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Comparative evaluation of two-phase and adaptive cluster sampling designs for acoustic surveys of southern blue whiting (*Micromesistius australis*) on the Campbell Rise

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1. Executive Summary

We compare the efficiency of adaptive cluster sampling and two-phase sampling designs for the acoustic survey of southern blue whiting on the Campbell Rise using simulation models based on previously collected acoustic data. This report meets Objective 1 of Project SBW1999/01 "To evaluate the use of alternative sample designs for acoustic surveys for southern blue whiting".

The simulations confirm previous work that two-phase designs are more efficient than standard stratified random sampling for southern blue whiting acoustic surveys. The simulations suggest that a two-phase survey strategy on the Campbell Rise will have approximately half the mean squared error of a standard stratified random sampling design with equivalent sample size, but will also have about a 20% bias in the resulting abundance estimates.

The simulations also suggest that adaptive cluster sampling designs, with appropriate selection of the critical value and initial allocation, can provide a more precise estimate than two-phase designs. However, this depends on the distribution of the population and the specific implementation of the adaptive cluster sampling design. In some cases, the choice of critical value or initial sample size can result in an estimate with lower precision, but these are also highly dependent on the distribution of the underlying population.

Adaptive cluster sampling is an open-ended sampling design. It is not possible to determine the exact number of samples required prior to any survey. The simulations showed that while the expected sample size may be similar to that for the two-phase design, the 95% upper bound of the simulated sample sizes is generally about twice the initial sample size. This introduces several practical problems, not least is the question of how to determine the length of time required to complete a survey.

Adaptive cluster sampling shows strong advantages over standard stratified random sampling or two-phase sampling, where the conditions are right. Situations where the additional cost of sampling within a network is small compared to new samples and where the population is highly clustered, are good candidates for adaptive cluster sampling. In particular, situations where an unbiased estimate is considered to be important, adaptive cluster sampling can be a more efficient choice of sampling design. However, the implementation problems of adaptive cluster sampling for acoustic surveys of the Campbell Rise would be difficult to surmount. While the choice of critical value and initial sample size could be evaluated using a more comprehensive set of simulations than presented here, the resulting sampling required would almost always be higher than the current allowed time for the survey. The two-phase sampling method used is much more efficient than standard stratified random sampling, and, in most scenarios, as good as or better than adaptive cluster sampling.

2. Objectives

This report is part of Project SBW1999/01 "To estimate the biomass of southern blue whiting (*Micromesistius australis*) using acoustic surveys". In particular, this report fulfils Objective 1 of this project, "To evaluate the use of alternative sample designs for acoustic surveys for southern blue whiting".

3. Introduction

The southern blue whiting (*Micromesistius australis*) fishery is a large fishery in New Zealand waters, with a catch limit of 58 000 t in 1997–98 (Annala et al. 1999). Southern blue whiting are found throughout the sub-Antarctic, but tend to spawn on reasonably well defined spawning grounds; Bounty Platform, Pukaki Rise, Campbell Rise, and the Auckland Islands Shelf. Each of these regions are currently managed as separate stocks. Figure 1 shows the location of the Campbell Rise within the New Zealand EEZ.

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 two-phase stratified random sampling design, with allocation of transects loosely based on prior information from acoustic surveys and historical commercial catch data. Acoustic surveys of the Campbell Rise were carried out in August and September of 1993, 1994, 1995, and 1998 (Hanchet et al. 1994, Hanchet et al. 2000, Hanchet & Ingerson 1996, Ingerson & Hanchet 1996). No acoustic surveys of the Campbell Rise were conducted in 1996 or 1997.

Conventional acoustic survey designs for estimating biomass typically apply a standard stratified random survey methodology to the region of interest, divided into strata, with straight line acoustic transects forming the basis of the sampling units. Samples are evaluated by integration of the acoustic back-scattered data continuously along each of the randomly allocated transects. Population biomass estimates over the survey region are then determined using standard stratified random sampling theory. (See Jolly & Hampton (1990) and Coombs & Cordue (1995) for more complete descriptions of the process of obtaining biomass or other abundance estimates from acoustic surveys.)

Acoustic surveys of marine fisheries are typically restricted in the time available for sampling and the prior information available for the optimal allocation of samples within strata can be limited. Standard stratified random sampling designs require good information on the population distribution for optimal allocation of sampling units but have the "desirable" statistical property of yielding minimum variance unbiased estimates. However, increased efficiency, in practise, can sometimes be obtained from the use of alternative sampling strategies.

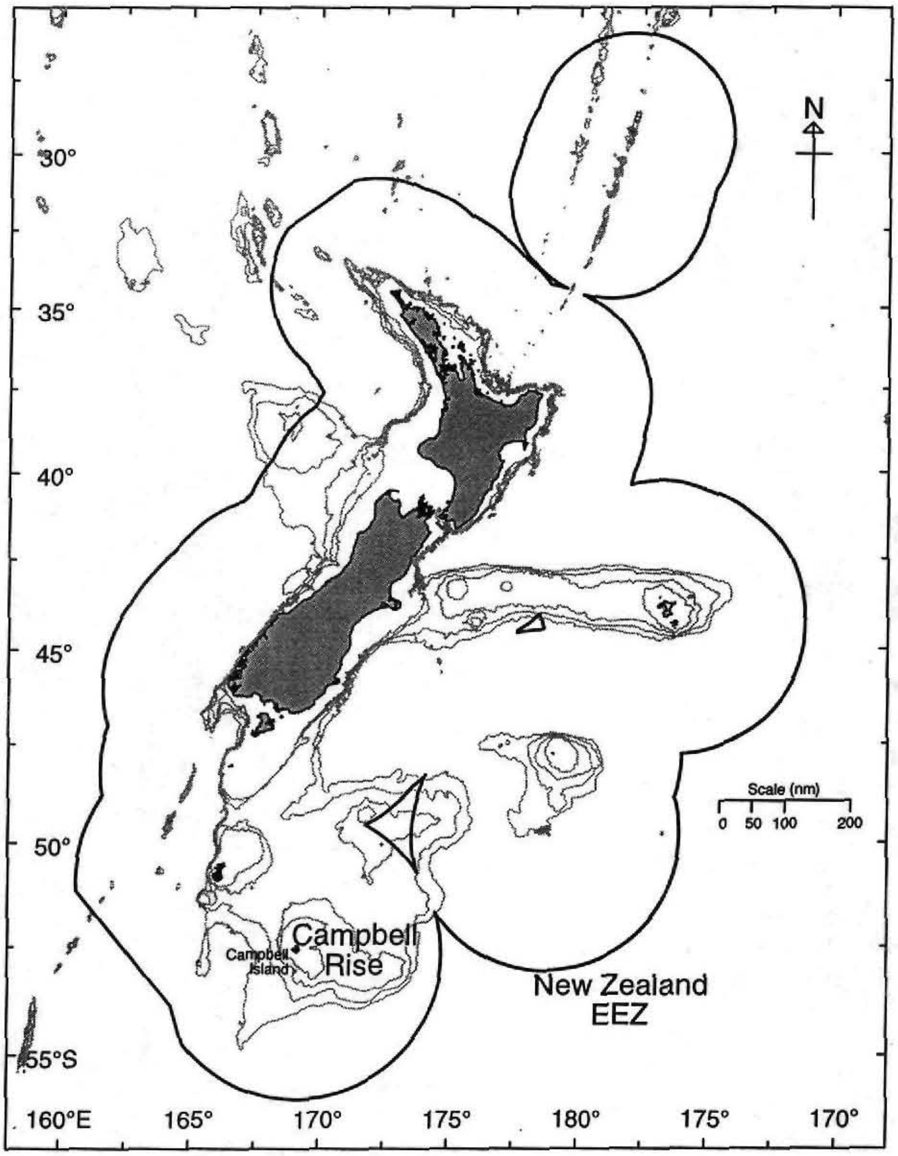

Figure 1: The location of the Campbell Rise within New Zealand's EEZ.

There can sometimes be an advantage in sampling in more than one step — where information gathered in the initial step (or phase) is used to inform the allocation of subsequent sampling. Many such designs are biased. Such methods are known as either multiphase or *adaptive* sampling strategies and are useful when the aim is to minimise variance, and hence increase precision.

Francis (1984) and Jolly & Hampton (1990) proposed an adaptive modification to the standard stratified sampling methodology, called two-phase sampling. In two-phase sampling, information obtained from a standard stratified random sample survey (called the first phase) is used to allocate additional sampling units (called the second phase) in a way that reduces the overall sampling variance. However, while this design often improves the overall efficiency of the survey, it is achieved at the expense of introducing bias.

Thompson (1990) proposed an alternative adaptive design, called adaptive cluster sampling. Here, in addition to the initial randomly allocated samples, additional sampling is allocated to areas found to be of "high" density during the survey (where "high" is defined as that greater than some previously defined critical value). Thompson derived an estimator for this design that has lower variance than the usual simple random sampling estimator (when the underlying population is clustered), and is unbiased.

We compare the efficiency of these two designs as methods for the acoustic survey of southern blue whiting on the Campbell Rise, using a simulation model based on previously collected acoustic data from the southern blue whiting fishery. This report meets Objective 1 of Project SBW1999/01 "To evaluate the use of alternative sample designs for acoustic surveys for southern blue whiting".

4. Methods

Data from the 1993, 1994, 1995, and 1998 acoustic surveys was analysed, using a simulation model to compare the relative efficiency of adaptive cluster sampling and two-phase sampling methods. We compare the efficiency of estimators using simulated samples generated from stratified random sampling, two-phase, and adaptive cluster sampling designs from this acoustic data.

Francis (1984) developed two-phase sampling for trawl surveys, introducing the idea of using information obtained in the course of a survey as a means of allocating additional effort, and hence improving the precision of estimates from the survey. Jolly & Hampton (1990) extended this to acoustic surveys. 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 the two phases is then analysed as if all the effort were allocated in a conventional stratified 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, albeit at the expense of bias.

Thompson (1990) showed that if a population was highly clustered, then adaptive cluster sampling designs could be more efficient that the usual simple random sampling. The key to this improvement is that the values and locations of the initial random samples are used to determine allocation of secondary samples. Adaptive cluster sampling, like two-phase sampling, is conducted in two steps. The first consists of selecting an initial N_1 samples from the population (in a manner analogous to the first phase of the two-phase sampling method). In the second step, the neighbourhood of any sample in the first step that has a value greater than some previously defined critical value is sampled. Then, for any sample that has a value greater than the critical value, the neighbourhood is sampled. This continues until there are no new values in any of the neighbourhoods that have a value greater than the critical value. Thompson (1990) defined any neighbourhood that was sampled in this way as a network, and the elements of that network that have a value greater than the critical value as a cluster. Further, he defines initial samples with value less than the critical value (i.e., a sample where no additional values in the neighbourhood were sampled) as a cluster of size one.

Thompson (1990) developed a number of different estimators, including the modified Hansen-Hurwitz type, modified Horvitz-Thompson type, and improved versions of these two using the Rao-Blackwell method. (See Thompson (1990) for an explanation of each of these estimators.) We investigate only the Horvitz-Thompson type estimator t_{HT*}, as the relative efficiency of this estimator is greater than the Hansen-Hurwitz estimator, but only very slightly less than the more computationally complex Rao-Blackwell version, $t_{\mathrm{RBHT}*}$.

If we assume initial random sampling without replacement, then we define

$$a_k^* = 1 - \binom{N_{total} - m_k}{N_1} \bigg/ \binom{N_{total}}{N_1},$$

where m_k is the number of units within the network that includes unit k; N_{total} is the number of units within the population; and N_1 is the initial sample size. For any unit not satisfying the condition of being greater than the critical value, then let m_k=1. Note that a_k^* can be considered to be the probability that a unit is used in the estimator.

The unstratified adaptive cluster sampling Horvitz-Thompson type estimator is then,

$$t_{\mathrm{HT}*} = N_{total}^{-1} \sum_{k=1}^{v} y_k J_k / a_k^*$$

where J_k is an indicator value that has value zero if the kth unit in the sample does not satisfy the condition being greater than the critical value and was not selected in the initial sample, and one otherwise; and v is the number of distinct units in the final sample. We also note that the expected value of the number of samples, N_μ, (i.e., the sum of the initial and secondary units sampled) can only be determined if the underlying population is known.

Note that Thompson (1991) also derived a stratified modification of standard (unstratified) adaptive cluster sampling. We do not use this, but instead evaluate the unstratified adaptive cluster sampling estimate for each stratum independently, and then combine the results over all strata to estimate the stratified estimate. A more complete discussion of the elements of adaptive sampling designs (including adaptive cluster sampling, stratified adaptive cluster sampling and two-phase designs) is given by Thompson & Seber (1996).

4.1 Measures of efficiency and bias

A useful method for comparing the relative efficiency of two or more sampling methods is *mean squared error*. For each estimator, we can estimate the bias $b(\theta)$, variance $Var(T|\theta)$, and hence the mean squared error MSE as

$$\begin{aligned} MSE &= E\left[(T-\theta)^2\right] \\ &= \left\{b(\theta)^2\right\} + Var(T|\theta) \end{aligned} \qquad [1]$$

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.

Also note that bias can be defined as

$$b(\theta) = E\left[(T|\theta)\right] - \theta \qquad [2]$$

Hence, we can compare between methods using *MSE*, where the method with the lesser *MSE* can be considered to be the most efficient. Within a simulation study, the estimate of *MSE* is relatively straightforward to calculate as the average squared difference between the "true" value and the estimated value.

4.2 Simulation methods

Data from the 1993, 1994, 1995, and 1998 acoustic surveys was used to investigate the relative efficiency of the two survey designs. For computational simplicity, we assumed that the survey region and the survey stratification were as for the 1995 acoustic survey (see Figure 2).

As adaptive cluster sampling requires knowledge of the location of potential samples relative to each other, the spatial distribution of biomass from each of the surveys was determined. Acoustic backscatter record data from individual "pings" for each transect were grouped into sets of about 200 pings, and the total absolute backscatter evaluated. As only the start and end positions of each transect were recorded, we estimated the start and end position of each set of pings from the start and end transect positions, multiplied by the proportion of the distance (in pings) along each transect from that which each group of pings were drawn. Further, each ping group was allocated to a stratum (based on the estimated location of the ping group and the stratification boundaries from the 1995 acoustic survey).

As the simulation model only requires the total biomass resulting from a (simulated) straight line transect, we combine (within bins) the data from all ping groups across bins of equal longitude within each strata, and hence evaluate the total marginal biomass. This results in a 1-dimensional spatial density curve for each stratum. An arbitrary bin width of about 0.05° (about 2 nautical miles) was used. This resulted in a survey region consisting of 7 strata with a total of 218 possible sampling units. For computational simplicity, the total biomass resulting from the surveys in each year was rescaled to have a sum of 1. Figure 3 shows the 1-dimensional spatial density (log scale) of each of the strata for each year of survey data.

Sampling for each of the methods (standard stratified random sampling, adaptive cluster sampling, and two-phase sampling) was simulated using the populations given in Figure 3. Acoustic surveys of Campbell Rise typically use a sample size of about 30–40 first phase samples, and about 5–8 second phase samples. We assume a sampling design for the two-phase sampling of 5 sampling units per strata in the first phase (35), and allocate 7 units to the second phase (following Francis 1984). Note that as we allocate an equal number of sampling units to the first phase, unlike the acoustic surveys, we are likely to over-estimate the variance of the actual two-phase sampling employed for analysing the survey.

The choice of initial sampling for the adaptive cluster sampling is more complex. We are required to choose the number of initial samples per strata and then the critical value that defines allocation of secondary sampling. The choice of these two parameters will determine the expected total sample size, as well as the resulting precision of the estimate. We use a selection of parameters, defining the critical value as 0.1, 0.5, and 1% of the total population biomass (see Figure 3) and the initial number of samples as 3 and 5 units per strata.

Brown (1999), in a comparative study of two-phase, stratified, and unstratified adaptive cluster sampling showed that the additional efficiency of stratified adaptive cluster sampling over unstratified adaptive cluster sampling was marginal (and resulted in a higher expected sample size). Hence, we also investigate an unstratified adaptive cluster sampling design with an initial sample size of 20 units. For the unstratified sampling design we use the same population (and hence relative positions of clusters) as earlier.

Simulations were run for the data for each year (1993, 1994, 1995, and 1998), and then by combining the results, to give an estimate of the *MSE* and other parameters over all years. The simulations were run on a 700 MHz Intel Pentium III computer using S-Plus 2000. For each set of parameter values, a total 500 simulated samples were generated. For each parameter set, the *MSE*, bias (where appropriate), and expected sample sized of adaptive cluster sampling were calculated.

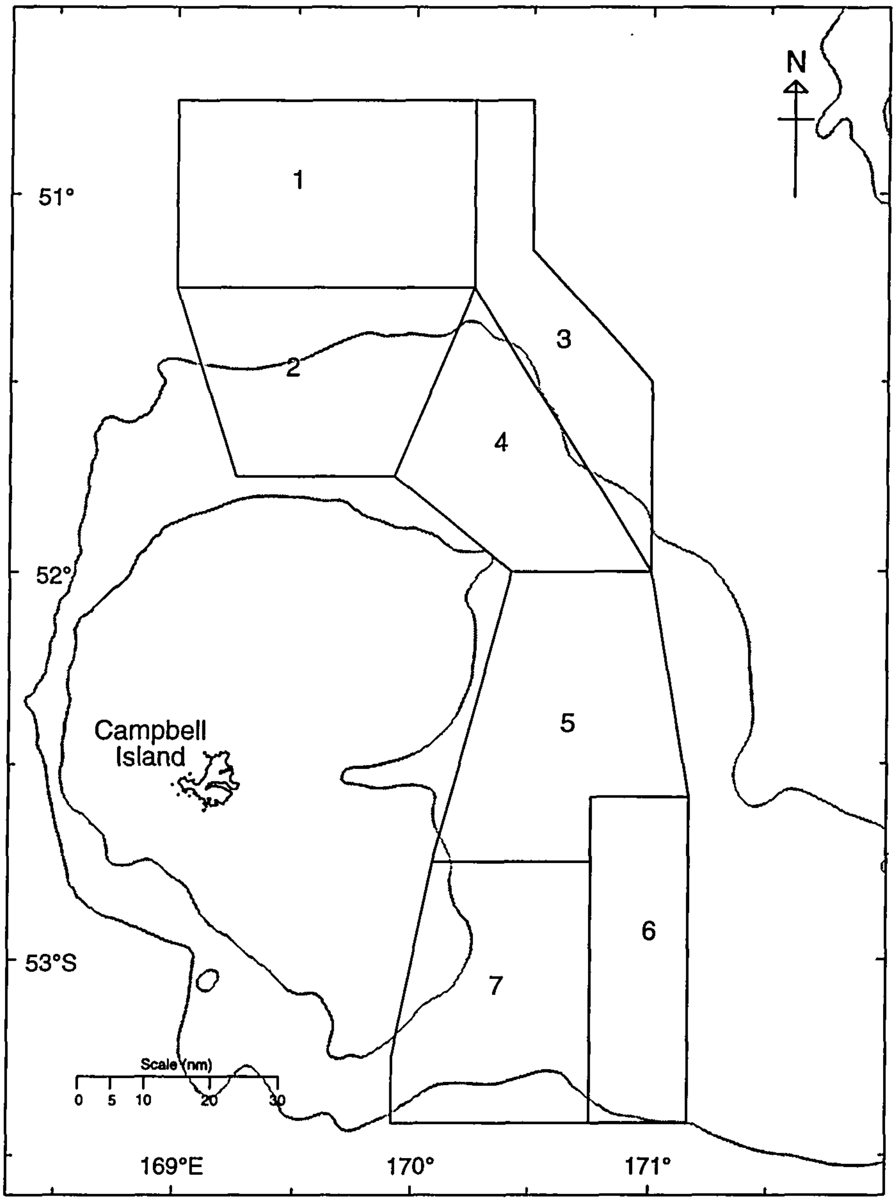

Figure 2: The Campbell Rise survey area, and the stratification used for the 1995 acoustic survey.

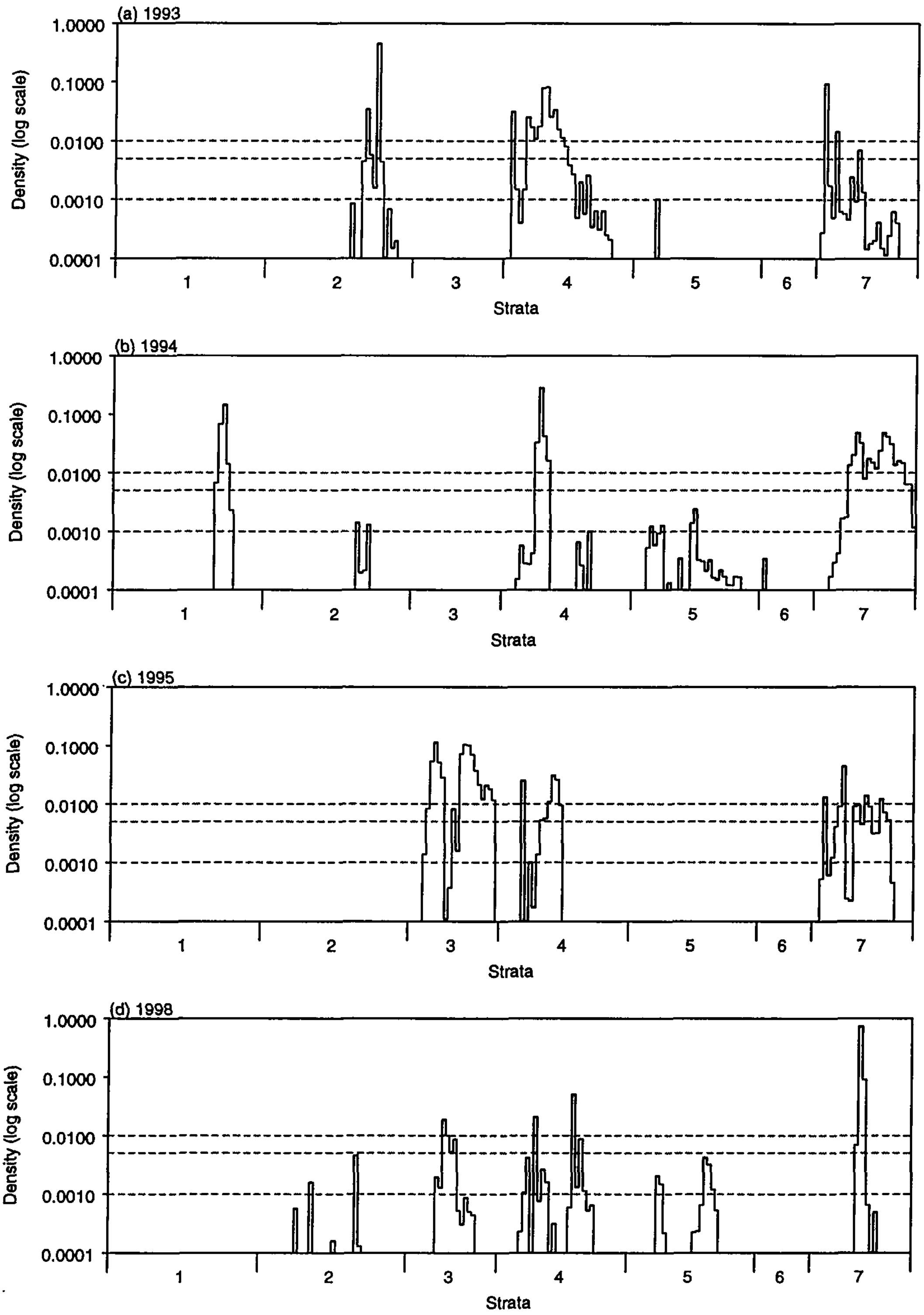

Figure 3: Relative density (log scale) by strata for (a) 1993, (b) 1994, (c) 1995, and (d) 1998 southern blue whiting acoustic surveys. Dashed lines represent the critical values of 0.1, 0.5, and 1%.

5. Results

Estimates of the variance, *MSE*, and expected sample sizes of the adaptive cluster sampling designs are given in Table 1 (for unstratified sampling with 20 initial sampling units), Table 2 (for stratified sampling with 3 initial sampling units per strata), and Table 3 (for stratified sampling with 5 initial sampling units per strata). Table 4 shows the results for the two-phase adaptive sampling design with first phase sample size of 5 units per strata and 7 units for the second phase. Table 5 shows the results of a standard stratified random sampling design with 6 units per strata.

In general, a higher threshold for the critical value resulted in a higher *MSE* and a lower expected sample size for all simulations of adaptive cluster sampling. Stratified adaptive cluster sampling showed some improvement over unstratified adaptive cluster sampling, however, the expected final sample size N_μ was slightly larger.

The increase in initial sample size from 3 units per stratum (Table 2) to 5 units per stratum (Table 3) for stratified adaptive cluster sampling resulted in a substantial reduction in the estimates of *MSE*. However, at the same time, expected sample size increased (from between 29–40 to 45–58 units respectively).

Two-phase sampling with the first phase allocation of 5 units per stratum and a second phase allocation of 7 units showed an average *MSE* of 0.54 over all years of the data. The average bias was about -22% — a value comparable to that found in similar studies of two-phase designs for southern blue whiting fisheries by Dunn & Hanchet (1998) and Bull (unpublished analysis). See Table 4.

The estimated *MSE* of two-phase sampling was comparable to the adaptive cluster design with 3 initial units per stratum and a critical value of 0.1%, and the adaptive cluster design with 5 initial units per stratum and a critical value of 0.5%. However, the adaptive cluster sampling designs in both cases potentially had much higher samples sizes ($N_{\max}$ of 65 and 69 respectively). See Table 5.

Plots of the expected sample size and resulting *MSE* for the adaptive cluster, two-phase, and the standard stratified random sampling designs are shown in Figure 4. Similarly, Figure 5 shows the maximum sample size found by *MSE* for each of the sampling designs.

The two-phase design showed a much lower *MSE* than the standard stratified random sampling design with equivalent sample size (0.54 versus 1.17). Some adaptive cluster designs performed better than the two-phase design, but the resulting expected sample size was always higher.

Table 1: Simulated unstratified estimates of variance, mean squared error (*MSE*), initial sample size (N_1), expected sample size (N_μ), the 95% upper bound of the expected sample size (N_{95}), and the maximum simulated sample size ($N_{\max}$) for adaptive cluster sampling of southern blue whiting acoustic data in 1993, 1994, 1995, and 1998, with critical values of 0.1, 0.5, and 1%, where initial sample size=20 units.

Critical value (%)	Year	Variance	*MSE*	N_1	N_μ	N_{95}	$N_{\max}$
0.1	1993	0.38	0.38	20	36	45	52
	1994	0.39	0.39	20	42	51	57
	1995	0.19	0.19	20	43	57	63
	1998	2.05	2.05	20	28	36	43
	All years	0.76	0.76	20	37	52	63
0.5	1993	2.66	2.67	20	29	35	40
	1994	0.42	0.42	20	37	46	48
	1995	0.25	0.25	20	34	45	52
	1998	2.06	2.06	20	23	29	33
	All years	1.35	1.35	20	31	43	52
1.0	1993	2.01	2.01	20	28	33	37
	1994	0.47	0.47	20	30	39	44
	1995	0.27	0.27	20	30	38	44
	1998	3.46	3.47	20	21	25	28
	All years	1.55	1.55	20	27	37	44

Table 2: Simulated stratified estimates of variance, mean squared error (*MSE*), initial sample size (N_1), expected sample size (N_μ), the 95% upper bound of the expected sample size (N_{95}), and the maximum simulated sample size ($N_{\max}$) for adaptive cluster sampling of southern blue whiting acoustic data in 1993, 1994, 1995, and 1998, with critical values of 0.1, 0.5, and 1%, where initial sample size=3 units per stratum.

Critical value (%)	Year	Variance	*MSE*	N_1	N_μ	N_{95}	$N_{\max}$
0.1	1993	0.48	0.48	21	38	47	51
	1994	0.38	0.38	21	45	52	57
	1995	0.09	0.09	21	49	63	65
	1998	1.68	1.68	21	30	38	44
	All years	0.66	0.66	21	40	57	65
0.5	1993	2.31	2.31	21	30	37	40
	1994	0.43	0.43	21	40	47	49
	1995	0.11	0.11	21	38	48	55
	1998	1.66	1.66	21	25	30	32
	All years	1.13	1.13	21	33	45	55
1.0	1993	2.44	2.44	21	29	34	38
	1994	0.57	0.57	21	33	40	45
	1995	0.14	0.14	21	33	40	46
	1998	2.63	2.63	21	23	26	29
	All years	1.45	1.45	21	29	39	46

Table 3: Simulated stratified estimates of variance, mean squared error (*MSE*), initial sample size (N_1), expected sample size (N_μ), the 95% upper bound of the expected sample size (N_{95}), and the maximum simulated sample size (N_{max}) for adaptive cluster sampling of southern blue whiting acoustic data in 1993, 1994, 1995, and 1998, with critical values of 0.1, 0.5, and 1%, where initial sample size=5 units per stratum.

Critical value (%)	Year	Variance	*MSE*	N_1	N_μ	N_{95}	N_{max}
0.1	1993	0.21	0.21	35	55	62	66
	1994	0.23	0.23	35	60	67	71
	1995	0.03	0.03	35	68	76	79
	1998	0.82	0.82	35	48	55	60
	All years	0.32	0.32	35	58	73	79
0.5	1993	1.47	1.47	35	47	51	55
	1994	0.22	0.22	35	55	61	62
	1995	0.05	0.05	35	57	65	69
	1998	0.87	0.87	35	40	45	48
	All years	0.65	0.65	35	49	62	69
1.0	1993	1.44	1.44	35	45	49	52
	1994	0.28	0.28	35	49	57	59
	1995	0.06	0.06	35	50	55	60
	1998	1.34	1.34	35	37	41	43
	All years	0.78	0.78	35	45	54	60

Table 4: Simulated estimates of variance, bias, and mean squared error (*MSE*) for two-phase sampling of southern blue whiting acoustic data in 1993, 1994, 1995, and 1998, where phase 1 sample size=5 units per stratum, and phase 2 allocation=7 units.

Year	Variance	Bias	*MSE*
1993	0.51	-0.28	0.59
1994	0.34	-0.19	0.37
1995	0.11	-0.03	0.11
1998	0.95	-0.38	1.09
All years	0.49	-0.22	0.54

Table 5: Simulated estimates of variance and mean squared error (*MSE*) for standard stratified random sampling of southern blue whiting acoustic data in 1993, 1994, 1995, and 1998, where sample size=6 units per stratum.

Year	Variance	*MSE*
1993	1.39	1.39
1994	0.62	0.62
1995	0.17	0.17
1998	2.56	2.56
All years	1.17	1.17

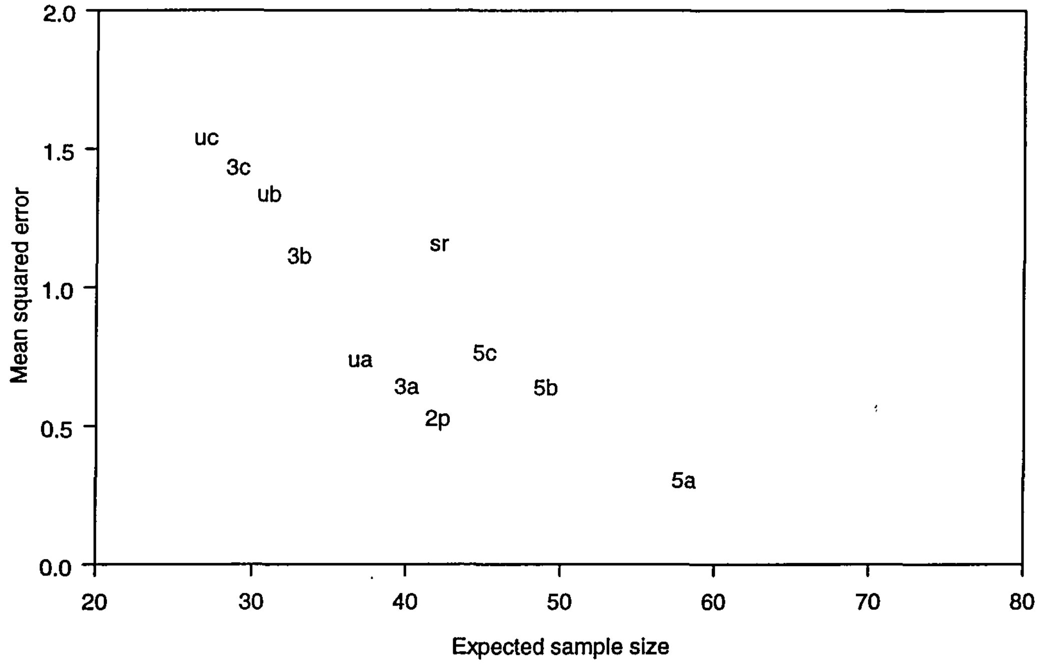

Figure 4: Estimated mean squared error by the expected sample size for adaptive cluster sampling (u=unstratified, 3=stratified with 3 initial units, 5=stratified with 5 initial units, with a=0.1% critical value, b=0.5% critical value, and c=1% critical value), two-phase sampling (2p), and stratified random sampling (sr), for all years.

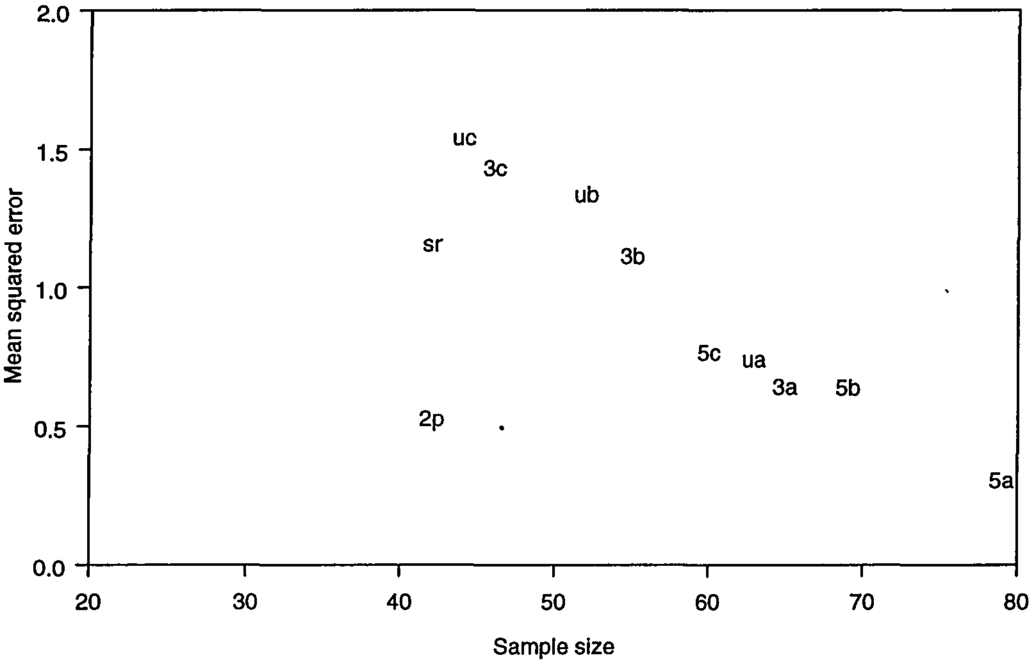

Figure 5: Estimated mean squared error by the maximum sample size for adaptive cluster sampling (u=unstratified, 3=stratified with 3 initial units, 5=stratified with 5 initial units, with a=0.1% critical value, b=0.5% critical value, and c=1% critical value), two-phase sampling (2p), and stratified random sampling (sr), for all years.

6. Discussion

The simulations confirm previous work (Dunn & Hanchet 1998, Bull, unpublished analysis) that two-phase designs are more efficient than standard stratified random sampling for southern blue whiting acoustic surveys where the underlying distribution of biomass is not well known. The simulations suggest that a two-phase survey strategy will approximately halve mean squared error over standard stratified random sampling, with about a 20% bias in the resulting abundance estimates.

The simulations also suggest that adaptive cluster sampling designs, with appropriate selection of the critical value and initial allocation, can provide a more precise estimate than two-phase adaptive designs, although this depends on the specific implementation of the various adaptive designs. In some cases, a poor choice of critical value or initial sample size can result in an estimate with lower precision.

Brown (1999) conducted a simulation study comparing the efficiency of two-phase adaptive design with stratified and unstratified adaptive cluster sampling analysis. She compared the relative efficiency of these designs for a simulated population using a clustered Poisson distributed population. Brown found that the benefits of stratified adaptive cluster sampling over unstratified adaptive cluster sampling were minor, and that the two-phase design performed better (i.e., lower *MSE*), in most cases, than adaptive cluster sampling designs. In general, this is consistent with the results that we report here, although the different choice of populations between the two studies makes detailed comparison difficult.

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, although the optimum proportion of effort to allocate to the second stage is mathematically difficult to estimate (though can be achieved by the use of simulations). In addition, the reduction in mean squared error and the increase in bias are highly dependent on the underlying distribution of the population — usually only very poorly known.

The choice of critical values and initial samples are key to the resulting efficiency of the adaptive cluster sampling design. However, these values are highly dependent on the spatial distribution of the underlying population. Thompson (1990) showed that adaptive cluster sampling has a strong advantage in cases where the underlying population is clustered and the cost of sampling a network is small compared to the cost of additional random samples. However, the additional cost of sampling within a network in acoustic surveys is not often less than the cost of an additional random sample.

The expected number of samples resulting from the adaptive cluster sampling simulations is a function of the bin width used to generate the underlying population. This analysis employed 0.05° bins to develop a suitable sampling frame for the simulations. This is unlikely to be a realistic choice. In practise, the area captured by the echo sounder on an acoustic transect is dependent on the frequency of the sounder and the depth of the sea floor. For a 38 kHz echo sounder, with a bottom depth of 500 m (assuming a 3 dB bandwidth and a tow body suspended 50 m deep with a 7° transducer angle), the diameter of the echo sounder coverage of the sea floor is only about 50 m. This would imply that to census each 0.05° width bin (about 3500 m), an additional 70 or so acoustic transects would be required. This would result in a much higher expected sample size than has been reported here. Binning at a higher level would hence lead to a much higher expected sample size for the adaptive cluster sampling designs. We assume that the choice of bins of 0.05° is adequate and ignore additional error due to an incomplete census of each strip. This, however, will not substantially impact on the relative estimates of *MSE* (as the same populations were used for all sampling designs) and only will effect the expected sample size calculations.

Adaptive cluster sampling is an open-ended sampling design. It is not possible to determine the exact number of samples required prior to the survey. The simulations above showed that while the expected sample size may be similar to that for the two-phase design, the 95% upper bound of the simulated sample sizes is generally about twice the initial sample size. This introduces several practical problems, not least in a question of how to determine the length of time required to conduct the survey.

Thompson & Seber (1996) discuss the relative merits of two-phase designs over adaptive cluster designs. An advantage presented by Francis (1984) of the two-phase design is that the survey (once the first phase has been completed) may be terminated at any point without any real loss. This allows for time lost to gear failure, weather, or any other factor that may not allow the completion of the second phase of the survey. However, adaptive cluster designs rely on each network sampled to be fully mapped. Thompson & Seber (1996), however, point out that a survey may proceed by mapping networks until only enough time remains to complete the remaining initial samples. The data may then be analysed by post-stratifying the survey region into the area where adaptive cluster sampling was completed, and the area where only simple random sampling was completed. The stratified estimates may then be combined using the usual theory.

Adaptive cluster sampling shows some very strong advantages over standard stratified random sampling or two-phase sampling, where the conditions are right. Situations were the additional cost of sampling within a network is small compared to new samples and where the population is highly clustered are good choices for adaptive cluster sampling. In particular, in situations where an unbiased estimate is considered to be important, adaptive cluster sampling is a better choice of sampling design. However, the implementation problems of adaptive cluster sampling for acoustic surveys of the Campbell Rise would be difficult to surmount. The choice of critical value and initial sample size could be evaluated using a more comprehensive set of simulations than presented here, however, the resulting sample sizes required would almost always be higher than the time allowed for the survey. Currently, the two-phase methods give a result that is more efficient than standard stratified random sampling, and, in most of the simulated scenarios, as good as or better than adaptive cluster sampling.

7. Acknowledgments

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8. Publications

None.

9. Data storage

No data from this project has been stored.

10. References

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