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THE INTERACTION BETWEEN FISH DISTRIBUTION, SURVEY DESIGN AND ANALYSIS

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ABSTRACT

Fish in an area will be distributed with varying density. Designing efficient surveys depends on what is known about this distribution and the way it varies from year to year, and the variability of sampling at a station. Together with the survey design, this information determines the appropriate method of analysing the survey data. This paper discusses the interaction between these three components, i.e. fish distribution, survey design and method of analysis, for both simple random sampling and fixed-station sampling. Compared with simple random sampling, fixed-station sampling may provide estimates with smaller variance, although these estimates might be biased in the sense of not being equal, on average, to the population mean. Although this bias may be unimportant for estimates made within a year, trends measured across years could be distorted if the spatial distribution is not persistent. The results are applied to data from the English groundfish surveys.

INTRODUCTION

Ideally, fish surveys would be carried out according to some pre-specified design, chosen to maximise the accuracy of the results. In practice, this ideal may have to be compromised. Data from surveys will often be used for more than one purpose; for example, estimates of abundance may be required for more than one species, or there may also be interest in the spatial distribution of these species. There will also be practical limitations, such as bad weather or restricted access to parts of the survey area, for example where gear damage is likely or where fishing is denied e.g. in the vicinity of pipelines. These limitations may constrain the original design, or lead to *ad hoc* modifications during the survey.

For discussion, we will consider a simplified problem and assume that we wish to estimate the annual mean index of abundance of some target group (e.g. a species, or a specified age group of a species) within a given area, and compare this index from year to year. We will then examine the way that the form, precision and interpretation of the estimates depends upon the survey design and on the spatial and temporal distribution of the fish.

METHODS

We will contrast simple random sampling (Cochran, 1977) with a design where the stations are fixed from year to year. Fixed-station designs have sometimes been advocated as a means of improving precision (Hunton, 1986). In particular, we will consider the effect of survey design and spatial distribution on the interpretation of the sample mean and variance.

We assume that the area to be surveyed consists of a finite number of non-overlapping subareas, referred to as stations.

The (true) mean index of abundance for the total area in year y is given by

$$\mu_y = \sum_{i=1}^{N} \mu_{iy}/N$$

where μ_{iy} is the (true) index of abundance at the i'th station in year y and N is the total number of stations in the area.

A survey consists of trawls made at stations selected according to some set of rules i.e. the survey design. If trawls are made at n stations the data for year y will consist of the observations

$$c_{1y}, c_{2y}, \ldots c_{ny}.$$

The sampling variance of c_{iy} observed at the i'th station is

$$V[c_{iy}] = \sigma_{iy}^2.$$

The interpretation and analysis of the c_{iy} depends upon how the stations were selected.

With simple random sampling (i.e. where the n are selected at random from the N stations), the sample mean, $\bar{c}_y$, will give an unbiased estimate of μ_y.

Its variance is easily shown to be

$$V[\bar{c}_y] = \{V[\mu_{iy}] + \sum_{i=1}^{N} \sigma_{iy}^2/N\}/n$$

where

$$V[\mu_{iy}] = \sum_{i=1}^{N} (\mu_{iy} - \mu_y)^2/N$$

is the variance between the station means. Thus $V[\bar{c}_y]$ depends on the sum of the average within- and the between-station variances. An unbiased estimator of $V[\bar{c}_y]$ is

$$\{\sum_{i=1}^{n} (c_{iy} - \bar{c}_y)^2 /(n-1)\}/n = s^2/n$$

where s^2 is the usual sample variance.

If the sampled stations are fixed, the data refer specifically to those stations. The expectation of the sample mean refers only to the means of the fixed stations, and is given by

$$E[\bar{c}_y] = \sum_{i=1}^{n} \mu_{iy}/n$$

which does not equal μ_y except in the unlikely event that

$$\sum_{i=1}^{n} \mu_{iy}/n = \sum_{i=1}^{N} \mu_{iy}/N$$

i.e. when the average over the fixed stations equals the average over all of the stations. The variance of the fixed-sample mean depends only on the within-station variances at the fixed stations, and is given by

$$V[\bar{c}_y] = \sum_{i=1}^{n} \sigma_{iy}^2/n^2.$$

Since the terms arising from between-station variance are omitted, this should be smaller than the variance from simple random sampling. However, this might not be true if stations with above average variance have been selected and/or the inter-station variance is small.

Note that estimating the variance of $\bar{c}_y$ from a fixed station design requires estimates of the corresponding σ_{iy}^2, unless these are known *a priori*. They can only be estimated from replicate trawls on each station, or from the residuals of some correctly specified model. The sample variance s^2 cannot be used to estimate $V[\bar{c}_y]$. It would generally lead to an over-estimate since

$$E[s^2/n] = \sum_{i=1}^{n} \sigma_{iy}^2/n^2 + V^*[\mu_{iy}]/n$$

$$= V[\bar{c}_y] + V^*[\mu_{iy}]/n$$

where $V^*[\mu_{iy}]$ is the variance amongst the subset of fixed-station means, which is not zero unless the spatial distribution is uniform.

Thus even in this relatively simple and apparently straightforward situation, the interpretation of the survey means and their variances requires care, and depends upon the survey design.

Similar problems of interpretation apply to estimates of the differences in the means from year to year. In general, differences between years at a specific station may not be the same as the difference between the overall means. i.e. using the usual notation for a two-way analysis of variance, the μ_{iy} can be written

$$\mu_{iy} = \mu + \varphi_i + \psi_y + I_{iy}$$

where μ is the overall mean, φ_i is the effect for the i'th station, ψ_y is the effect for the y'th year, I_{iy} is the interaction between the i'th station and the y'th year and

$$\sum_{i=1}^{N}\varphi_i = \sum_{y=1}^{Y}\psi_y = \sum_{i=1}^{N} I_{iy} = \sum_{y=1}^{Y} I_{iy} = 0$$

where Y is the number of years for which there are surveys.

The I_{iy} terms are very important when interpreting data from fixed-station designs. Only when

$$I_{iy} = 0 \qquad \text{for all } i,y$$

will the difference between years at any specific station be the same as the difference between the overall means. This characteristic has been described by Houghton (1987) as persistence.

Persistence is important if trends are measured from differences in the sample means. When stations are selected at random within each year, trends measured between e.g. years 1 and 2 will be unbiased, since

$$E[\bar{c}_2-\bar{c}_1] = \sum_{i=1}^{N}(\mu+\varphi_i+\psi_2+I_{i2})/N - \sum_{i=1}^{N}(\mu+\varphi_i+\psi_1+I_{i1})/N$$

$$= (\psi_2-\psi_1).$$

For trends measured between years 1 and 2 with fixed stations, however,the expected difference is

$$E[\bar{c}_2-\bar{c}_1] = \sum_{i=1}^{n}(\mu+\varphi_i+\psi_2+I_{i2})/n - \sum_{i=1}^{n}(\mu+\varphi_i+\psi_1+I_{i1})/n$$

$$= (\psi_2-\psi_1) + \sum_{i=1}^{n}(I_{i2}-I_{i1})/n + \sum_{i=1}^{n}(\varphi_i-\varphi_i)$$

$$= (\psi_2-\psi_1) + \sum_{i=1}^{n}(I_{i2}-I_{i1})/n$$

The important thing to note here is the change to a limited summation over n stations. For this subset of interaction terms, the sum is not constrained to be zero. Differences between sample means no longer yield unbiased estimates of $(\psi_2-\psi_1)$ unless the interaction terms are negligable, or, less strictly but somewhat unlikely, the biases are identical in each year, i.e.

$$\sum_{i=1}^{n} I_{i2} = \sum_{i=1}^{n} I_{i1}.$$

Note that the sum involving the φ_i is only zero if exactly the same series of fixed stations is sampled in each year.

RESULTS 1. Application to Hypothetical Scenarios.

To demonstrate, suppose that in each of two years a population consists of 10 stations, and that the stations means have the values 1 to 10. Hence there is a zero year effect, i.e. a zero trend. Let the within-station variance be 1. Since we are only concerned with demonstrating the interactions between sampling scheme, persistence and bias, we will remove all the unnecessary statistical clutter, and assume that the variances are known, and that we sample only one station in each year. Thus the data consist of observations c_1 and c_2 collected in year 1 and year 2 respectively.

We will consider three scenarios, chosen to demonstrate the effect of sampling scheme and spatial distribution on estimated trends. First, the distribution of the station means is the same in each year (persistence); second, the distribution is random in each year, giving a non-zero interaction; and third

$$\mu_{i1} = i$$
$$\mu_{i2} = 10\text{-}i.$$

i.e. there is a fixed, high interaction component.

Figure 1 shows a series of pairs of histograms of 100 simulations of the two sampling schemes under the different scenarios. With simple random sampling (SRS) a station was chosen at random each year. With fixed-station sampling (FSS), Station 4 was chosen in the first year and re-sampled in the second year. The left-hand histograms (A,C,E,G) show the distribution of (c_2-c_1), the estimated trend. The right-hand histograms (B,D,F,H) show the distribution of the statistic (under the null hypothesis, a Normally distributed variable with zero mean and unit variance) to test that the trend is actually zero.

The first pair (A,B) is for SRS, and applies to all three scenarios. Here we see zero bias but a relatively large amount of variability in the estimated trend. The test correctly controls the significance level at the 5% level; i.e. the proportion outside the range ± 1.96.

The next three pairs are for FSS with scenario 1, 2 and 3 respectively.

Under scenario 1 (C,D), persistence, FSS performs very well, and better than SRS. The trend is estimated without bias, and there is less scatter in the estimated trend. The significance level is correctly controlled at the 5% level.

Under scenario 2 (E,F), random station effects within years, the advantages of FSS disappear. Firstly, it has similar variation in the estimated trend to SRS. This is because the bias is variable and combines with the precision of the estimated trend to give the same mean square error as with SRS, which has zero bias but poorer precision. Secondly, the distribution of the test statistic now shows a large number of significantly large increases and decreases. This is because although we may think we are testing for a change in the overall mean, with FSS we are effectively testing for change at Station 4, which, in this example, will have by chance a different mean 90% of the time.

Under scenario 3 (G,H), the trend at Station 4 is always 3 [7-4]. Its estimate has the same small amount of scatter as that achieved under persistence since it is determined only by the within station variance, but now the estimated trend is precisely wrong, and once more leads to an inappropriate test of the overall year effect, showing a significant increase most of the time.

Again, we see that the interpretation of data depends on the method of collection, and now also on the characteristics of the population sampled. Although this example is stylized and to some extent has been constructed to emphasise the effects of sampling design, the levels of between- and within-station variability and the station-year interactions will be shown in the following section to be similar to those seen in data collected in the English Groundfish Surveys.

RESULTS 2. Application to the English Groundfish Surveys.

The ideas from the previous sections can be used to gain insight about trends in numbers of 1- and 2-group cod observed in the English Groundfish Surveys.

For each of the years 1977 to 1981, triplicate hauls were made at up to fifty stations in the North Sea between the 200m contour to the north, and 51° latitude in the south. The total area is approximately 135000 nm^2. Not all stations were sampled in all years. Although, after the first year, stations were fixed, trawls were not made at identical positions in each year. In the present case, stations are therefore defined by an area of 450 nm^2, the smallest area that will enclose all of the trawling positions on the most dispersed station. Hence the total number of potential stations in the Groundfish survey area is approximately 300.

Preliminary analysis of the data suggested that the distribution of cpue on a station for both 1- and 2-group cod is approximately lognormal. A log(cpue+0.1) was chosen to satisfy the simplifying assumption of a Normal distribution with constant variance within stations. This assumption was tested from plots of residuals, and found to be reasonable. The constant 0.1 was estimated from the smallest observed non-zero cpue, and is equivalent to a log(catch+1) transformation. The following table shows the analyses of variance to test the station*year interaction for the 1- and 2- group cod data:

		1-Group		2-Group	
Source	D.F.	M.S.E.	F	M.S.E.	F
Interaction	165	5.14	4.3	2.99	2.3
Residual	351	1.20		1.29	

Both show a significant interaction, i.e. a lack of persistence. These results are similar to those found by Houghton (1987).

Given these results, it is not clear how to combine the station means to provide the most meaningful measure of trend. Simply averaging the results is likely to be misleading. The following table gives the mean log(cpue+0.1) in each year for those 37 stations which were sampled in all five years with the standard errors appropriate for fixed-station sampling:

	1+ Cod		2+ Cod	
Year	log(cpue+0.1)	s.e.	log(cpue+0.1)	s.e.
1977	2.33	0.11	0.16	0.12
1978	1.90	0.11	1.30	0.12
1979	1.65	0.11	0.69	0.11
1980	2.45	0.12	0.64	0.12
1981	0.23	0.12	0.93	0.12

To get some measure of the potential bias that may be present in these estimates, we can estimate the variance of the I_{iy} from the analysis of variance table by subtracting the residual mean square error from the interaction mean square error and dividing by the number of replicate hauls on a station. This gives 1.31 [i.e. (5.14-1.20)/3] for the 1-group cod, and 0.57 for the 2-group cod. If we then treat the I_{iy} as independent and approximately Normally distributed, 95% tolerance limits for the biases in the yearly means for the 1- and 2-group are (-30%,45%) [i.e. $\exp(\pm 1.96 * \sqrt{1.31/37})$] and (-22%,28%) respectively.

DISCUSSION

We have shown that the interpretation of survey means and their variances depends upon the survey design. Further, obtaining unbiased estimates of differences in year effects for fixed-station surveys also depends upon the spatial property of persistence.

In the analysis of the data for 1- and 2-group cod we found that spatial patterns were not persistent, which could be a source of variation in the results not measured by their apparent precision.

Obviously, this must be acknowledged in an appropriate method of analysis. Some previous methods that have been suggested assume that the distribution of μ_{iy} within a year is highly structured and can be modelled using some simple function (c.f. Pope and Woolner, 1985). Houghton (1987) called this simplicity, and suggested a quadratic surface as the simplest possible form. For the cod data, the analyses of variance can be extended to test for this form of simplicity, giving

		1-Group		2-Group	
Source	D.F.	M.S.E.	F	M.S.E.	F
Lack of fit to Quadratic	189	7.44	6.2	6.66	5.2
Residual	351	1.20		1.29	

from which, for both age groups, there is a significant lack of simplicity, acording to this stringent definition.

Simplicity and persistence provide useful criteria for judging the difficulty of analysing fixed-station surveys. If there is simplicity but not persistence, observations from the fixed stations can be extended to the total area to yield unbiased estimates of differences between years. With persistence, as we have shown, these differences are unbiased whether the spatial distribution is simple or not. If, as here, there is neither simplicity nor persistence, the appropriate way forward is more problematical.

However, note that, to some extent, the lack of persistence detected in these analyses may have arisen from our definitions of station. The large area used to define these could have introduced interactions between years and stations if there was small scale spatial variability in catch per unit effort within stations, and this was sampled differently in different years. Similarly, a quadratic response surface is a very severe definition of simplicity, and an alternative might have led to different conclusions.

Clearly there is more work to be done, possibly building on the various methods discussed in Anon. (1990), methods which included contouring, and Kriging (Matheron, 1971; Delhomme, 1978).

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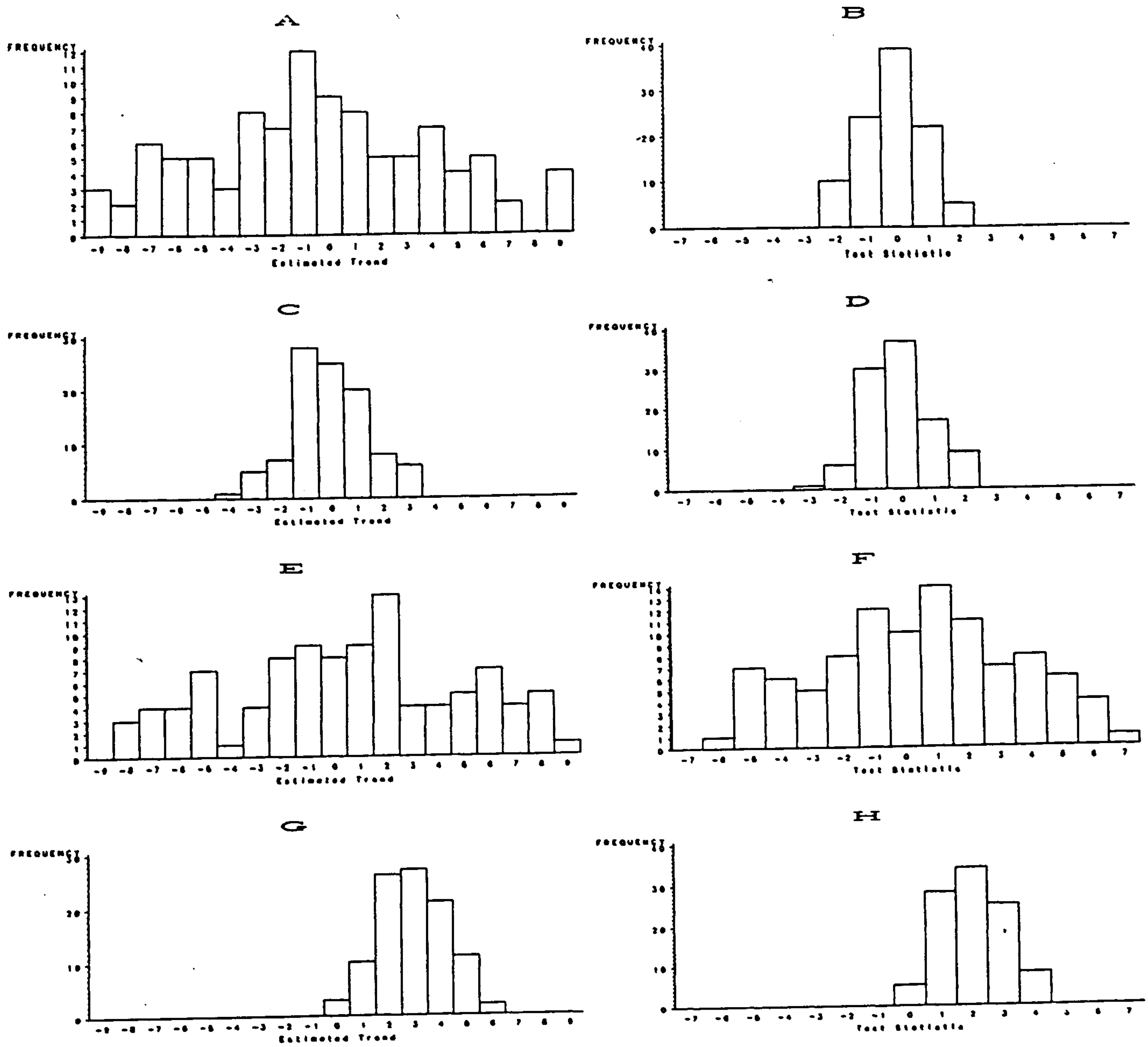
FIGURE 1


A
FREQUENCY
Estimated Trend
B
FREQUENCY
Test Statistic
C
FREQUENCY
Estimated Trend
D
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E
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H
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