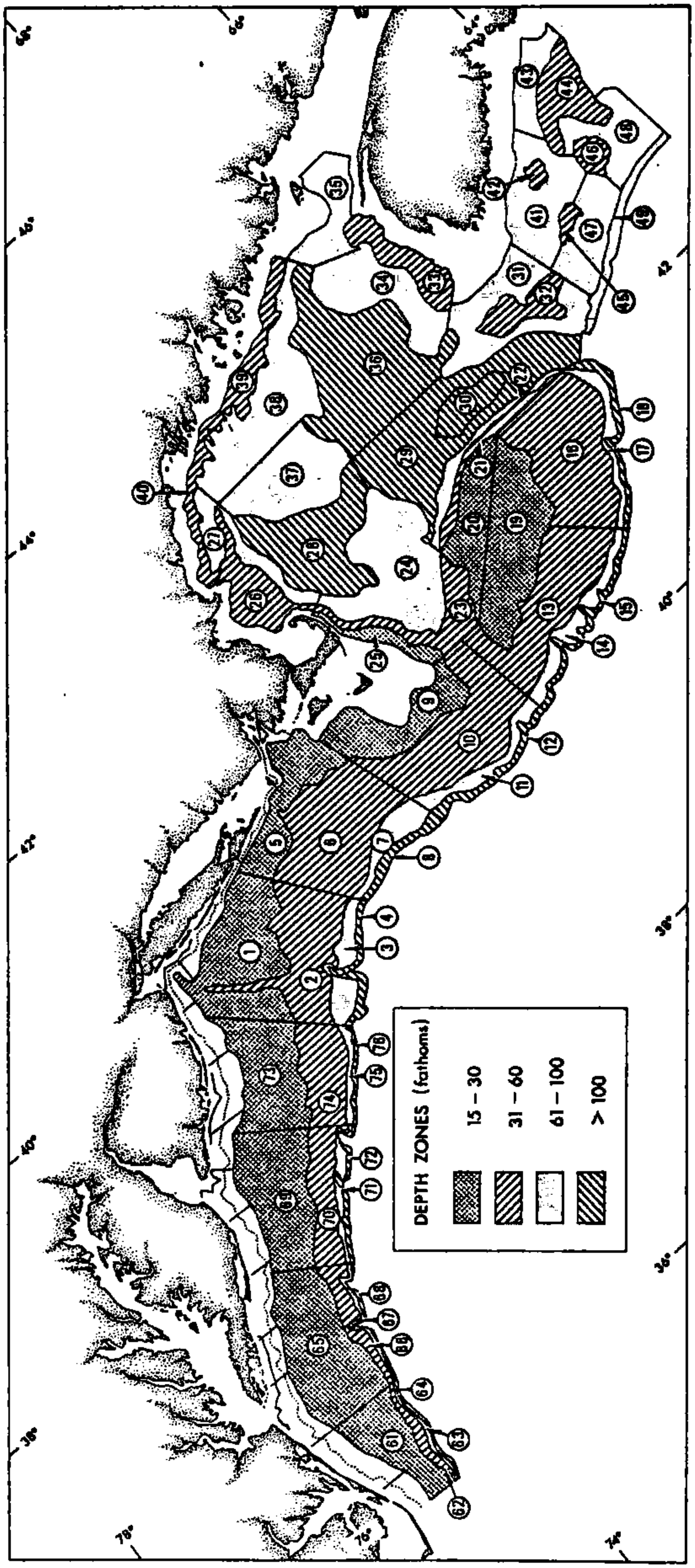
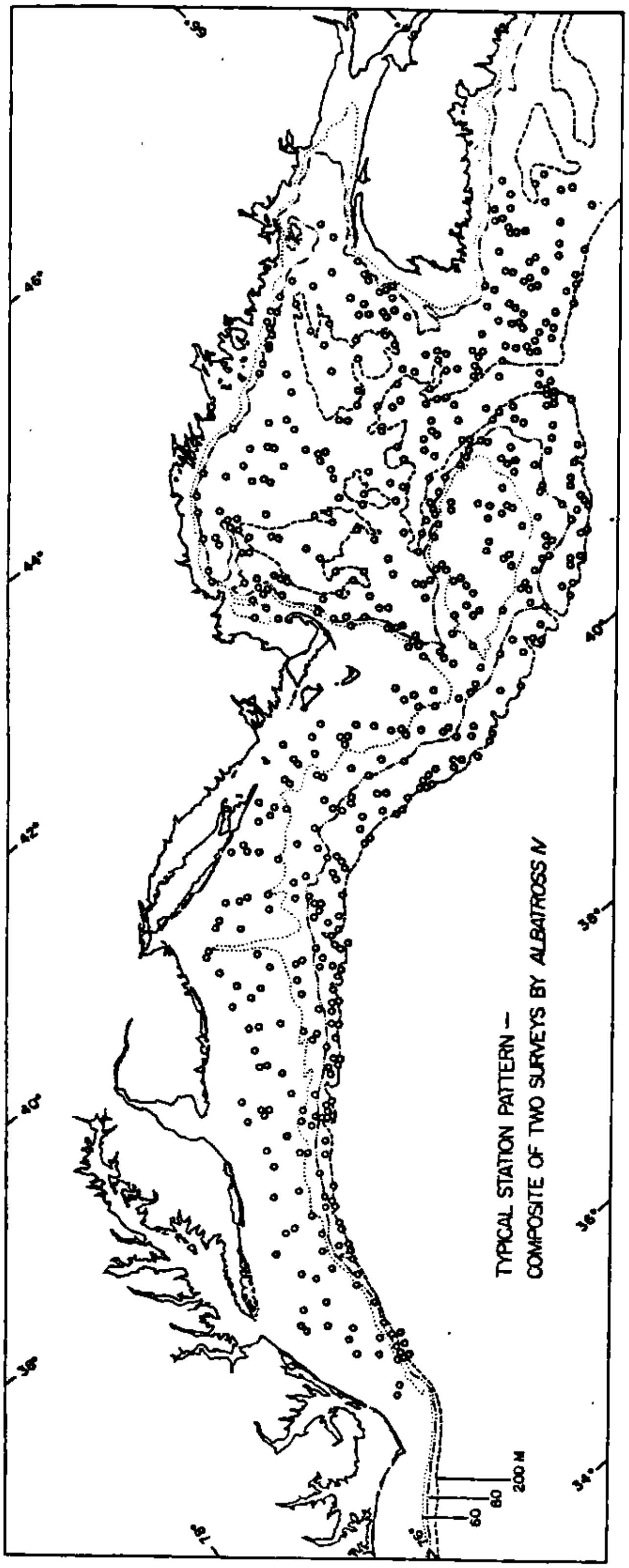


Figure 1. Groundfish survey sampling strata.


TYPICAL STATION PATTERN —
COMPOSITE OF TWO SURVEYS BY ALBATROSS IV
200 M
80
60
34°
36°
38°
40°
42°
44°
46°
66°

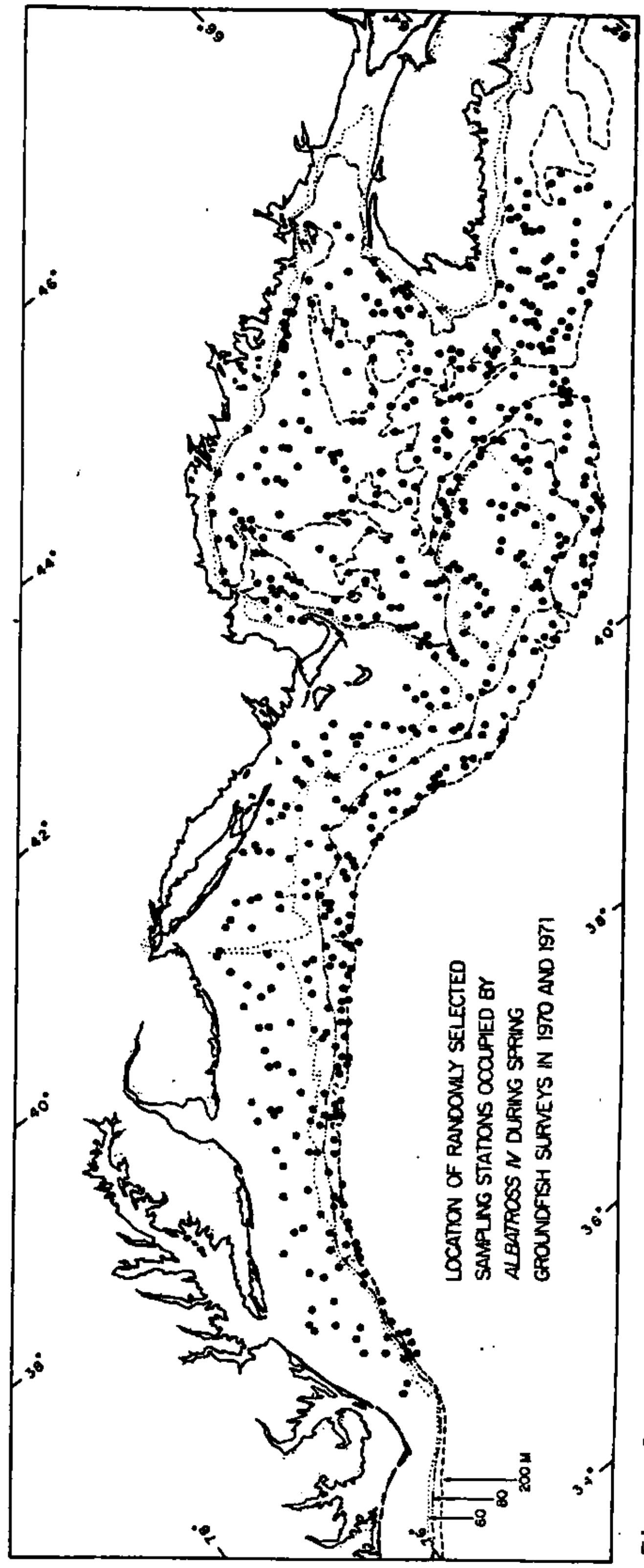

LOCATION OF RANDOMLY SELECTED
SAMPLING STATIONS OCCUPIED BY
ALBATROSS IV DURING SPRING
GROUNDFISH SURVEYS IN 1970 AND 1971
200 M
80
60
36°
38°
40°
42°
44°
46°
66°

Figure 2.

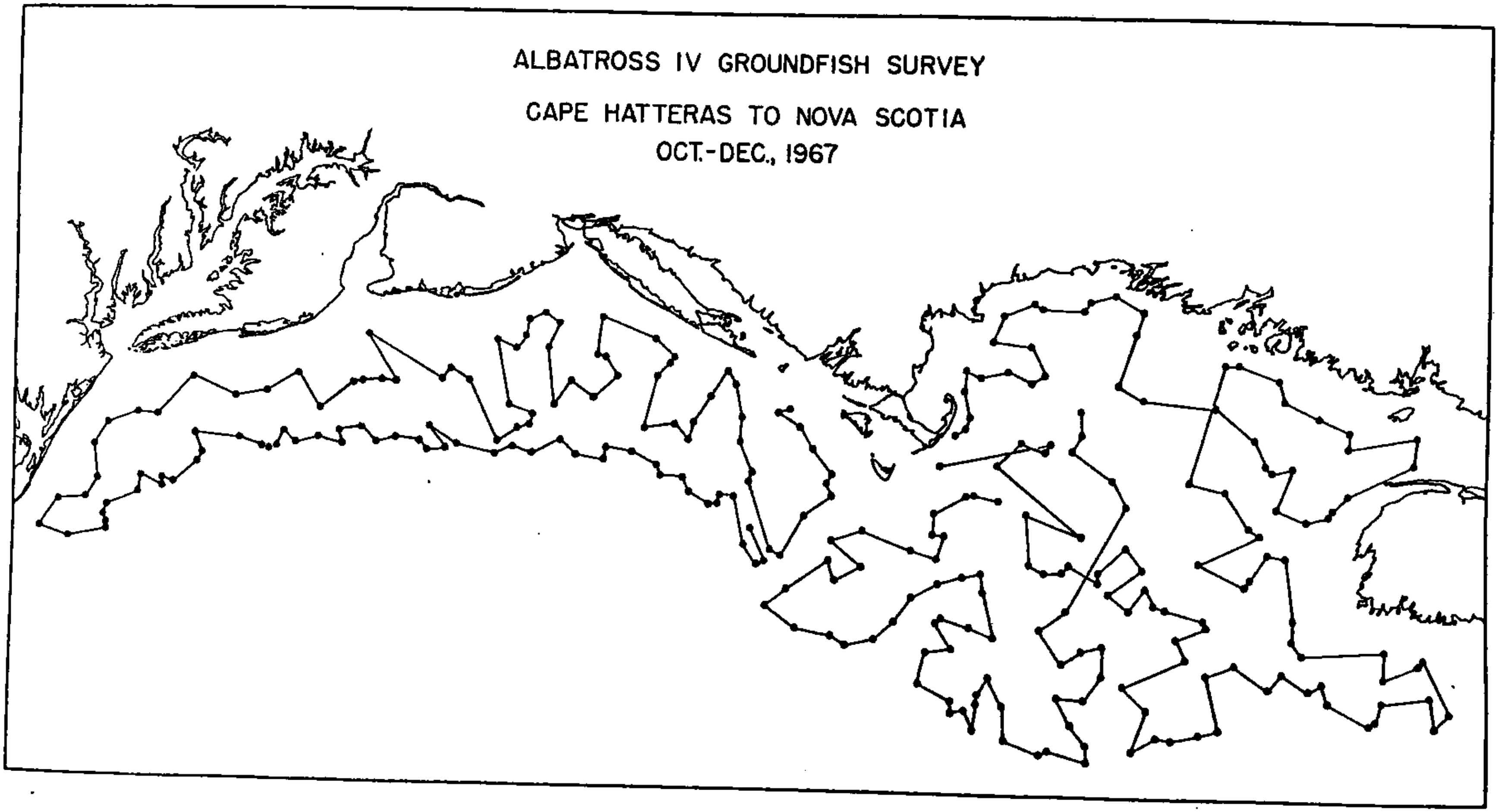


Figure 3. Cruise track followed on a typical survey

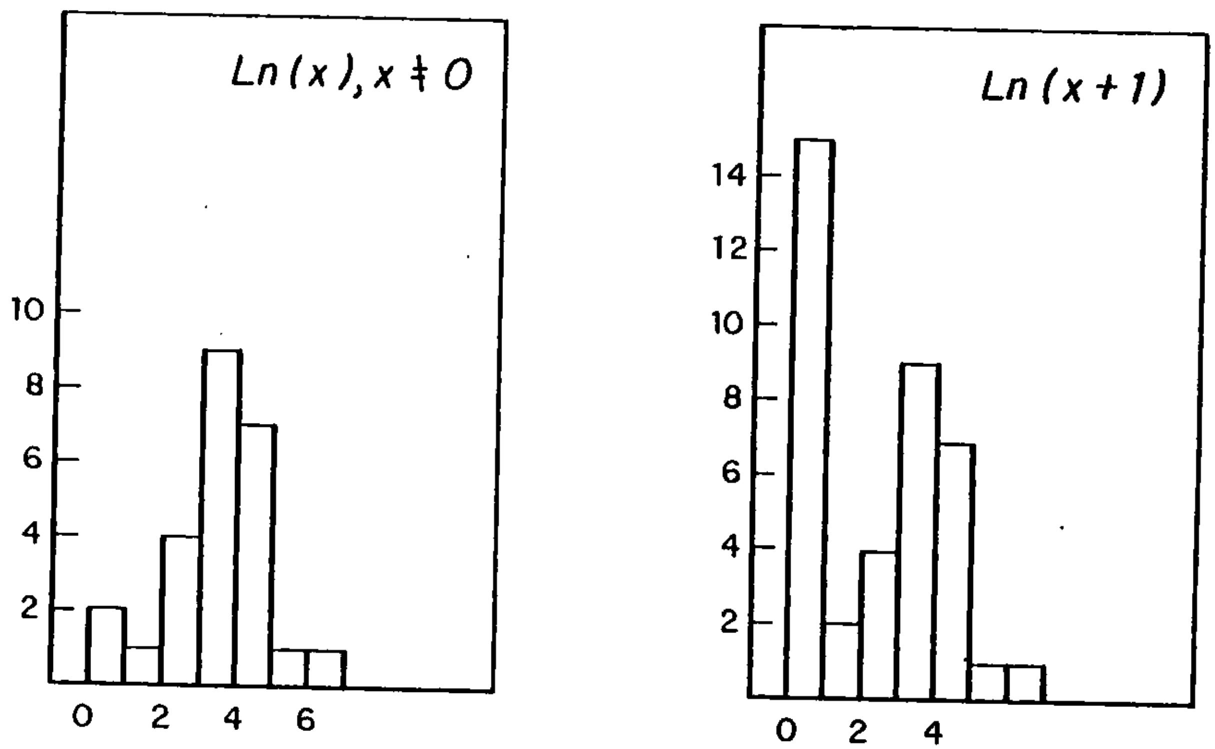


Figure 4. Frequency distribution of log transformed data of number of fish per tow for herring.

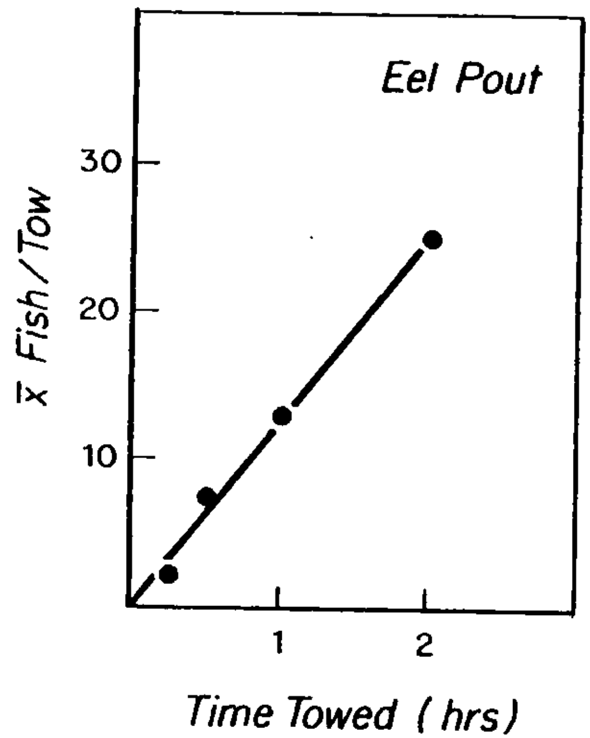


Figure 5. Plot of mean catch versus time towed for eel pout.

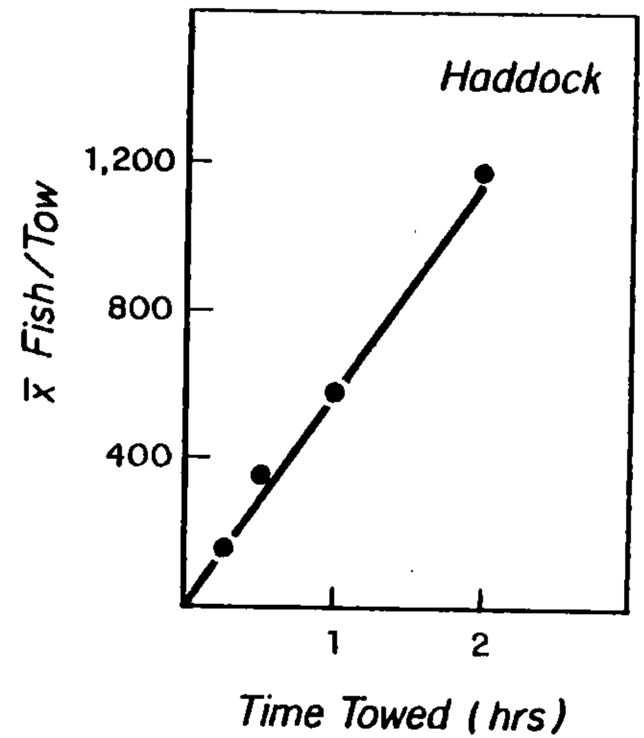


Figure 6. Plot of mean catch versus time towed for haddock.

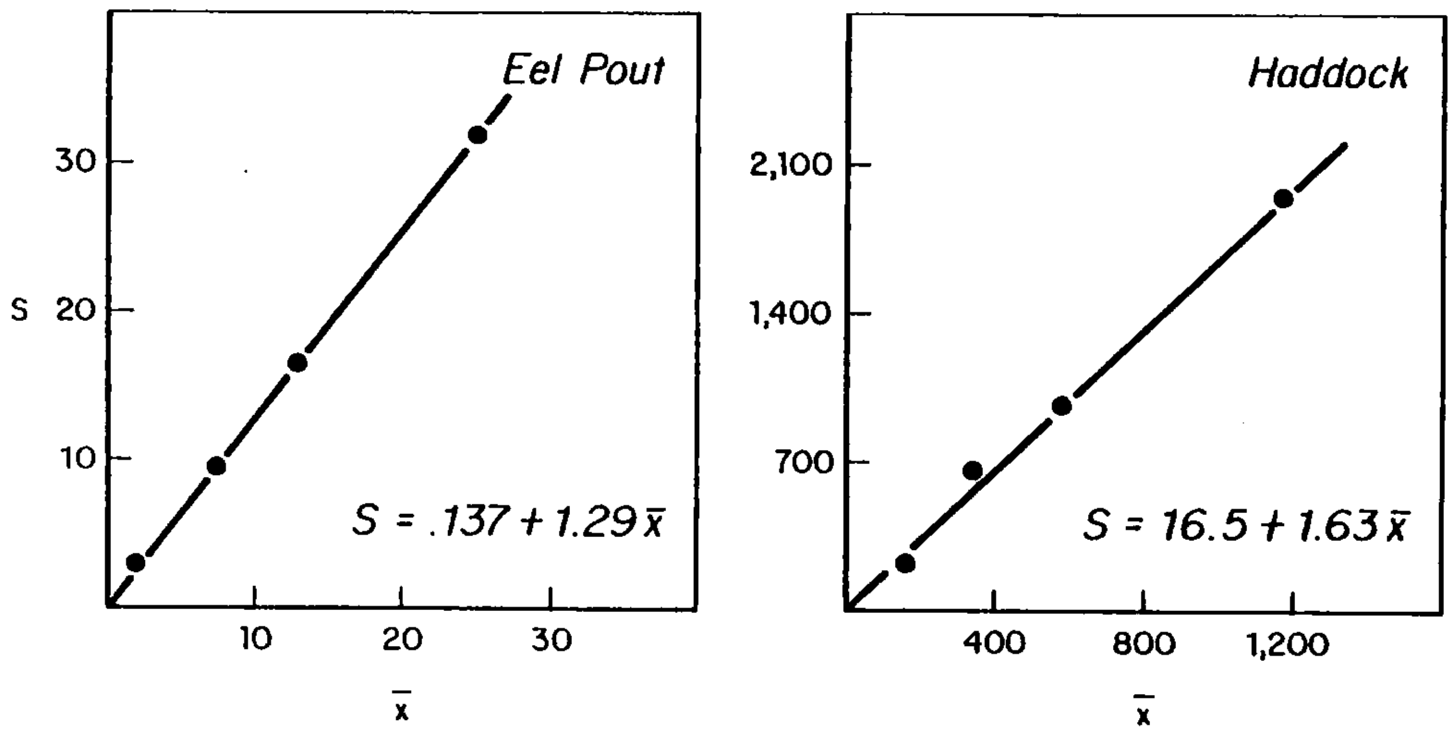


Figure 7. Standard deviation versus the mean corresponding to tows of varying duration.

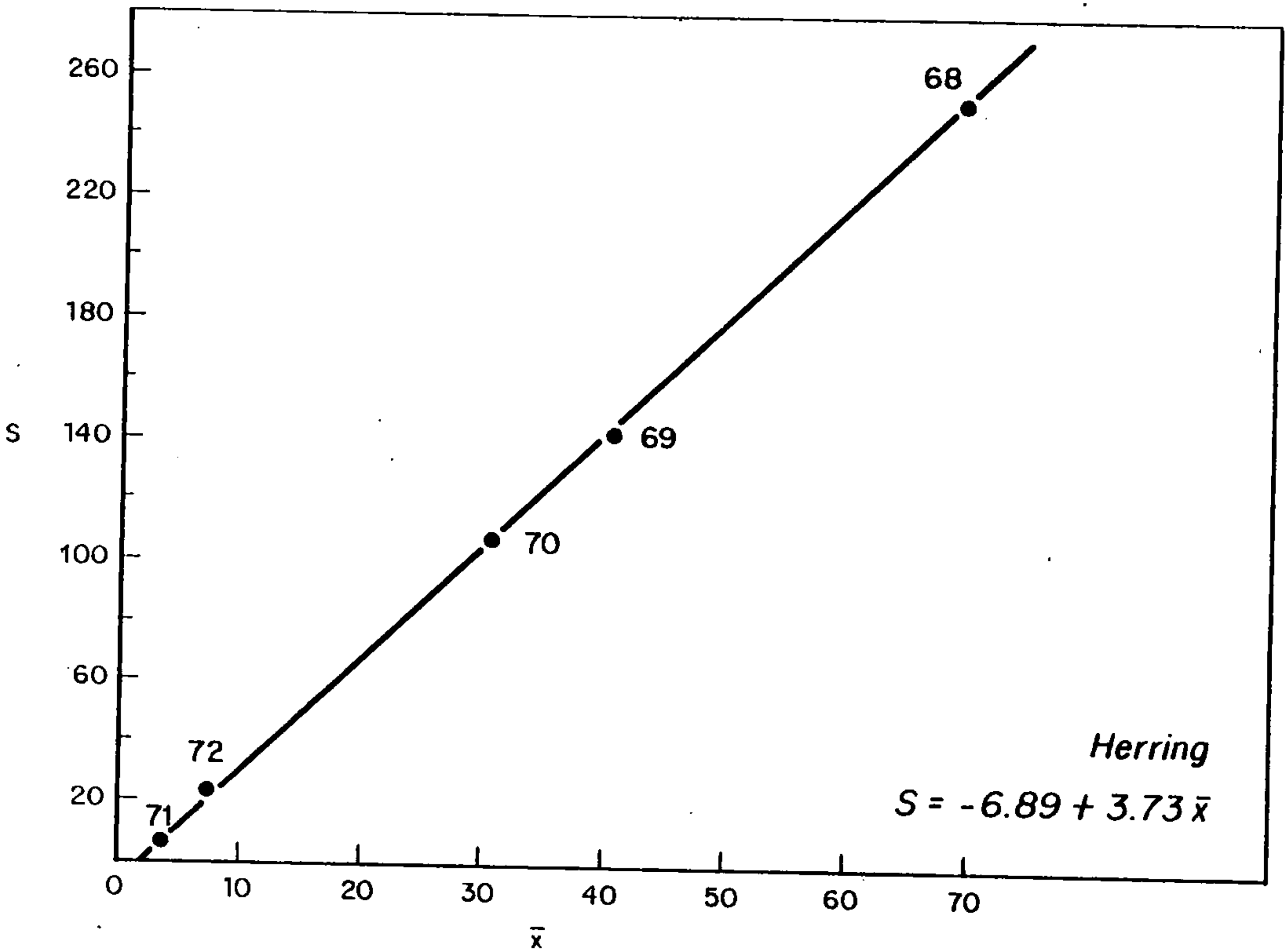
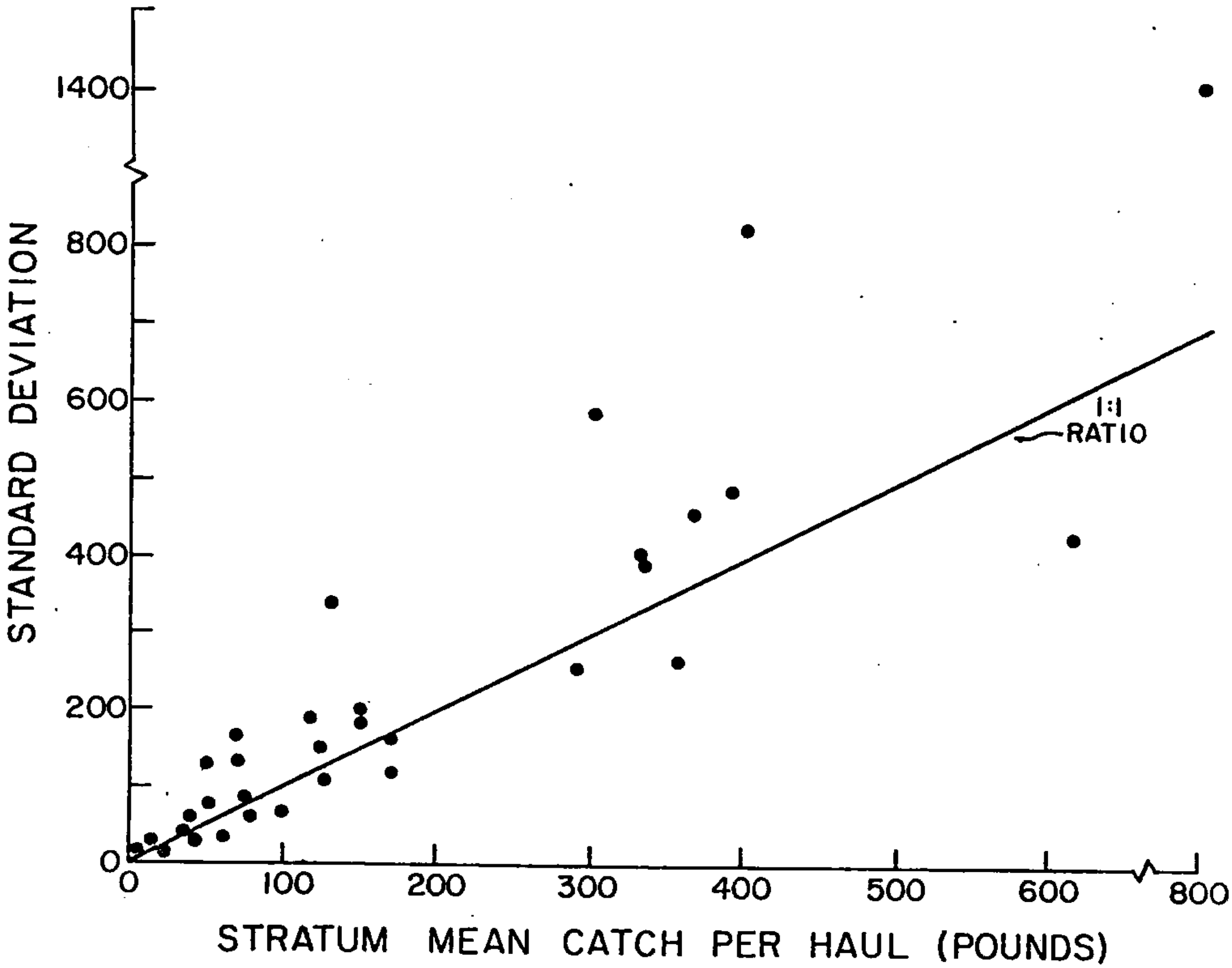


Figure 8. Standard deviation versus mean over a 5-year period (from groundfish survey Stata 1, 5, 9, 25, 65, 69, 73. See fig. 1).

Figure 9. Scatter diagram of standard deviations and corresponding stratified means.



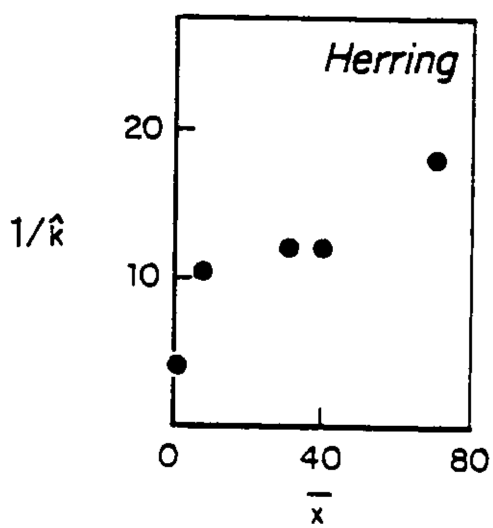


Figure 10. Plot $1/\hat{k}$ versus $\bar{x}$ from the survey daya over a 5-year period.

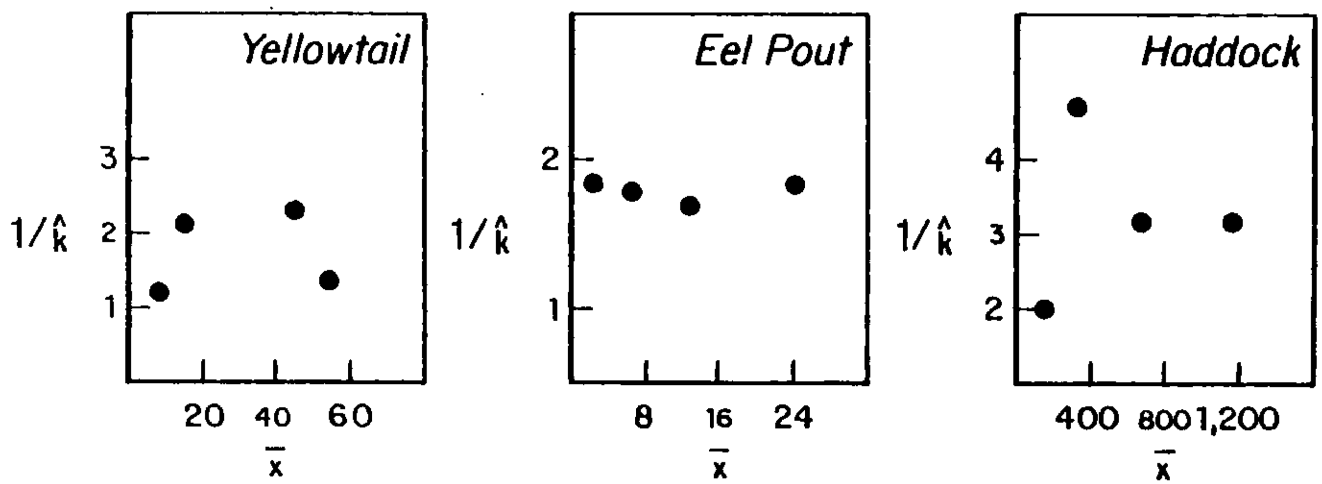


Figure 11. Plot of $1/\hat{k}$ versus $\bar{x}$ for sampling unit size.

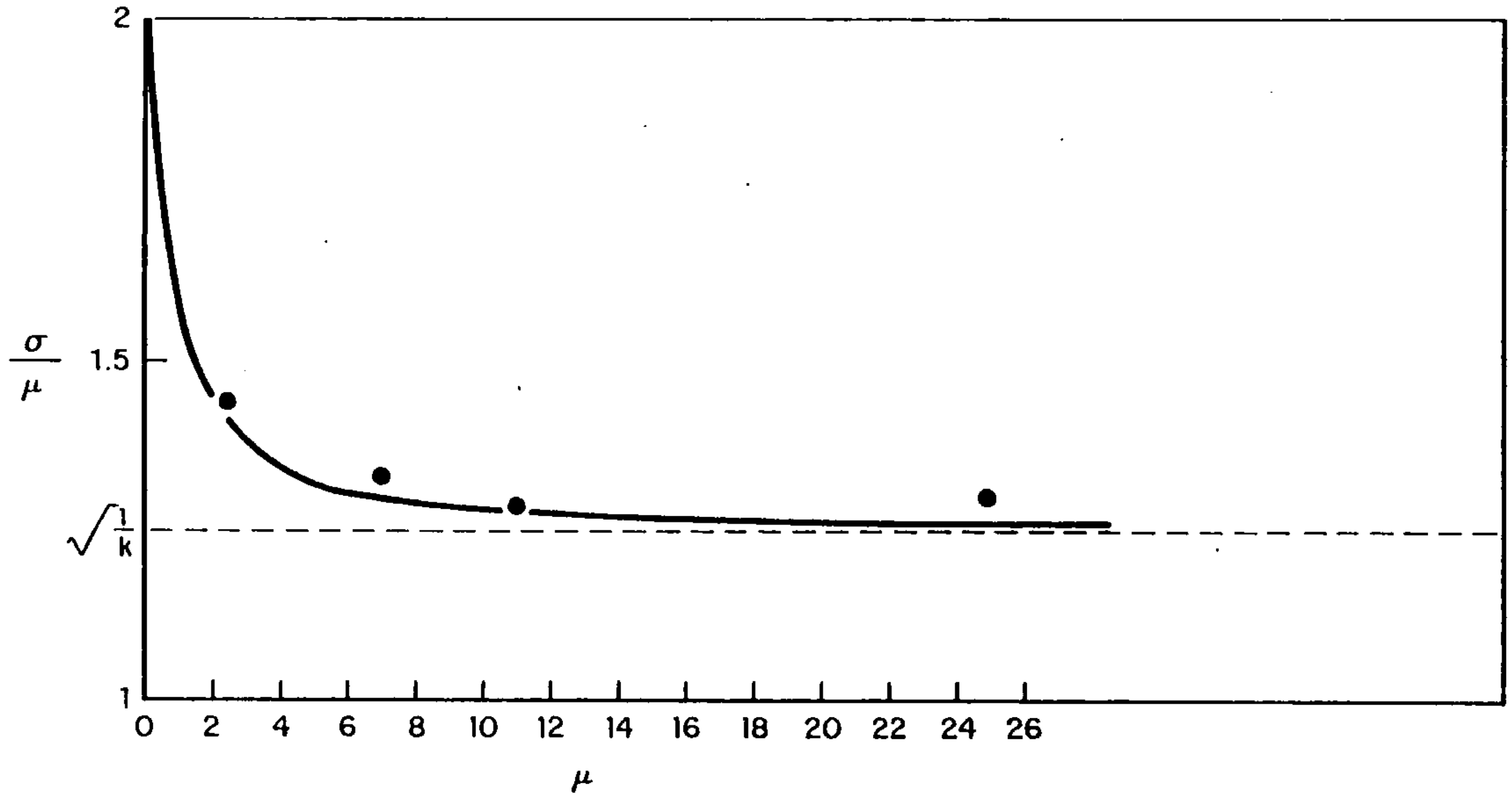


Figure 12. The coefficient of variation as a function of the mean ($C = (\frac{1}{\mu} + \frac{1}{k})^{1/2}$) for eel pout. k was estimated to be .64. The points are actual sample values of C.

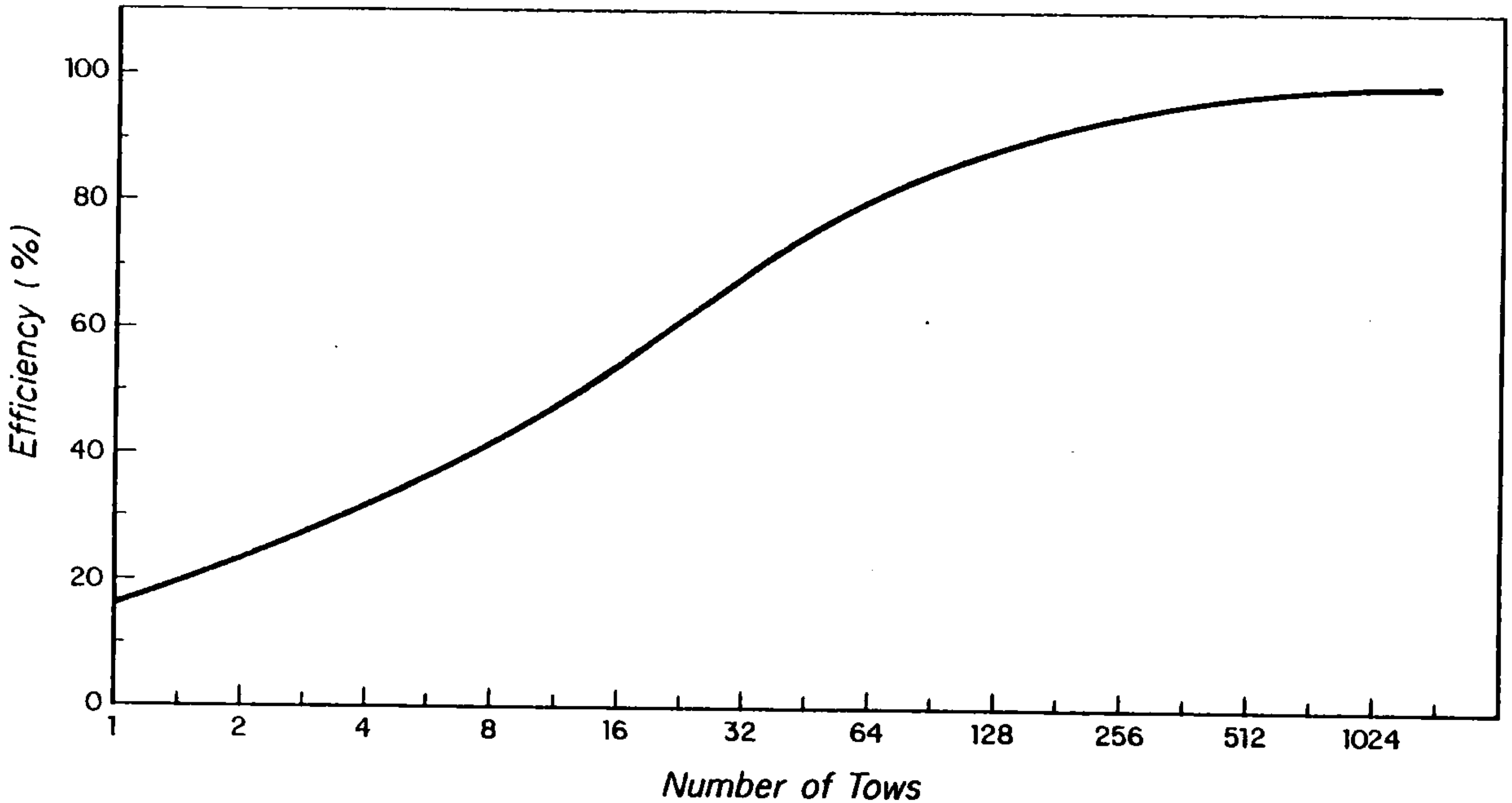


Figure 13. Efficiency of decreasing duration of tow and proportionately increasing the number of tows.

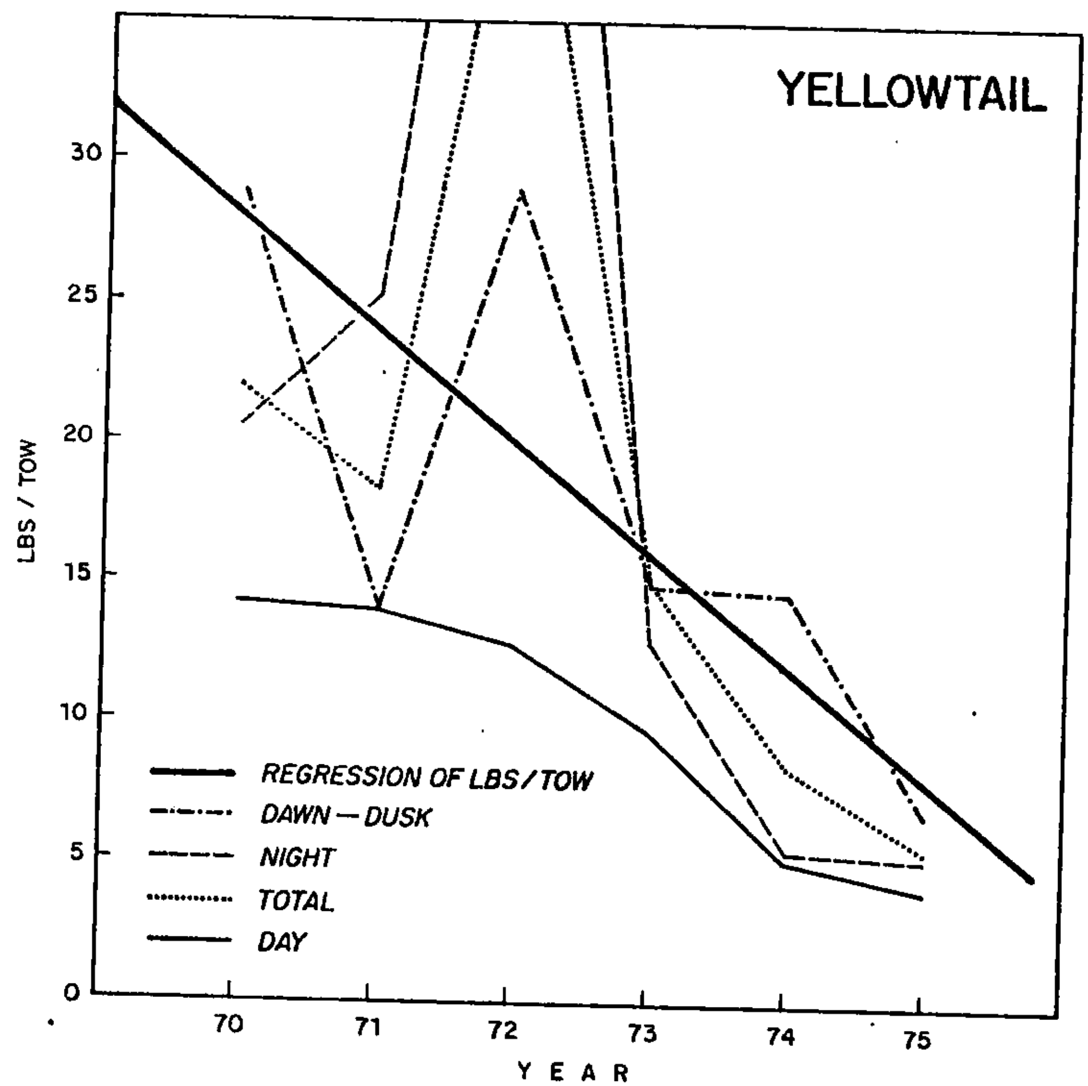


Figure 14. Mean catch per tow for night, day dawn-dusk tows and for all periods combined for yellowtail, along with the regression of total catch on time.

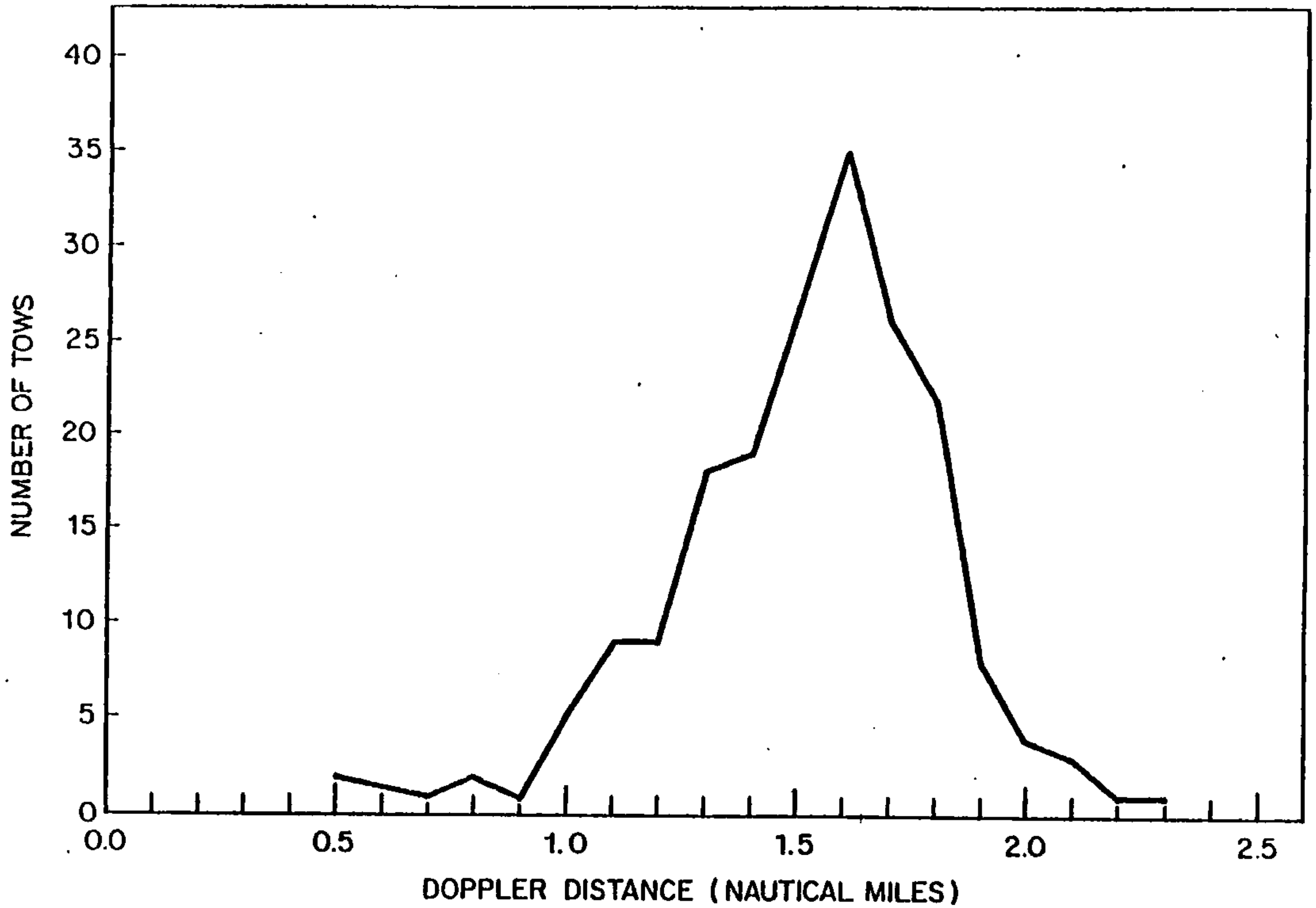


Figure 15. Doppler distances for the 1976 spring bottom trawl survey of the ALBATROSS IV (from Overholtz and Lewis 1978).