Two-phase acoustic survey designs for southern blue whiting on the Bounty Platform and the Pukaki Rise

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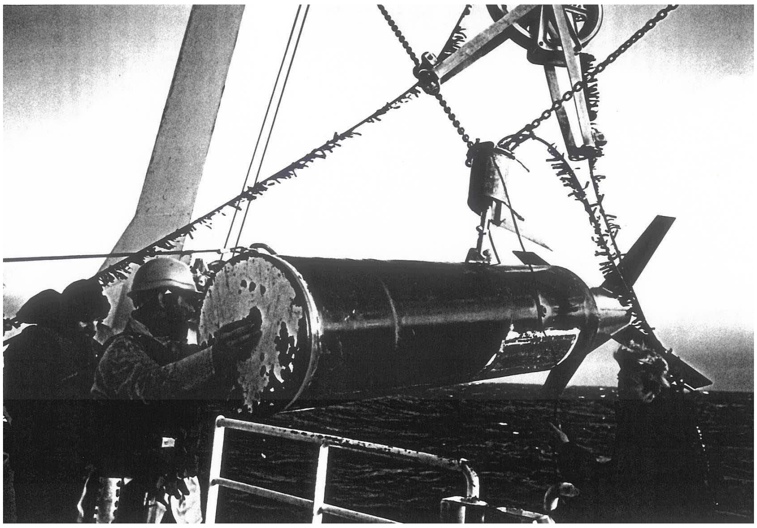

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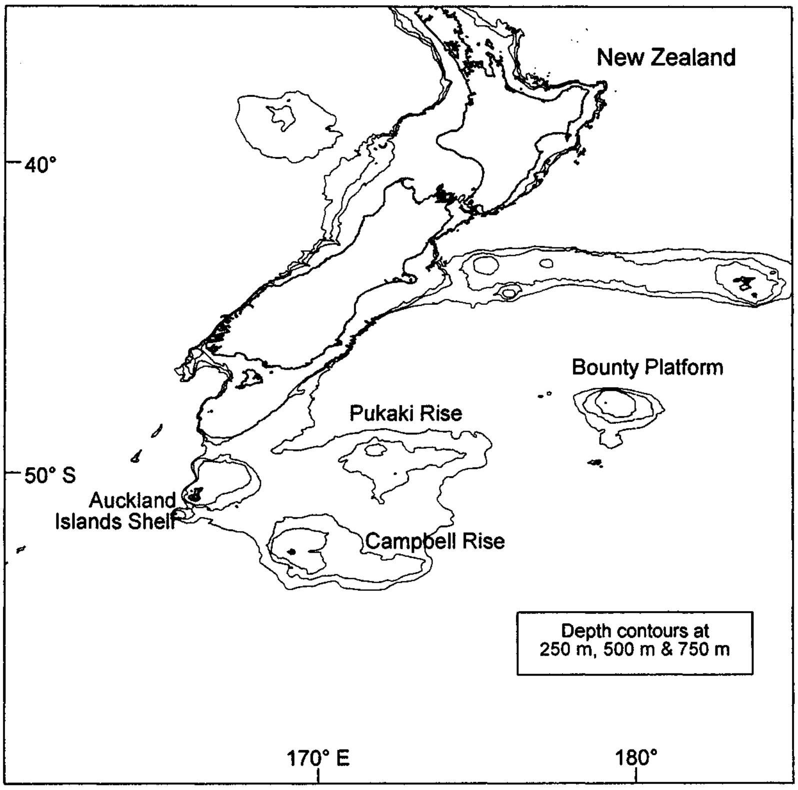

Figure 1: **Southern blue whiting spawning grounds in the New Zealand subantarctic.**

Abstract

Dunn, A. & Hanchet, S. M. 1998: Two-phase acoustic survey designs for southern blue whiting on the Bounty Platform and the Pukaki Rise. ***NIWA Technical Report 28.*** **29 p.**

The adequacy of two-phase sampling strategies in relation to the acoustic survey design for southern blue whiting on the Bounty Platform and the Pukaki Rise fishing grounds was investigated. Historical information on the spatial distribution of southern blue whiting on these grounds was examined and used in the design of a more efficient survey.

A two-phase sampling strategy was found to be of some benefit in acoustic surveys of the Bounty Platform fishing ground, but of little benefit on the Pukaki Rise fishing ground. Estimates of introduced bias from the two-phase methodology ranged up to 15% for the Bounty Platform with a corresponding halving of mean squared error. Similar estimates of bias were obtained for the Pukaki Rise, but with much smaller reductions in the corresponding mean squared error.

The spatial distribution of southern blue whiting from historical catch effort data and from previous acoustic surveys was investigated. Based on this information, strata boundaries and the sampling effort that minimised expected variance were suggested.

Introduction

The southern blue whiting (*Micromesistius australis*) fishery is one of the largest fisheries in New Zealand waters, with a catch limit of 32 000 t in 1996 (Hanchet 1997). Southern blue whiting are found throughout the subantarctic, but tend to spawn on reasonably well defined spawning grounds: Bounty Platform, Pukaki Rise, Campbell Island Rise, and the Auckland Islands Shelf (Figure 1). Each of these regions is currently managed as a separate stock.

A time series of acoustic surveys to monitor the relative abundance of each of these stocks began in 1993. These surveys were based on a standard random stratified design, with allocation of transects loosely based on historical commercial catch rates. Because of the highly aggregated nature of the fish there was concern that using a standard random survey the main aggregations may not be sampled, or, if sampled, that the precision of the biomass estimate would be poor (i.e., the estimate would have a high coefficient of variation (*c.v.*)). To counteract this concern an informal adaptive survey approach was trialled in an attempt to improve the precision of the survey estimate. Concerns that this approach may have caused bias in the estimates of biomass or *c.v.*s led to a desire for a more thorough analysis of the statistical properties of this survey design.

This report investigates the performance of two-phase or adaptive sampling strategies against conventional stratified sampling strategies, with particular reference to the acoustic survey design for southern blue whiting on the Bounty Platform and the Pukaki Rise fishing grounds. Historical information on the spatial distribution of southern blue whiting on these two grounds is examined and used to design a more efficient survey.

The analysis is presented in two sections. The first investigates the performance of two-phase sampling strategies across a range of population models. The second reviews the historical data, and considers techniques to improve the design of the current southern blue whiting acoustic survey.

The southern blue whiting fishery

The southern blue whiting fishery was developed by the Soviet foreign licensed fleet in the early 1970s (Figure 2). During the 1970s and early 1980s fishing was carried out throughout the year. With the arrival of the Japanese surimi vessels in 1986 the fishery switched to a predominantly spawning fishery. Vessels targeted the dense southern blue whiting schools as they aggregated to spawn on each of the different fishing grounds. There was a steady increase in fishing effort over the next few years, culminating in the peak catch of 75 000 t in 1992. A 32 000 t catch limit was introduced in 1993 and since then annual landings have averaged about 20 000 t.

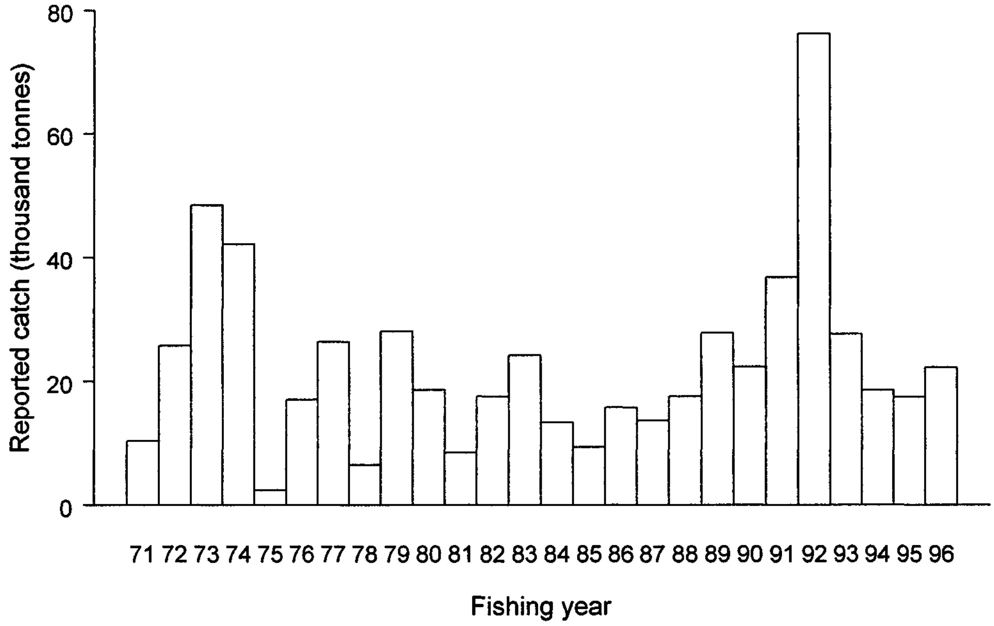

***Figure 2*: Estimated catch of southern blue whiting for the 1 October to 30 September fishing year, 1978–96 (Hanchet 1997).**

Southern blue whiting are a good candidate for acoustic surveys. They spawn at roughly the same time each year and in a roughly similar location. They form large dense aggregations or schools that can be readily identified, with few other species present within the aggregations. There is also little evidence of stock turnover. Confidence in the species identification, target strength, and lack of turnover has resulted in survey estimates being used as absolute estimates of biomass in stock assessment modelling (Hanchet 1997).

Acoustic surveys of the Bounty Platform, Pukaki Rise, and Campbell Island Rise were carried out in August and September of 1993, 1994, and 1995 (Hanchet *et al.* 1994, Hanchet & Ingerson 1996, Ingerson & Hanchet 1996). The Auckland Islands Shelf was surveyed in 1995. No acoustic surveys of the fishery were conducted in 1996.

Survey design

Conventional design

Conventional acoustic survey design typically applies a standard stratified random survey methodology to the region of interest, as described by Jolly & Hampton (1990). Sampling occurs by integrating acoustic back-scattering data continuously along random transects. Biomass or abundance estimates can then be determined by combining this information using standard sampling theory. See Jolly & Hampton (1990) and Coombs & Cordue (1995) for more complete descriptions of the process of obtaining biomass and abundance estimates from acoustic surveys.

It is common survey design practice to partition the survey region into sub-regions, or strata, according to habitat types (i.e., depth zones) and known or suspected spatial patterns of fish distribution (Francis 1984). This stratification reduces the variance of the biomass estimate, enables estimates to be made in separate sub-regions of interest, and ensures that sampling occurs across all sub-regions.

In addition, Cochran (1963) described the principal reasons for stratification as including:

- estimation of sub-populations within a survey population
- administrative or financial convenience
- consideration of differing sampling problems relating to different locations and sub-populations
- gain in precision (or equivalently, reduction in variance)

Conventional stratified sampling theory was described in detail by Cochran (1963) and Raj (1968). Stratified sampling is used in most acoustic surveys primarily as a means of reducing variance. Optimal (in the sense of minimising variance) allocation of survey effort between strata can be related to the density and area of each stratum, the variance within and between each stratum, and the cost of sampling from each stratum. In practice, we assume that the cost of sampling is fixed and does not vary between strata. Hence, optimal allocation occurs when the number of random samples within strata is proportional to its density multiplied by its area and its standard deviation. Assuming that the cost function can be ignored we get the following result.

For a fixed sample size, n, with fixed total cost, the ith strata sample size, n_i, which minimises the estimated point estimate variance, $var(y_{strata})$, is

$$n_i = \frac{nA_i d_i S_i}{\sum A_i d_i S_i} \qquad [1]$$

where A_i is the area of a stratum, d_i is the relative density of stratum i, and S_i is a measure of the standard deviation within stratum i.

Often, particularly where the underlying spatial distribution of the fishery stock is unknown, it is simpler to allocate an equal number of transects to a number of roughly equal sized strata. This results in simple stratified random sampling, typically with lower efficiency than proportional allocation, though with the advantage of a lower risk of obtaining estimates with very poor precision.

Efficient allocation of acoustic transects within strata is therefore dependent on accurate knowledge of the underlying spatial distribution of the fishery. Historical information, fish biology, and other factors can be used to provide information on the underlying distribution. Even so, because of the dynamic nature of most fish populations, such spatial distributions often vary markedly over the fishing season and between years of study. Any proposed sampling design must attempt to cater for such variations, or at least acknowledge them.

Multiphase survey designs

There can sometimes be some advantage in sampling units in more than one step, where information gathered in the initial steps (or phases) is used to determine the sampling strategy for subsequent steps. Often there is a trade-off in such a strategy between improved precision and bias. The aim is to minimise the variance (i.e., improve precision) while keeping bias to within acceptable levels. Such methods are known as either multiphase or adaptive sampling strategies.

A number of multiphase or adaptive techniques have been explored as a means of improving precision in sampling estimates. Francis (1984) introduced the idea of using information obtained in the course of a survey as a means of improving the design of trawl surveys. He suggested using information gathered within the first phase of a survey as a means of allocating second phase effort.

The basic principle is to sample initially using standard stratified random sampling techniques, then use this information in allocating additional effort in such a way as to maximise overall precision. The resulting data from all phases is then analysed as if all the effort were allocated in a single phase conventional random survey design. If prior information of the spatial distribution and location of fish stocks is weak or even non-existent, such a strategy may substantially improve overall precision.

While this process can introduce bias into point estimators derived from a survey, done properly, Francis found that the technique could result in improved precision (i.e., a reduction in variance), specifically in orange roughy trawl surveys, at a cost of only a small increase in bias.

Previous acoustic sampling method for southern blue whiting

Previous acoustic surveys of southern blue whiting biomass have combined a conventional stratified random survey approach with an *informal* adaptive approach. Typically, the initial phase of these surveys is a conventional stratified random sampling design, with parallel transects as described by Jolly & Hampton (1990). The region encompassing the fish stock is stratified with between five and eight strata. Each stratum is then sampled with a roughly equal number of random transects. Transects are usually placed normal to the depth contours, as fish tend to aggregate in schools parallel to depth contours. The allocation of transects to each stratum was loosely based on historical commercial catch rates, resulting in a strategy of simple stratified random sampling. Figure 3 shows a stratification used for the Bounty Platform (Ingerson & Hanchet 1996).

Once the main spawning aggregation or aggregations were believed to have been found, either additional strata or additional transects within a single stratum were then introduced in a second phase (*see* Figure 3). Aggregations were identified from noting fishing vessel behaviour or noting high density first phase transects. As a large proportion of the estimated southern blue whiting biomass was found to be located within one large spawning aggregation, particularly on the Bounty Platform, the adaptive design was perceived to provide a more accurate estimate of the overall biomass or at least provide an estimate with a lower variance — although at the expense of introducing some bias.

This results in an *informal* two-phase design, as it is not only the allocation of effort that is being determined by the initial phase information, but also the location and weight of additional adaptive strata. As such a design is difficult to either replicate or mathematically analyse, it is difficult to formally assess. (For the same reasons, such informal methods are rarely recommended as appropriate sampling strategies.) Because of the informal nature of this method, effects of the introduced bias are difficult to estimate. We can, however, look at more formally specified two-phase sampling strategies and compare them with conventional designs. This may give some insight into the relative advantages and disadvantages of two-phase methods for acoustic surveys.

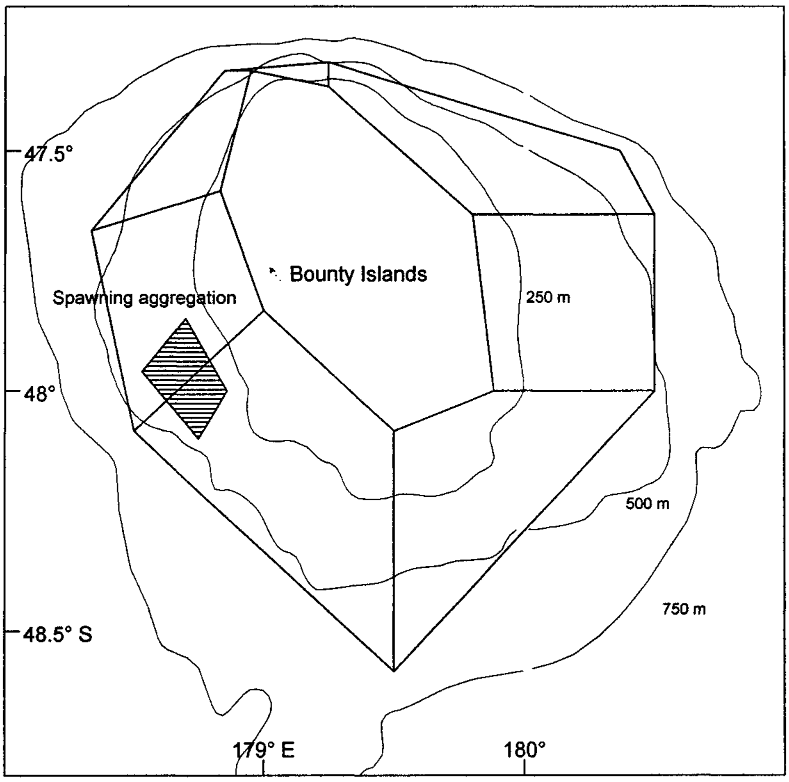

***Figure 3*: Typical strata boundaries on the Bounty Platform, with spawning aggregation strata.**

Adaptive survey design

An adaptive or two-phase sampling strategy may be useful in surveying southern blue whiting because of their particular spatial distribution. Southern blue whiting tend to aggregate into extremely dense but physically small groups. This implies that simple random sampling may have a low probability of detecting such aggregations. For example, the main spawning aggregation or aggregations may contribute up to 60% of the total biomass for a region, and yet may often not be detected under a conventional random sampling strategy. A conventional approach would result in an unbiased estimate, but the resulting low precision of biomass estimates may make it impractical for stock management.

The underlying spatial distribution of southern blue whiting in each of the sub-regions can be estimated only by rough approximation. In some regions, particularly the Bounty Platform, there can be large movements in this distribution over the spawning season. Hence, an adaptive design may have some advantage in that it may help to compensate for gross departures from the assumed prior spatial distribution.

Computer based simulations of sampling methods

Methods

Simulation techniques provide a general, easy to implement method for analysis and comparison between different scenarios, particularly when comparison would be difficult or mathematically intractable. Simulations were carried out on two implementations of a two-phase sampling design and compared with conventional random sampling designs. In addition, simulations were compared with bootstrapped estimates derived from previous acoustic survey data.

Simulations used a computer-generated model of the fish population. Fish were assumed to be located in discrete schools or aggregations, where the size of individual schools followed a lognormal distribution across a pre-set number of strata. Model parameters were introduced to describe the mean, μ, and the *c.v.* of the distribution. As not all transects in a survey will detect a school or aggregation, an extra parameter, p, was introduced to simulate this probability.

Simulations were carried out using the following sampling strategies:

- simple stratified random sampling with an equal number of random transects per strata
- proportional stratified random sampling with the number of random transects proportional to the true (and assumed known) abundance
- two-phase stratified random sampling

Depending on the sampling strategy used, random samples were taken to simulate the effect of random acoustic transects. To correctly simulate the higher probability of large schools being detected over small schools (i.e., that large schools occupy a larger physical area than small schools), the probability of detecting a school was assumed to be proportional to the square root of the school size. Under the simple stratified random sampling strategy, roughly equal numbers of random samples were taken from each stratum. Abundance estimates were computed directly from the stratified random sample estimates in the usual way (Cochran 1963, Raj 1968).

Proportional stratified random sampling requires that the number of samples or transects in each stratum be proportional to the product of abundance and the standard deviation of abundance within each stratum. If we assume that the only constraint on the allocation of random transects to strata is the total number of transects (i.e., the only constraint is the total sample size), then proportional stratified random sampling can be shown to be the optimal strategy, in the sense of minimising variance, for an unbiased estimator. However, as we often require transects to be located across all strata of a region of interest, in practice, the number of transects within each stratum was restricted within these simulations to be at least two. This has the overall effect of a small reduction in the efficiency of this form of allocation with, however, the advantage of replicating the practical constraints of this design.

Two-phase sampling was simulated using two variations. The first carried out simple stratified random sampling as described above. Then, to simulate the second-phase component of the design, the stratum with the largest estimated abundance was resampled. Information from both phases was then combined as if from a single phase survey, and abundance estimates determined in the usual way. Usually, proposed two-phase sampling strategies suggest resampling in areas of increased variance. However, if we allow the assumption that variance is proportional to the mean, we can resample areas with the highest abundance estimate without loss of generality. The proportion of effort allocated to the second phase of the sampling strategy was controlled by a separate parameter in the model, π.

The second implementation of the two-phase design employed a similar method as above, with the additional modification that the first phase transects were allocated using proportional allocation. Clearly this will show a marked benefit over the two-phase simple stratified sampling method within the simulation study, though the level of improvement is difficult to determine before investigation. As conventional proportional stratified random sampling results in optimal allocation of effort across strata, it is unlikely that multiphase methods will show any improvements over this design. Again, the proportion of effort allocated to the second phase of the sampling strategy was controlled by a separate parameter in the model, π.

In summary, simulations were based on a lognormal distribution of schools, spatially distributed over a pre-set number of strata. The probability of detecting a school was proportional to the square root of the size of that school combined with a pre-set parameter describing the overall detection probability for that set of simulations. The distribution of schools was determined by a lognormal distribution with parameters describing the mean and variance. Random samples were then taken, simulating random transects in an acoustic survey, in accordance with the sampling strategy employed, and with the proportion of second phase effort determined by a pre-set parameter.

Strategies can be compared using *Bias* and *Mean Squared Error*. For each set of simulations, we can estimate the bias, $b(\theta)$, variance, $Var(T|\theta)$, and hence the mean squared error, MSE, as

$$\begin{aligned} MSE &= E\left[(T-\theta)^2\right] \\ &= \left\{b(\theta)^2\right\} + Var(T|\theta) \end{aligned} \qquad [2]$$

where T is the estimated point estimator of θ, i.e., the mean squared error is the expected value of the square of the difference between the true parameter, θ, and the estimated value of that parameter, T.

Similarly, bias can be defined as

$$b(\theta) = E\left[(T|\theta)\right] - \theta \qquad [3]$$

Simulations were run on a 200 MHz Intel Pentium II computer using S-Plus. A range of parameter values was selected and between 1000 and 2000 simulations were generated for each parameter set. For each parameter set, estimated bias and mean squared error were computed and compared in tables and by plots.

Initial simulations were carried out on a lognormal distributed population of schools with mean abundance of 2000 and *c.v.* of 3 across a range of detection probabilities $0.05 < p < 0.95$. One hundred aggregations were generated from this distribution, then assigned to one of six strata. Thirty samples were then taken from this population using both conventional and two-phase strategies. Under both of the two-phase sampling strategies, 20% of samples were reserved for the second phase effort.

Simulation results

Figure 4 shows a plot of bias expressed as a proportion of the true abundance over a range of detection probabilities for these simulations. Smooth *B*-spline curves were fitted to estimated data to show the trends across parameter values. Because both simple and proportional stratified random sampling methods return unbiased estimators, bias for both these strategies is estimated as zero. As the probability of detecting an aggregation or school tends to one, the bias of two-phase strategies becomes negligible. However, at very low detection probability levels, the bias becomes more extreme. At all detection probabilities, the estimated bias from the two-phase proportional allocation strategy is typically less than half that for the two-phase simple allocation strategy.

Comparisons of mean squared error for each sampling strategy are shown in Figure 5. Again, smooth *B*-spline curves were fitted to the estimated points to show trends. Mean squared error was calculated for each of the sampling strategies, and compared with simple stratified sampling. As we would expect from an optimal strategy, proportional stratified random sampling returns the lowest values for mean squared error. However, both two-phase strategies perform considerably better than simple stratified random sampling. There was little practical difference between the conventional proportional stratified strategy and two-phase proportional allocation. At extremely low detection probabilities, the two-phase proportional allocation strategy performed better than the conventional proportional stratified random sampling design. This is most likely due to the imposed design constraints that there be a minimum of two transects allocated to each strata. This constraint reduces the effectiveness of the conventional strategy, with a similar, but smaller, reduction in effectiveness for the two-phase proportional strategy when considering the simulated population structure.

Figure 6 shows the change in mean squared error against increasing school aggregation variance, $0.1 < c.v. < 6.0$. At low levels of variance, the population is distributed into schools or aggregations with similar densities. At high variance, the population consists of a few very large aggregations and many very small aggregations. At low variance, where there is little variation in density across strata, little benefit is obtained from proportional stratification. At this point two-phase strategies have high levels of bias and high relative mean squared error. As the population becomes skewed, the benefits of proportional allocation become apparent. Again, conventional proportional stratified random sampling shows up as an optimal strategy, with slightly more benefit than the two-phase proportional strategy. The two-phase strategy based on simple allocation showed a much smaller level of benefit, with reductions in mean squared error becoming discernible only at high levels of variance.

We can also consider the effectiveness of each sampling strategy in providing a better estimate of the true abundance more often. Figure 7 shows the probability that each strategy will overestimate the true abundance by a factor of more than two. At very low detection probabilities, the two-phase sampling strategies will overestimate the true abundance less often than either of the conventional designs. Simple stratified random sampling performs worse than any other strategy, i.e., grossly overestimating the true abundance more often than any other strategy.

We can also consider the probability of each sampling strategy grossly underestimating the true abundance. Figure 8 shows the proportion of under estimates of the true abundance. There are only small differences between conventional designs and the matching two-phase design. All designs showed a high propensity to underestimate the true abundance at very low detection rates, and there was little to distinguish between strategies at high detection levels.

Figure 9 shows the variation in bias with different proportions of second phase allocation. To generate a range of data points, simulations were based on 100 random samples from 10 strata, and hence values obtained are not absolutely comparable with earlier simulations As the proportion of allocation to the second phase increases, the estimated bias of the two-phase methods increases. In addition, the level of bias for two-phase simple stratified random sampling increases at a far greater rate than that for two-phase proportional stratified random sampling. Figure 10 shows the change in mean squared error with increasing allocation of effort to the second phase. Large improvements are noted in the estimated mean square error at low levels of effort allocated to the second phase, with a decline in improvement as the proportion increases.

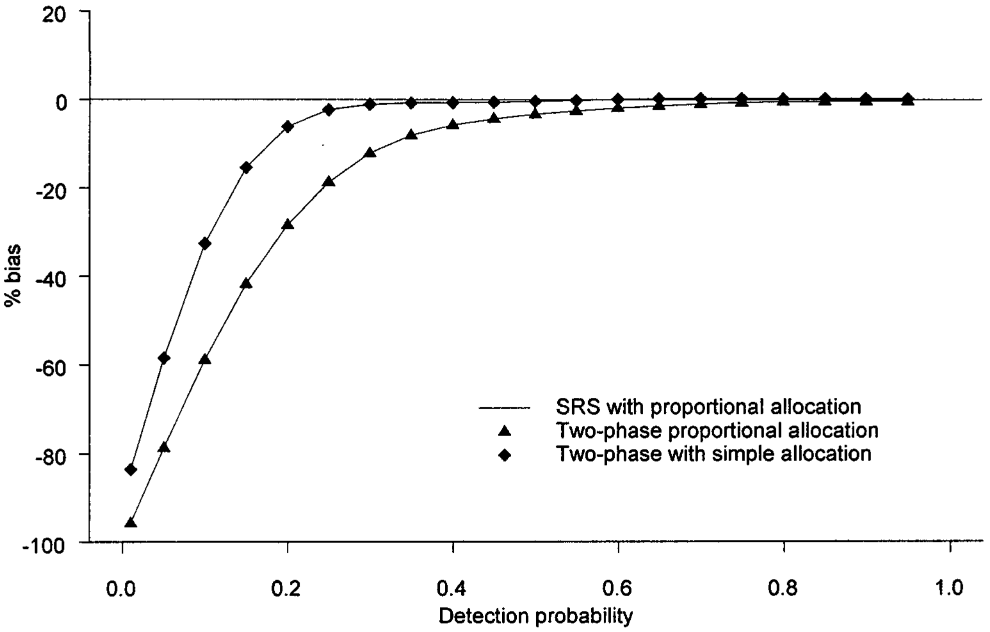

Figure 4: **Per cent bias by detection probability for each sampling strategy.**

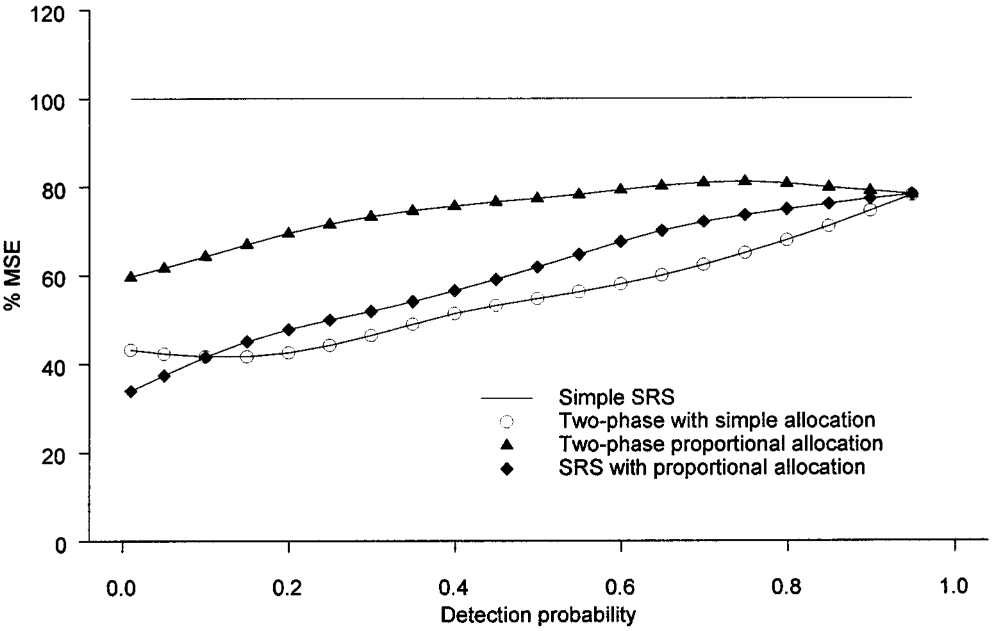

Figure 5: **Per cent MSE by detection probability for each sampling strategy compared with simple stratified random sampling.**

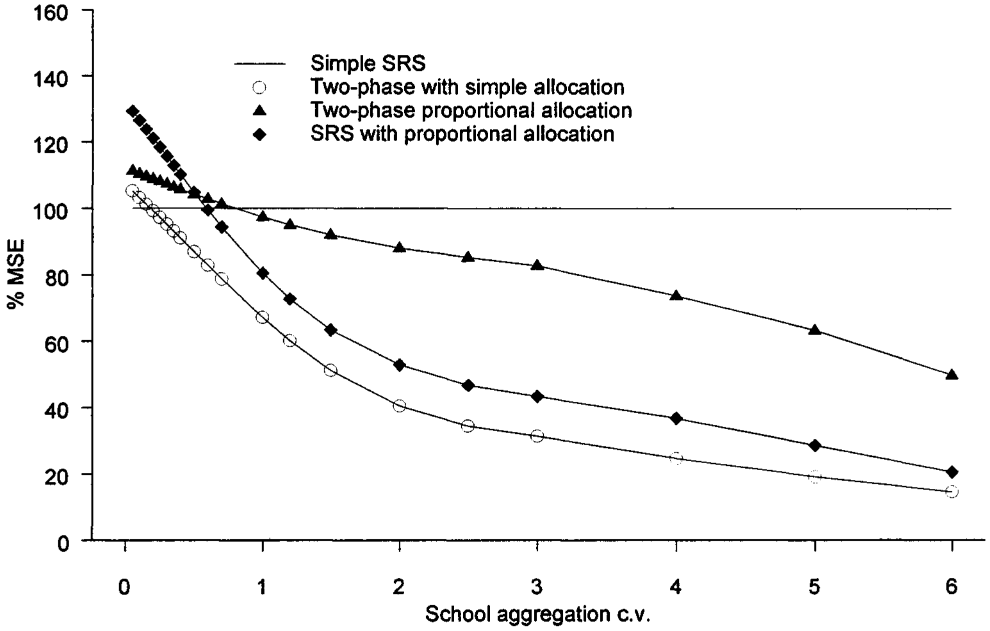

***Figure 6*: Per cent MSE by school aggregation variance for each sampling strategy compared with simple stratified random sampling.**

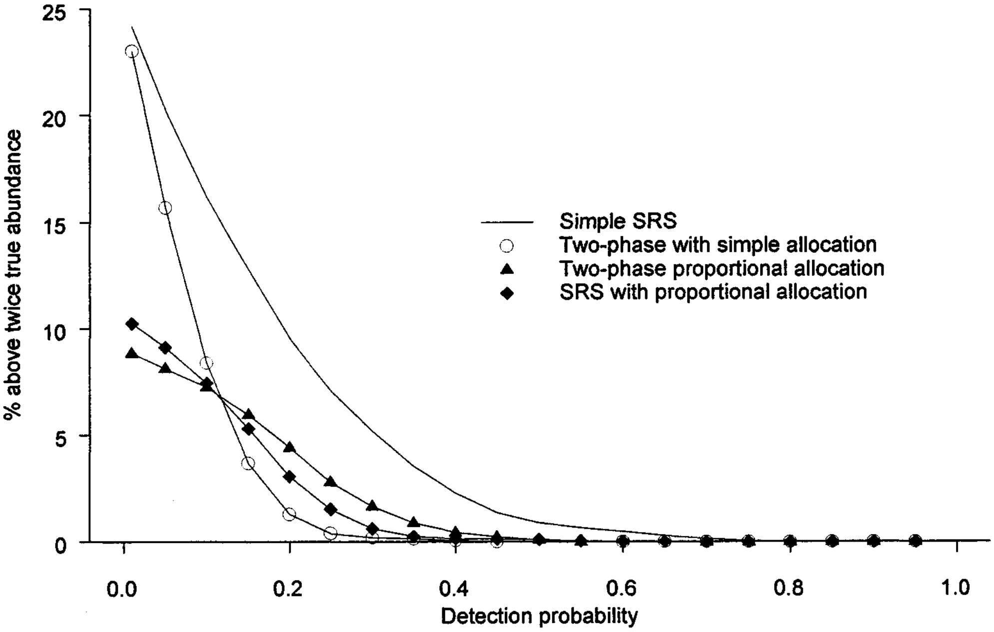

***Figure 7*: Proportion of overestimates of true abundance by detection probability for each sampling strategy.**

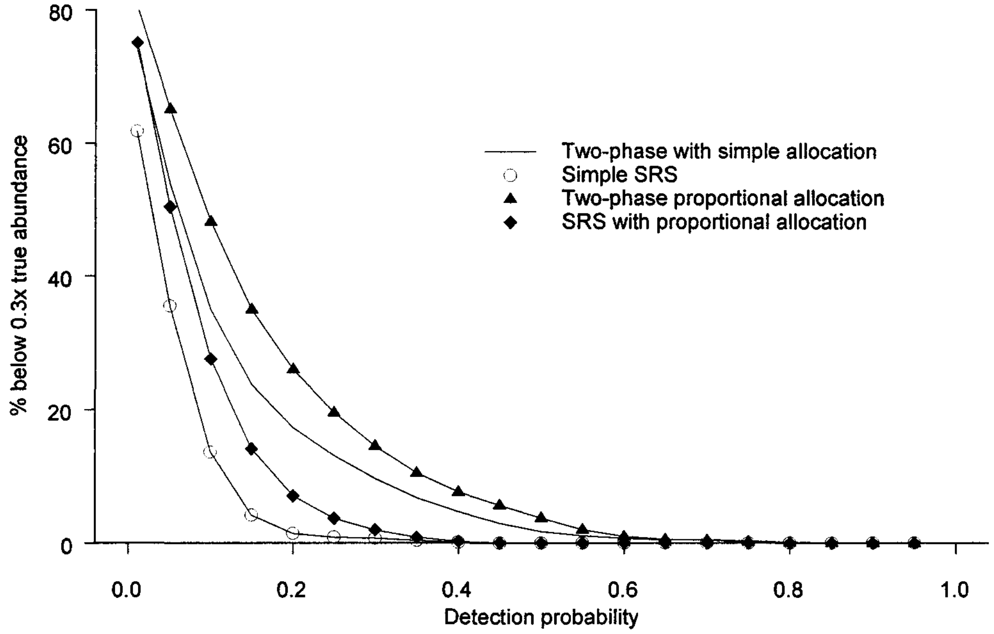

***Figure 8*: Proportion of underestimates of true abundance by detection probability for each sampling strategy.**

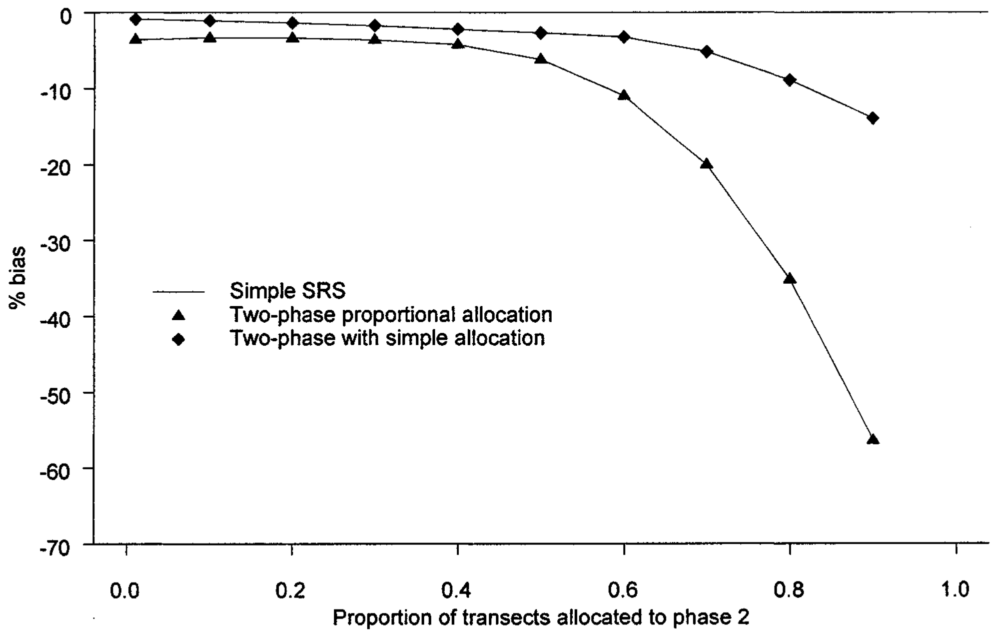

***Figure 9*: Per cent bias by proportion of effort allocated to the second phase for each sampling strategy compared with simple stratified random sampling.**

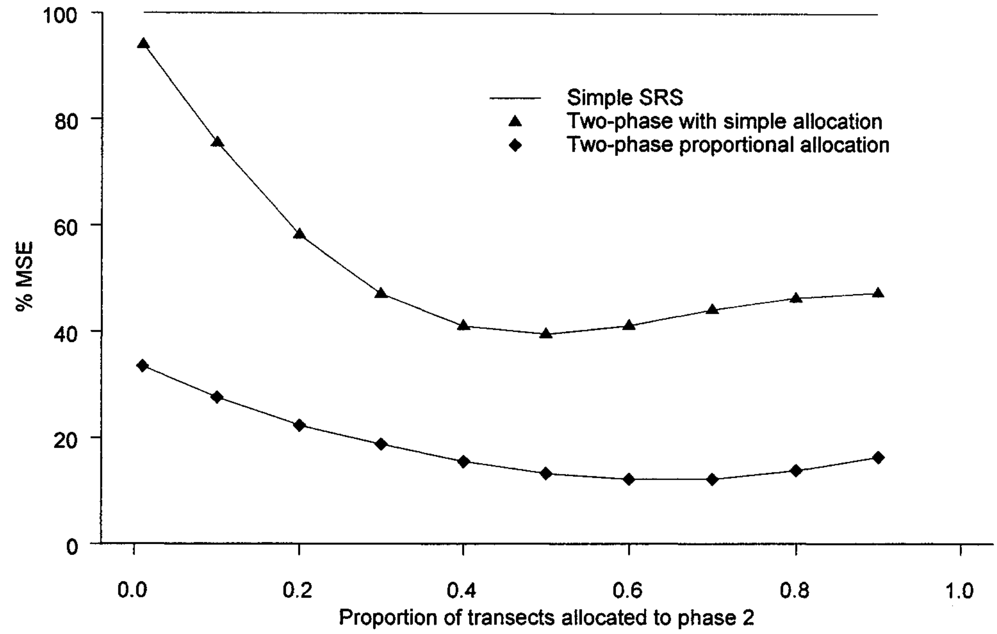

***Figure 10*: Per cent MSE by proportion of effort allocated to the second phase for each sampling strategy compared with simple stratified random sampling.**

Discussion

Two-phase sampling methodologies have some advantages over conventional sample survey designs if there is doubt over the spatial distribution of the population in question. Although, when this distribution is either known or can be estimated two-phase methods do not perform as well as conventional sampling strategies. For example, when the population is known to have a skewed spatial distribution, but the precise location of the variation in location is largely unknown, two-phase methods can show some improvement over conventional simple stratified sampling design at the expense of only small bias.

The simulations suggest that two-phase designs can provide a more precise estimate with minimal bias when the probability of detecting an aggregation is high and when the variation between sizes of aggregations is low. However, these conditions also apply when we are more likely to have a good idea of the spatial distribution of the underlying population. As a greater proportion of effort is allocated to the second phase, we find that we get increasing bias with only small reductions in mean squared error. Simulations suggest that as this proportion increases to above half of the total effort, bias becomes extreme.

Two-phase sampling strategies do assist in the improvement of precision albeit at the expense of bias, but this is only of use when the underlying spatial distribution is to some extent unknown. Two-phase proportional stratified random sampling appears to provide a useful increase in precision, at the expense of small increases in bias, when the underlying distribution is subject to some uncertainty.

It is difficult to directly simulate the informal adaptive survey approach used in the previous acoustic surveys of southern blue whiting (Hanchet *et al.* 1994, Hanchet & Ingerson 1996, Ingerson & Hanchet 1996) because of the informal and ad hoc nature of the location of adaptive stratum boundaries. The adaptive stratum boundaries sometimes incorporated all or some information on the location of fishing fleets and transect densities. However, the simulations suggest that the use of adaptive strata is likely to have resulted in a reduction in the mean squared error (and hence *c.v.*) at a cost of an increase in bias. The question is, how much bias? The degree of bias would clearly depend on the underlying distribution of the fish during the surveys. If all the fish in the survey area were included within the boundary of the adaptive stratum, then the bias would be zero. However, as the proportion of fish outside the adaptive stratum increased, so the bias would increase. Although the underlying fish distribution during the surveys is unknown, both the similarity of fish distributions between snapshots and the catch rates of the commercial fleet in relation to the transect densities suggest that a high proportion of the fish were probably located within the adaptive survey boundaries. This suggests that the bias from those previous survey estimates may not be high.

Optimisation of the survey design

Optimisation of survey design requires a knowledge of the true spatial distribution of fish in each of the southern blue whiting fishing grounds. If the true spatial distribution of fish were known, then the position of the strata boundaries, and the allocation of transects within strata boundaries, becomes a relatively straightforward exercise. Historical catch data and data from previous acoustic surveys are examined to determine some of the characteristics of the spatial distribution of spawning southern blue whiting.

Historical catch and effort data

Historical catch and effort data are available for 1978 to 1996 from vessel deepwater logbooks (Fisheries Statistics Unit (FSU) and Trawl Catch and Effort Processing Returns (TCEPR)). Data include the geographic location of trawls, information on the catch, and the distance towed. We can use historical catch and effort data as well as previous acoustic data in describing the distribution of fish in each of the southern blue whiting fishing grounds.

Most fishing takes place during spawning, in August and September (Figure 11) (*see also* Hanchet 1997). Figure 12 shows the spatial distribution of total catch on the Bounty Platform for 1990–96, over the entire fishing year. High catch data were noted in the area to the southwest of the Bounty Islands, with a smaller, but still apparent peak, to the southeast. We can calculate a gross approximation to catch per unit effort (CPUE) data by considering the catch per kilometre of each individual trawl. However, little spatial variation is evident (Figure 13).

Some data quality problems arise when we consider the use of historical catch effort data. Extreme and improbable data values occur within the data sets and give rise to some misgivings about their overall accuracy. In particular, catch and catch rates appear prone to data entry and recording errors, most probably due to the nature of such data. However, we may avoid some of these problems if we consider a simple measure of effort, i.e., the location of individual trawls on each fishing ground. Here, errors may arise, as with the total catch and the catch per distance of each trawl, from recording errors in the geographic location, but as each recorded trawl is only counted as one unit of effort, extreme errors have much less influence. A similar pattern to that for the total catch emerges when considering location of trawl as a measure of effort (Figure 14), though with less pronounced small scale variation.

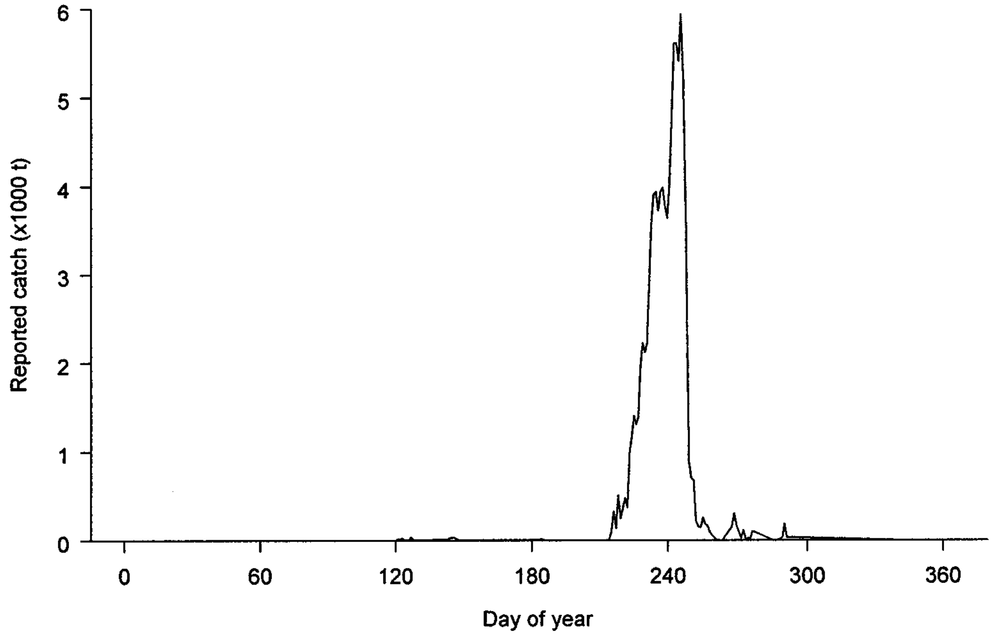

***Figure 11*: Total catch by day of the year caught, Bounty Platform, 1990–96.**

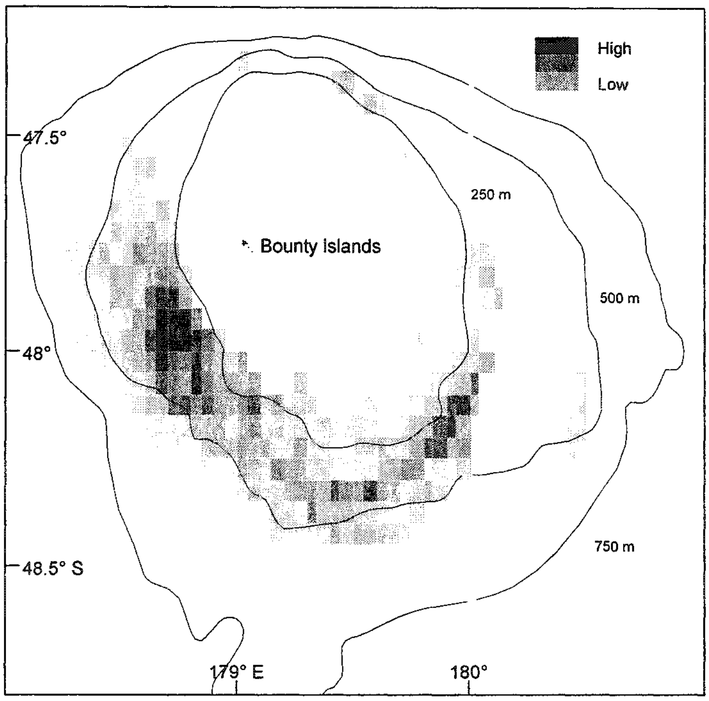

Figure 12: **Distribution of total catch from fishing vessels on the Bounty Platform, 1990–96.**

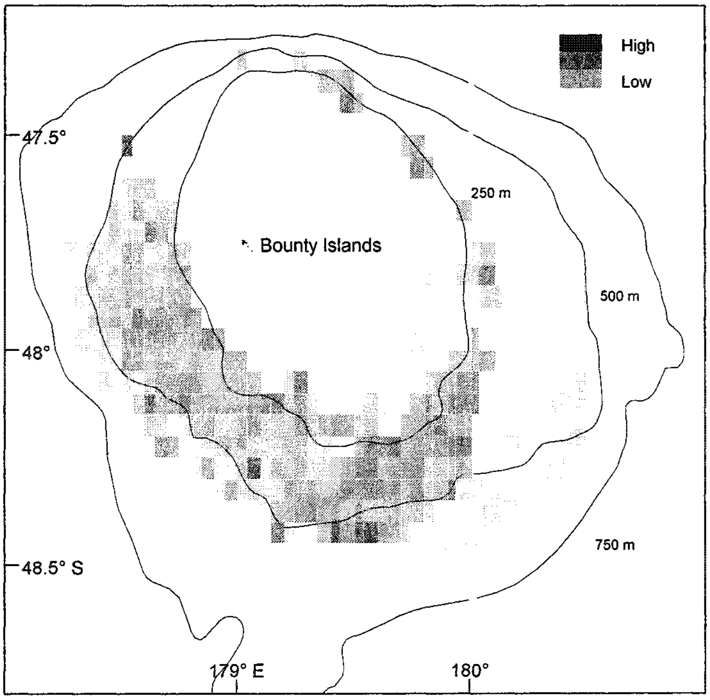

Figure 13: **Distribution of mean CPUE from fishing vessels on the Bounty Platform, 1990–96.**

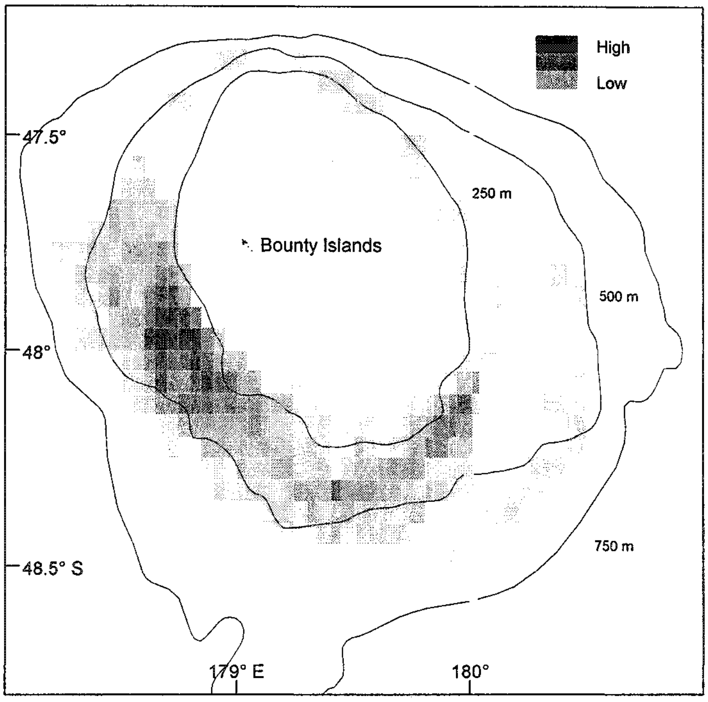

Figure 14: **Distribution of effort from fishing vessels on the Bounty Platform, 1990–96.**

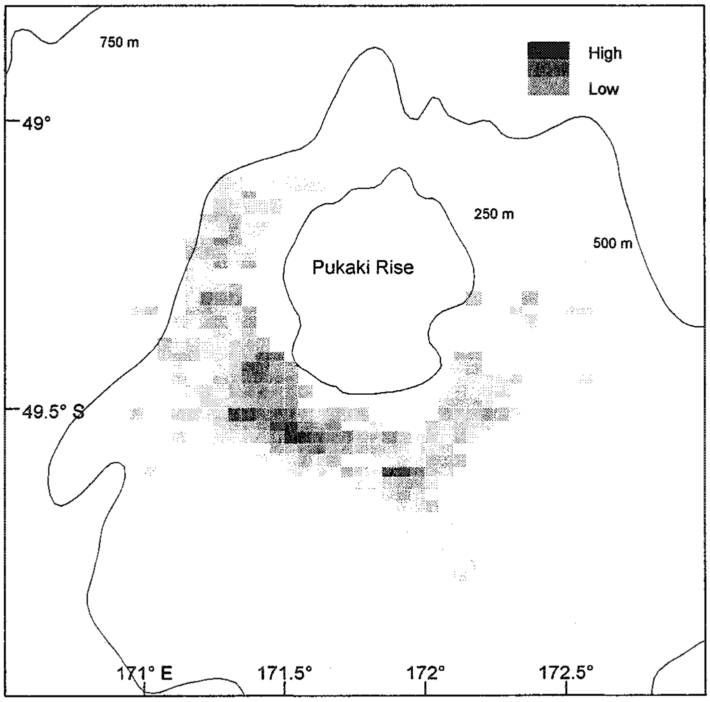

Figure 15: **Distribution of effort from fishing vessels on the Pukaki Rise, 1990–96.**

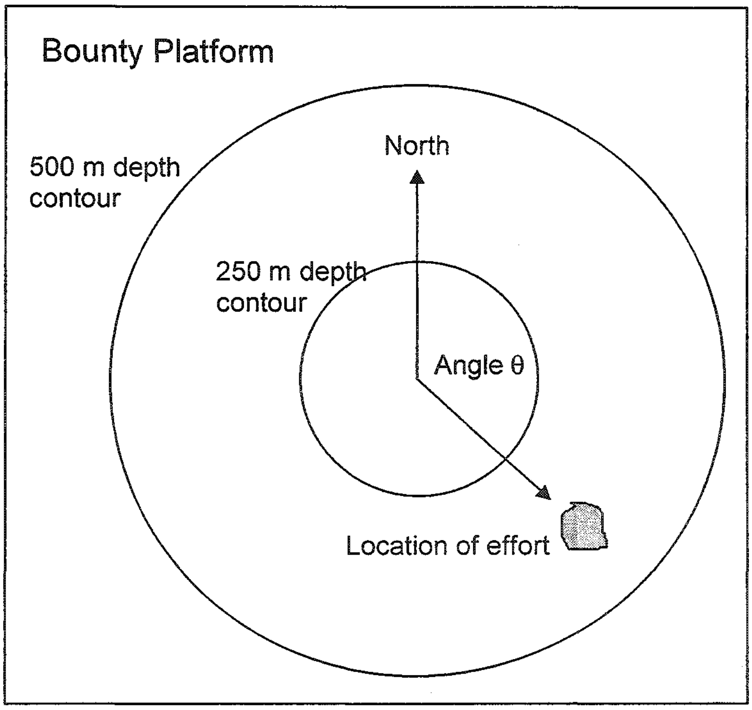

Figure 16: **Calculating the angle of the location of effort, Bounty Platform.**

If we assume that fish are aggregated along depth contours (i.e., parallel to depth), then we can consider the spatial distribution of fish in a circle around the Bounty Platform. The location of effort was converted to a linear scale by computing the angle from an arbitrary centre to the location of effort. The resulting data were then plotted to determine the variation in distribution around each region. Figure 16 shows the calculation of the angle of spatial effort for the Bounty Platform, and Figure 17 shows the distribution of fishing effort on the Bounty Platform.

Similar computations can be made for the Pukaki Rise. Figures 15 and 18 show the corresponding distribution of fishing effort on the Pukaki Rise.

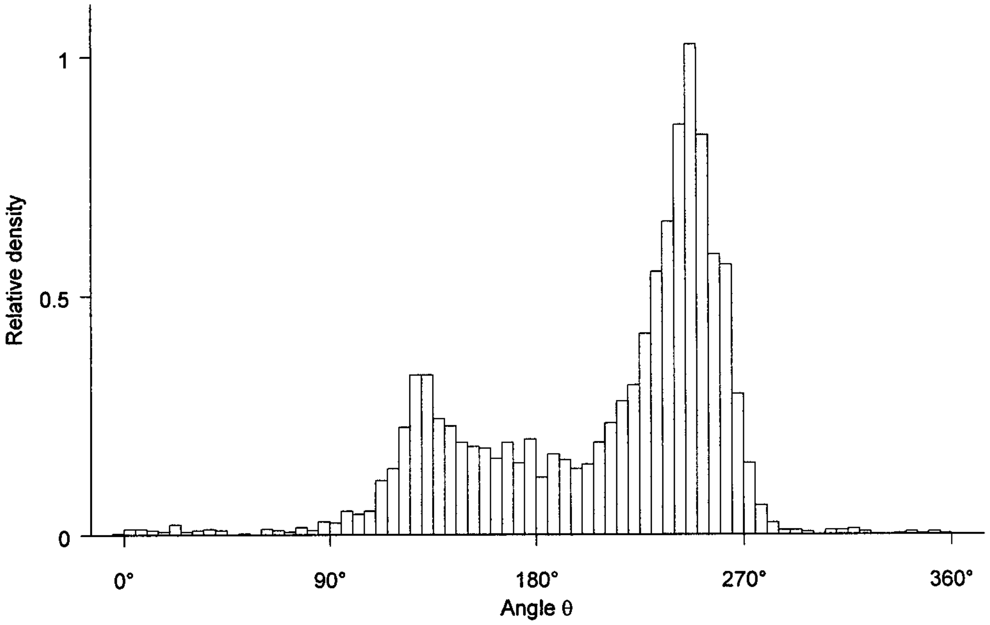

Figure 17: **Spatial distribution of fishing effort on the Bounty Platform, 1990–96.**

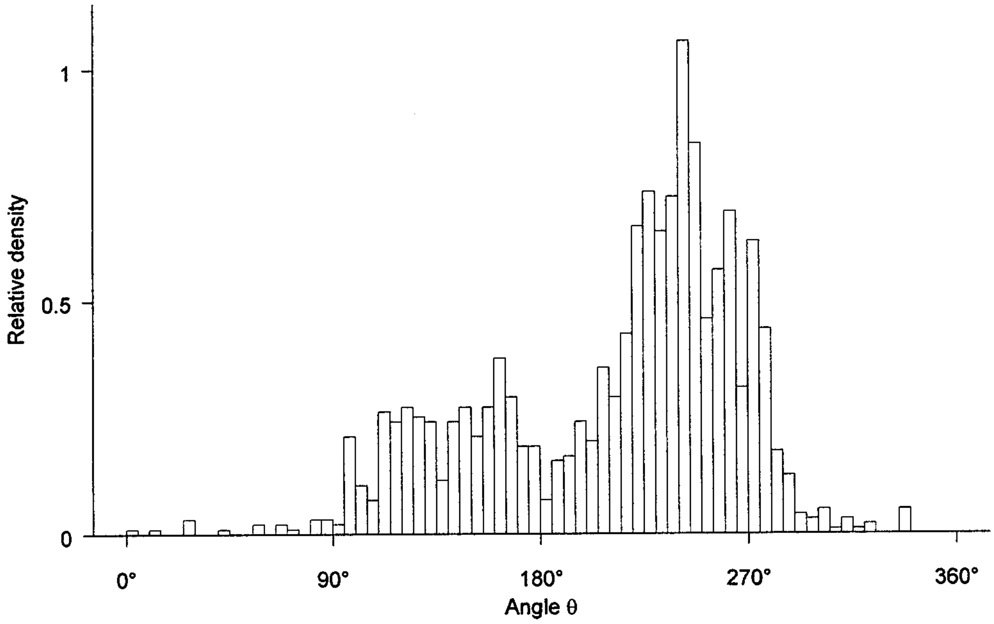

Figure 18: **Spatial distribution of fishing effort on the Pukaki Rise, 1990–96.**

Acoustic survey data

Like historical catch data, acoustic data can provide an insight into the spatial distribution of the fishery in each of the southern blue whiting spawning regions. Acoustic data are available for 1993, 1994, and 1995. As acoustic transects run normal to depth contours, we can use the acoustic data to look at the spatial distribution of fish around each region. Integrated densities from each acoustic transect were converted to a linear scale using the angle of the midpoint of each transect as a measure of density location — in a similar manner to the method of converting location of fishing catch and effort used earlier. Figure 19 shows a smoothed *B*-spline plot of the relative density of acoustic backscattering from adult fish over all acoustic transects on the Bounty Platform. Data consist of the 171 acoustic transects collected from the three acoustic surveys in 1993, 1994, and 1995 for adult southern blue whiting. Data for juvenile southern blue whiting have been excluded from this analysis.

The pattern is very similar to that of the historical catch effort data, with a large peak at about 240°. However, the location of the smaller peak (southeast of the Bounty Islands) is slightly different, being at about 160° on the acoustic data set, but at about 140° on the historical catch effort data set.

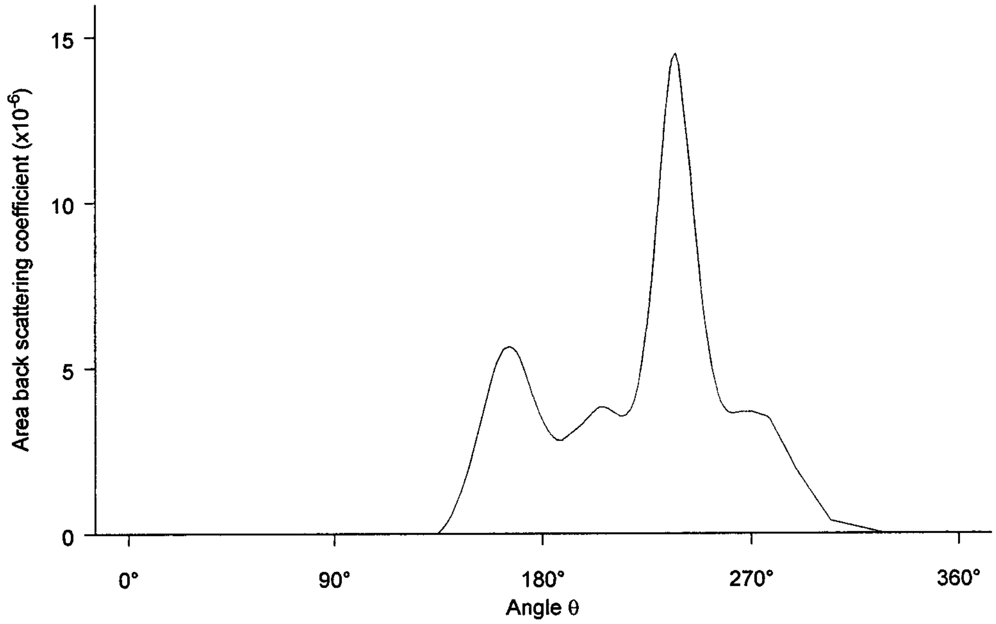

***Figure 19*: Spatial distribution of southern blue whiting on the Bounty Platform from acoustic surveys, 1993–95.**

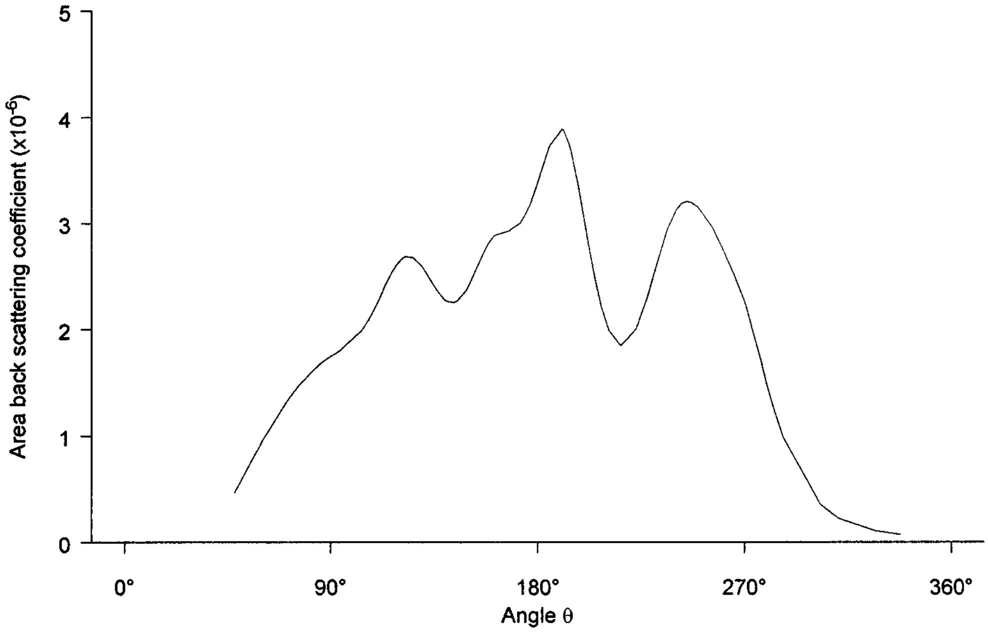

***Figure 20*: Spatial distribution of southern blue whiting on the Pukaki Rise from acoustic surveys, 1993–95.**

Figure 20 shows a smoothed *B*-spline plot of the relative density of acoustic backscattering from adult fish over all acoustic transects on the Pukaki Rise. Data consist of 121 acoustic transects collected from the three acoustic surveys in 1993, 1994, and 1995. A quite different pattern emerges compared with the historical catch effort data. The acoustic data suggest a smooth pattern of abundance over a similar region to the historical catch effort data (90–270°), with a less pronounced peak in the southwest (240°).

Allocation of strata boundaries

Similarities between the acoustic density and historical catch and effort data give some confidence that the pattern we are observing represents an underlying spatial distribution of southern blue whiting on the Bounty Platform and Pukaki Rise. However, when we investigate the change of historical catch and effort data over time, we find that large movements in the location of effort and catch are apparent. Further, there appears to be a consistent trend within each fishing year for the location of this effort to move in a counter-clockwise direction — on one occasion completing a circle, returning back to the starting point over a 3 week period (*see* Hanchet *et al.* 1994). It is unknown whether this represents mobility of fish over the spawning season, or a realisation of some aspect of fishing vessel behaviour. Evidence from acoustic surveys suggests that the main spawning aggregation on the Bounty Platform tends to move to the southeast over the period of spawning (Ingerson & Hanchet 1996), but not to the extent suggested by the historical catch effort data.

If we are able to assume the underlying spatial distribution of fish is approximated by the historical catch and effort data, we can readily stratify each region into reasonably optimal strata. In addition, if we can also assume that the variance of a population within a stratum is proportional to mean density of that stratum, i.e., proportional to the strata abundance multiplied by the area of the strata, we can then use estimates of relative abundance as a means of allocating sampling effort between strata.

Allocating stratifications then becomes an exercise in defining strata boundaries that encompass areas of equal density, while noting that the locations of dense aggregations may fluctuate over time. Figure 21 and 22 show an allocation of strata by angle of location that allows for some variation in the location of aggregations while maintaining a high between-strata variance. For each plot, bars represent strata, with bar boundaries representing strata boundaries, and the height of each bar represents the relative fish density that would be expected to be found within that stratum.

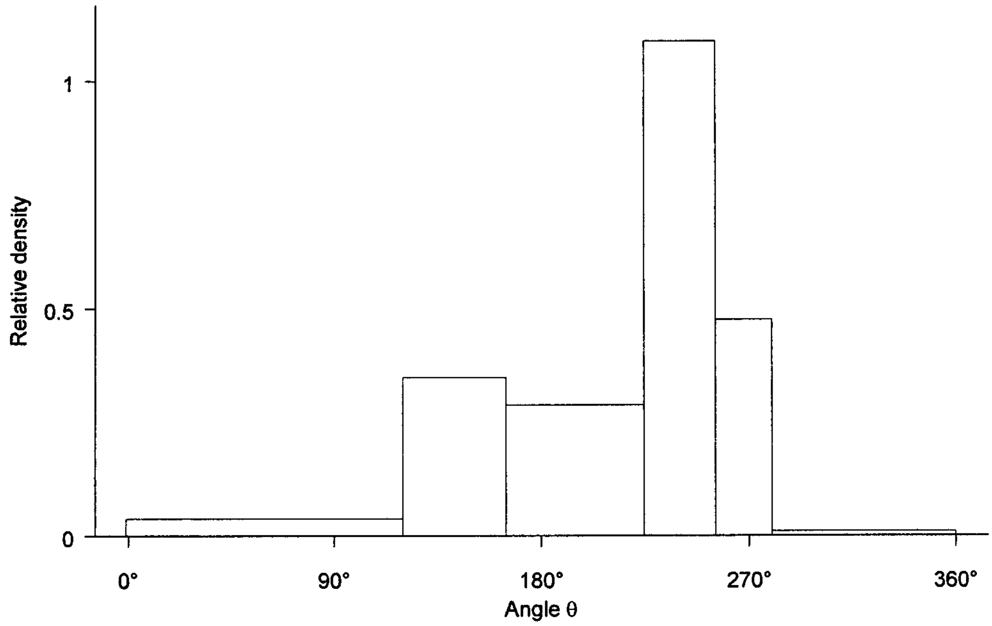

***Figure 21*: Estimated density by strata based on historical catch effort data, 1990–96, Bounty Platform.**

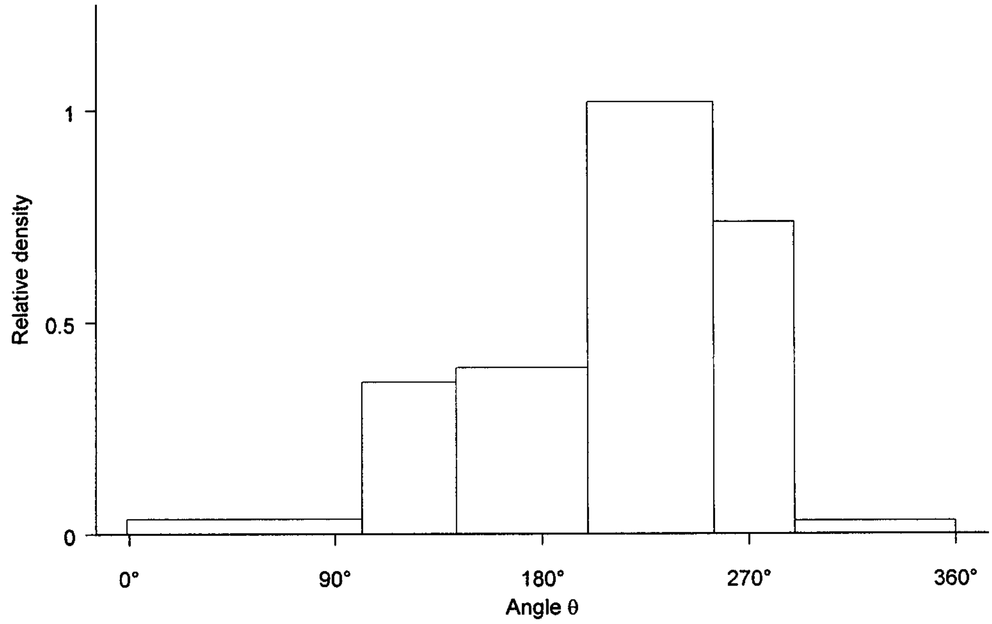

***Figure 22*: Estimated density by strata based on historical catch effort data, 1990–96, Pukaki Rise.**

Comparison of strategies using the acoustic data distribution

Using the above stratifications, based on historical catch effort data, we can attempt to approximate (via simulation) the levels of bias and mean squared error we would expect to have found from previous acoustic surveys. Simulations were carried out in a similar manner to that described earlier in this report, but this time simulated populations were generated from actual transect data from the previous acoustic surveys. As in earlier simulations, 20% of sampling effort of the two-phase sampling strategies was reserved for the second phase. Transects from the acoustic data were assigned to strata and then sampled with replacement, generating 1000 bootstrapped populations. Simulations for each sampling strategy were then carried out on each of these bootstrapped populations. These results are shown in Tables 1 and 2.

Table 1: **Estimated bias as a percentage of true abundance for each sampling strategy from the empirical acoustic spatial distribution, using stratifications based on historical catch effort data.**

	Year	SRS (simple)	SRS (proportional)	Two-phase (simple)	Two-phase (proportional)
Bounty Platform	1993	0.4	0.2	-15.9	-5.2
	1994	-2.2	-0.7	-14.9	-11.2
	1995	-0.1	-0.1	-12.5	-9.0
	All years	-0.6	-1.13	-12.9	-14.2
Pukaki Rise	1993	-0.3	0.7	-7.5	-7.5
	1994	3.2	-1.2	-14.7	-8.3
	1995	0.7	-0.1	-3.0	-1.9
	All years	-1.2	2.2	-9.0	-14.5

Table 2: **Estimated mean squared error as a percentage of the simple stratified random sampling strategy for each strategy from empirical acoustic spatial distribution, using stratifications based on historical effort catch data.**

	Year	SRS (simple)	SRS (proportional)	Two-phase (simple)	Two-phase (proportional)
Bounty Platform	1993	100.0	30.1	61.4	42.2
	1994	100.0	50.0	78.7	55.4
	1995	100.0	62.6	82.1	62.3
	All years	100.0	48.5	75.2	45.8
Pukaki Rise	1993	100.0	103.4	108.4	104.5
	1994	100.0	55.3	77.9	56.2
	1995	100.0	55.5	80.8	63.5
	All years	100.0	97.4	84.6	83.9

The proportional allocation two-phase strategy performs almost as well as the optimum strategy (proportional stratified random sampling) in terms of overall mean squared error, with bias of not more than about 15%. The two-phase sampling strategies show sizeable reductions in mean squared error as compared with simple stratified random sampling. Performance is more improved on the Bounty Platform than on the Pukaki Rise, possibly because of lower within-stratum variance compared with between-strata variance.

Discussion

Although a strategy of proportional stratified random sampling is a theoretical optimum: when the underlying spatial distribution of fish is to some extent unknown, simulations suggest that suitably designed two-phase methods can provide increased precision at the expense of small increases in bias.

The bootstrapped simulations estimating the bias and mean squared error on previous acoustic surveys suggest that a two-phase survey strategy on the Bounty Platform will approximately halve mean squared error, at a cost of about 15% bias in the resulting abundance estimates. A much smaller reduction in mean squared error is apparent on the Pukaki Rise, and, in some years may provide no additional benefit.

The usefulness of a two-phase strategy is dependent on the level of bias that is acceptable in exchange for increased precision. Lower bias levels will be introduced into abundance estimates if the proportion of effort allocated to the second phase is reduced. The optimum proportion of effort to allocate to the second stage is mathematically difficult to estimate. In addition, the reduction in mean squared error and the increase in bias are highly dependent on the underlying spatial distribution — usually unknown. Sizeable reductions in mean squared error become apparent at very low proportions of effort allocated to the second phase, whereas bias rapidly becomes extreme at more moderate proportions. For the Bounty Platform, simulations suggest that an allocation of effort of 40% to second phase effort would result in large reductions in mean squared error with relatively low bias. A more prudent estimate, however, may be 20%. At this level, indications are that bias is relatively low (and perhaps more importantly, stable), with sizeable reductions in mean squared error still apparent.

Acknowledgments

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