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Selecting the number of transects in multispecies acoustic surveys in northern Chile using a surface occupation index

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Abstract – An empirical approach was used to determine the sample size of transects in acoustic surveys to estimate the abundance of three pelagic species in northern Chile. Relationships between the coefficient of variation of fish density and modified degree of coverage were established, where the modified degree of coverage is proportional to the distance sailed and the surface occupation index (Co) of the species and inversely related to the square root of the study area. From this relationship, an equation was obtained to estimate the number of transects required in order to obtain a predefined level of precision, given a known level of occupation. The surface occupation index corrects the degree of coverage and explains to a large degree the differences in the estimated coefficients of variation among the different species. Results showed that sample size declined with an increase in the surface occupation index of the species, and the magnitude of that reduction was appreciably greater for higher levels of precision. The number of transects must be limited to sample sizes with a minimum transect separation in order to assure independence between transect densities. The empirical procedure used for the estimation of the number of transects can be applied to other species situations if the information is available from previous surveys, since the approach only requires repeated echo integrator surveys.

Key words: Acoustic surveys / Pelagic species / Anchovy / Jack mackerel / Sardine / Spatial autocorrelation

Résumé – Une approche empirique est utilisée pour déterminer la taille de l'échantillon de transects nécessaire lors de campagnes acoustiques afin d'estimer l'abondance de 3 espèces de poissons pélagiques dans la partie septentrionale du Chili. Les relations entre le coefficient de variation de la densité de poissons et le degré modifié de couverture sont établies, où ce degré de couverture est proportionnel à la distance parcourue et à l'index de surface occupée (Co) par l'espèce et inversement proportionnel à la racine carrée de l'aire d'étude. De cette relation, une équation est obtenue pour estimer le nombre de transects nécessaires afin d'obtenir un niveau de précision prédéfini, en regard d'un niveau connu d'occupation. L'index de surface occupée corrige le degré de couverture et explique en grande partie les différences dans les estimations des coefficients de variation entre les différentes espèces. Les résultats montrent que la taille de l'échantillon diminue lorsque qu'augmente l'index de surface occupée par l'espèce, et l'amplitude de la réduction est plus importante pour des niveaux élevés de précision. Le nombre de transects doit être limité à la taille de l'échantillon afin d'assurer l'indépendance entre les densités des transects. La procédure empirique utilisée pour l'estimation du nombre de transects peut être appliquée à d'autres espèces si l'information est disponible provenant d'autres campagnes acoustiques, cette approche demande seulement des campagnes répétées d'écho-intégration.

1 Introduction

Several different survey designs have been used for fish stock abundance estimation using acoustic surveys (overview in ICES 2005). Although systematic transect sampling is widely employed, many arguments for and against this design of acoustic survey can be found in the literature (Williamson 1982; Francis 1985; Jolly and Hampton 1990; Simmonds et al. 1992; ICES 2005). In a systematic design, the position of the first transect is chosen randomly and subsequent transects are located at regularly spaced intervals from it. The principal argument against the systematic design is that, according to sampling theory, the variance cannot be reliably estimated (Cochran 1977). Among the principal arguments in favour of the systematic design, however, are the simplicity of its application and the uniform distribution of sampling effort it allows over large study areas.

An issue not generally considered in the design of acoustic surveys under a systematic sampling scheme is the selection of the number of transects (i.e. sample size). In many acoustic

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surveys the number of transects is determined simply as a function of total available vessel time or the distance sailed, without considering the precision of the abundance/biomass estimates. This is possibly due to the exploratory nature of acoustic surveys. Surveys are usually designed with multiple objectives, one of which is the stock assessment of the species of interest (Hampton 1996). When multiple species are assessed simultaneously, the survey may not be efficient for all species (Barange et al. 2005). The level of precision attainable for a population is a factor of its spatial distribution (level of aggregation) and the sample size. For highly clumped distributions, an increase in effort will not necessarily result in an increase in precision.

Determination of sample size has been investigated in different contexts. Self and Mauritsen (1988) and Liu and Liang (1997) proposed methods to compute sample size and power from studies with correlated observations employing generalized linear models (McCullagh and Nelder 1995). Schabenberger and Gotway (2005) analyzed the effects of positive autocorrelation on statistical inference and found that the effect of positive correlation is that n correlated observations do not provide the same amount of information as the same number of uncorrelated observations. Thus, when the samples are correlated there is less information to estimate a mean from than in a set of purely random values. Cressie (1993) approached this problem by using the concept of effective sample size, defined as “the number of uncorrelated samples required to obtain the same precision as a sample of correlated observations”. When an autocorrelation structure can be inferred from the spatial distribution of a fish population, geostatistical techniques may be applied to estimate the variance of the abundance estimate (Petitgas 1993) regardless of the survey design used. Furthermore, a procedure to estimate the effective sample size from the geostatistical semivariogram has also been developed (Griffith 2005).

The effect of an increase in sampling effort on the reduction of the coefficient of variation (CV, relative precision) has been analyzed using geostatistical techniques (Petitgas 1991) and from repeated acoustic surveys (Aglen 1989). Both these approaches failed to include a component related to the underlying spatial structure of the populations. This is an important factor that may, to a large extent, explain the differences observed in the estimated coefficients of variation among surveys of different stocks (Gerlotto and Stequert 1983).

The objective of this article is to present an empirical method for estimating the optimal number of transects in multispecies acoustic surveys. A sample size equation derived from the precision-effort relationship proposed by Aglen (1989), was modified by incorporating a surface occupation index (Castillo and Robotham 2004) of the species.

2 Materials and methods

2.1 Relationships between spatial patterns and sample size

Aglen (1989) studied the relationship between the coefficient of variation (CV) of mean fish density per transect and the degree of coverage (DC) from repeated surveys, fitted to a power model given by

$$CV = \alpha(DC)^{\beta} \tag{1}$$

where DC is defined by Aglen (1989) as the ratio between the sailed distance (D) and the square root of the study area (A) ($DC = D/\sqrt{A}$). The DC index has also been defined as sampling effort and is similar to the term sampling intensity used by Kimura and Lemberg (1981).

The present article proposes to modify that relationship by including a surface occupation index (Co) of the species (Castillo and Robotham 2004), see Appendix:

$$CV = \alpha\,(MDC)^{\beta} \tag{2}$$

where α and β are parameters in the equation, and MDC is the modified degree of coverage index, defined as the product between the degree of coverage and the surface occupation index:

$$MDC = DC \cdot Co. \tag{3}$$

The index Co is obtained as the ratio between the total number of elementary sampling distance units (ESDU) containing the species (E^{+}) and the total number of ESDU sampled during the survey (Et) ($Co = E^{+}/Et$). An ESDU for one species is considered as positive (E^{+}) when at least one school of the species is within the ESDU.

From Eqs. (2) and (3) an expression is derived to determine the sample size of transects

$$\frac{D\,Co}{\sqrt{A}} = \left(\frac{CV}{\alpha}\right)^{1/\beta} \tag{4}$$

making $D = n\bar{D}$ in the first term of Eq. (4), where $\bar{D}$ is the average distance covered per transect, we get an expression of the sample size of transects n:

$$n = \frac{\sqrt{A}}{\bar{D}\,Co}\left(\frac{CV}{\alpha}\right)^{1/\beta}. \tag{5}$$

The sample size n can be expressed as an equation inversely proportional to the product of Co and $CV^{-1/\beta}$. In particular, when $\beta = -0.5$, the term $CV^{-1/\beta}$ is equal to CV^{2}. We assume in Eq. (5) that the transect length does not vary greatly.

2.2 Acoustic data and cruises

The acoustic data considered here are from seven seasonal multi-species acoustic surveys of pelagic fish off northern Chile. These were carried out between 1984 and 1990 from 18°20’ S to 24°00’ S, from the coastline to 185 km offshore. The main pelagic fish species studied included anchovy (*Engraulis ringens*), sardine (*Sardinops sagax*) and jack mackerel (*Trachurus murphyi*). The vessels used were “Itzumi” (1984), a 40.6-m stern trawler, and “Carlos Porter” (1985-1990), a 27-m trawler. The equipment employed included a scientific SIMRAD system composed of EKS (“Itzumi”) and EKR (Carlos Porter) 38-kHz echosounders and QM-MK II analogue echo integrators, calibrated following the standard procedure

(Foote et al. 1987). The acoustic data were collected along parallel diurnal transects separated by 55.6 km, and integrated over 3.7 km elementary sampling distance units (ESDU). The acoustic school density in each ESDU was obtained from the echograms. In order to transform acoustic density measurements, with the echo integrator into biomass values, the target strength per kg (TS kg) of –32.5 dB kg^{-1} was used. The species in the acoustics readings were identified using samples from purse–seine fishing performed by an auxiliary fishing vessel (surveys on the "Carlos Porter"), and midwater trawling (surveys on the "Itzumi").

2.3 Data processing

Analysis of variance was used to determine whether the surface occupation index (*Co*) values calculated for each transect showed significant effects by year and by species, and if these indices interacted. The coefficient of variation (*CV*) was fitted as a function of the modified degrees of coverage (*MDC*) using a power model. Additionally, the relationship between *CV* and the degree of coverage (*DC*), as defined by Aglen (1989), were analyzed and compared through the fitting of power models. The total sum square error ($SE = \sum_{i=1}^{3}\sum_{j=1}^{n_i}(CV_{ij} - CV_i)^2$) and the relative square error ($RSE_i = \sum_{j=1}^{n_i}(CV_j - CV_i)^2/SE$) by species were computed with a power model, where i is the species and j is the survey. Experimental isotropic variograms of fish school density for the sardine were computed using Matheron's (1971) estimator. Variograms were computed using the EVA software (Petitgas and Prompart 1995).

3 Results

The estimated surface occupation index varied with species and year. The surface occupation index for anchovy shows the lowest values (Fig. 1). The sardine shows a decreasing tendency in Co over a time period that coincided with the steady decline observed in the abundance of this resource (Castillo et al. 1994; Castillo and Robotham 2004). The jack mackerel shows both greater variability and range in *Co* than the other species. The analysis of variance (Table 1) indicated that the *Co* shows a significant species-year interaction effect.

Table 2 contains the estimated parameters of the coverage area and the precision of fish density by species and year. For the same degree of coverage (*DC*), the coefficient of variation differed considerably among species. The relationship between *CV* and *DC* for jack mackerel (Fig. 2a), shows that the degree of coverage was a poor predictor of *CV* ($r^2 = 0.092$), while for anchovy and sardine there was a better fit with the data ($r^2 = 0.48$). When the correction by surface occupation of fish on the degree of coverage index was applied, the relationship between *CV* and the estimated *MDC* of the surveys improved (Fig. 2b). The power models fitted to the data for each species were: sardine, $r^2 = 0.80$; jack mackerel, $r^2 = 0.78$; and anchovy, $r^2 = 0.54$.

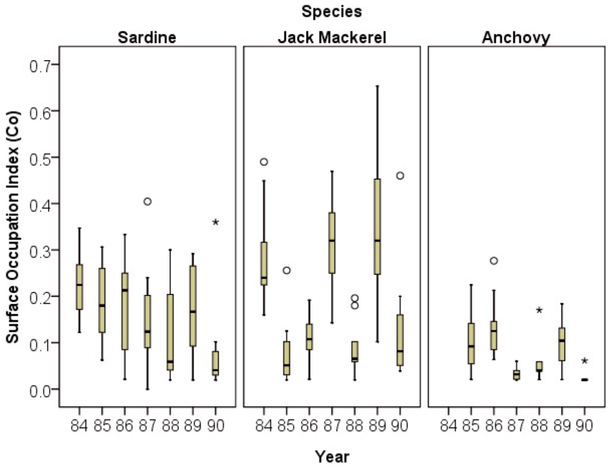

Fig. 1. Box-plot surface occupation indices (*Co*) on the transects studied off northern Chile during the period 1984 –1990.

Table 1. Analysis of variance of the surface occupation indices (*Co*) obtained from seven seasonal acoustic surveys in northern Chile during the period 1984-1990.

Dependent variable: surface occupation index (*Co*)

Source of variation	Sum of squares	*d.f.*	Mean squares	*F*
Corrected model	1.465	19	0.077	9.07**
Intercept	3.994	1	3.994	469.66**
Species	0.281	2	0.140	16.51**
Year	0.389	6	0.065	7.63**
Species * Year	0.617	11	0.056	6.60**
Error	1.548	182	0.009	
Total	8.152	202		
Corrected total	3.013	201		

(**) The effect is significant at the 0.05 level.

In the study period, the dominant species in the north of Chile was the sardine; the anchovy emerged as an important species after 1995. In this context, in order to choose a single model and obtain an equation for estimating the number of transects, we propose selecting the model fitted for the most important resource, in this case sardine. The sardine curve was projected for all distributions of *MDC* values (Fig. 3). In this model *CV* decreased rapidly with increasing *MDC* to approximately a level of 1.22, after which, the improvement in precision decreased considerably. For this threshold, a *CV* is equal to 0.20. The power curve used was:

$$CV = 0.2284\,(MDC)^{-0.6588}. \qquad (6)$$

The standard error of estimate β was 0.1483. The estimate value β (–0.6588) was not significantly different from –0.5 (t-test = 2.57, $p > 0.05$), hence there is not enough evidence to reject the assumption of independent transects (see appendix). The sum square error for the power model fitted was equal to 0.01815 and the relative square error for anchovy, jack mackerel and sardine, were 87.9%, 9.4% and 2.7%, respectively.

Table 2. Summarized information and indicators obtained per year from the cruises studied (1984-1990), area of study, numbers of transects (n), degree of coverage (DC), modified degree of coverage (MDC) by species; surface occupation index (Co) by species, and the estimation of coefficient of variation (CV) by species.

Year	Area (km^2)	Transect n	Degree coverage (DC)	Index	*Sardinops sagax*	*Trachurus murphy*	*Engraulis ringens*
1984	133 622	12	6.08	MDC	1.342	1.559	-
				Co	0.221	0.256	-
				CV	0.183	0.180	-
1985	128 480	14	7.23	MDC	1.239	0.449	0.641
				Co	0.171	0.062	0.088
				CV	0.245	0.325	0.545
1986	128 480	14	7.23	MDC	1.304	0.559	0.888
				Co	0.180	0.077	0.123
				CV	0.195	0.271	0.272
1987	128 480	13	6.72	MDC	0.891	2.048	0.127
				Co	0.133	0.305	0.019
				CV	0.202	0.151	0.551
1988	92 507	9	5.48	MDC	0.532	0.495	0.198
				Co	0.097	0.090	0.036
				CV	0.413	0.209	0.834
1989	102 787	11	6.35	MDC	1.096	2.263	0.625
				Co	0.173	0.356	0.098
				CV	0.193	0.167	0.381
1990	71 949	8	5.52	MDC	0.445	0.751	0.111
				Co	0.081	0.136	0.020
				CV	0.363	0.244	0.629

(-) indicates that the anchovy species (*Engraulis ringens*) was not found on the 1984 survey.

Finally, the following empirical expression was obtained to estimate the optimal number of transects:

$$n = \frac{1}{\bar{D}}\frac{\sqrt{A}}{Co}\left(\frac{CV}{0.2284}\right)^{-1/0.6588} \tag{7}$$

where $\alpha = 0.2284$ and $\beta = -0.6588$ are parameters of the power model fitted, CV is the coefficient of variation of the estimator, A is the area of the study, Co is the surface occupation index and $\bar{D}$ the mean length per transect.

For these acoustic surveys the transects had an approximate mean length of 185 km, and the average area surveyed was 110 000 km^2.

The curves of sample size are shown as a function of the Co for values of the CV, which ranges between 0.10 and 0.30 (Fig. 4). For a Co value between 0.15 and 0.30 and a CV value of 0.15, the number of transects ranged between 11 and 23, while for a CV of 0.20, between 7 and 14 transects were required. A CV lower than 0.15 greatly increased the number of transects required, for a CV value of 0.10, the sample size varied from 21 to 42 transects.

The fitted parameters of the normalized isotropic models for sardine are presented in Table 3. The sardine displayed autocorrelation ranges between 18.5 km and 33 km.

4 Discussion

This article proposes an empirical approach to estimate the sample size of transects in multispecies acoustic surveys in northern Chile. The sample size formula was derived as an extension of Aglen's (1989) work, assuming independence of transect densities (density of schools summed over transects). The estimation of the β parameter in Eq. (2) was not significantly different from –0.5. This estimation is an informative index about independence between transects. In this context, the coefficient of variation (CV) differs considerably among species for the same degree of coverage (DC). This can, in part, be attributed to the fact that different stocks of fish often show different patterns of spatial distribution within the study area (Gerlotto and Stequert 1983; MacLennan and Mackenzie 1988; Barange et al. 2005), which the DC is not capable of representing, explaining the lack of fit to the empirical model (Eq. (1)) of Aglen (1989) when working with a multispecies fishery. In order to improve the fit of the model and obtain an equation for estimating the sample size of transects, we propose that the DC be corrected by the surface occupation index (Co) of each species. According to our results the surface occupation index explains in large measure of the differences in the estimated coefficients of variation.

The high contribution of the anchovy to the sum square error (RSE = 87.9%) indicates that the model chosen does not seem appropriate when the Co value is low and the CV value is high, as occurs principally with the anchovy in this study. The high CV and low Co values observed for anchovy can be explained by the low abundance of the species and by the fact that its distribution is restricted to a small area of the survey. In relation to the anchovy, an alternative would be to design a particular survey according to the expected distribution of the species. Nevertheless, if Co continues to low values (whatever the species) a large number of transects will probably be necessary to achieve a reasonable value of precision (i.e. CV

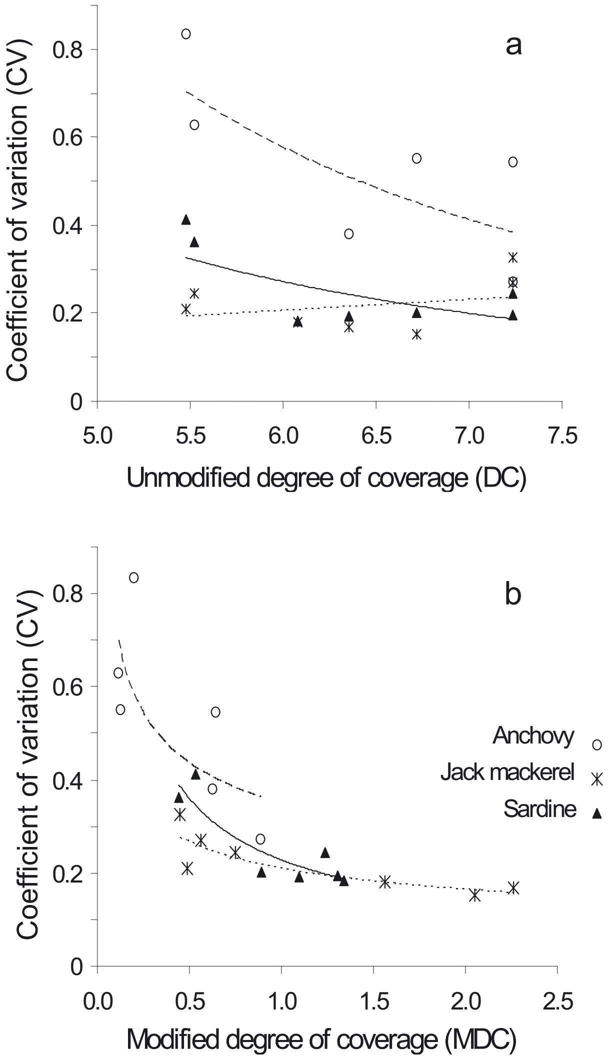

Fig. 2. Relationships between the coefficient of variation (CV) of the estimated density and (a) the unmodified degree of coverage (DC), fit (CV and r^2) of the power model is shown by species: $CV_a = 28.871\,DC^{-2.1843}$; $r^2 = 0.480$ for anchovy; $CV_j = 0.0561\,DC^{-0.725}$; $r^2 = 0.092$ for jack mackerel; $CV_s = 9.7376\,DC^{-1.9971}$; $r^2 = 0.486$ for sardine; (b) the modified degree of coverage (MDC): $CV_a = 0.343\,MDC^{-0.3178}$; $r^2 = 0.54$ for anchovy; $CV_j = 0.2096\,MDC^{-0.3482}$; $r^2 = 0.78$ for jack mackerel; $CV_s = 0.2284\,MDC^{-0.6588}$; $r^2 = 0.80$ for sardine.

less or equal to 0.2). On the other hand, the least contribution to the sum square error of the sardine ($RSE = 2.7\%$) and the jack mackerel ($RSE = 9.4\%$) suggest the validity of the proposed model for these two species. Based on this information, the number of transects performed by the sample Eq. (5) was directed mainly at sardine and jack mackerel.

The equation obtained for estimating the number of transects is inversely proportional to the product of Co and $CV^{1.5}$ where the Co index is a measure of homogeneity in the distribution of fish schools in the study area. This index does not, however, consider homogeneity in density among transects, which is measured by the CV index in the equation. For a fixed value of precision (CV), species with a higher Co require a lower number of transects, while if the value of the surface occupation index is low, the required number of transects may greatly increase (Fig. 5). On the other hand, for a fixed number of transects, while Co increases, CV decreases. The reduction in the required number of transects due to the increases of the surface occupation of the species is appreciably greater for higher levels of precision.

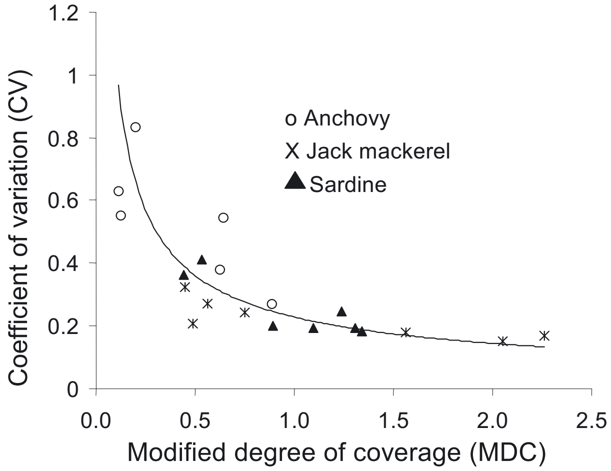

Fig. 3. Relationship between the coefficient of variation of the estimated density (CV) and the modified degree of coverage (MDC); off northern Chile, during the period 1984-1990. The sardine curve line equation is shown $CV_s = 0.2284\,MDC^{-0.6588}$.

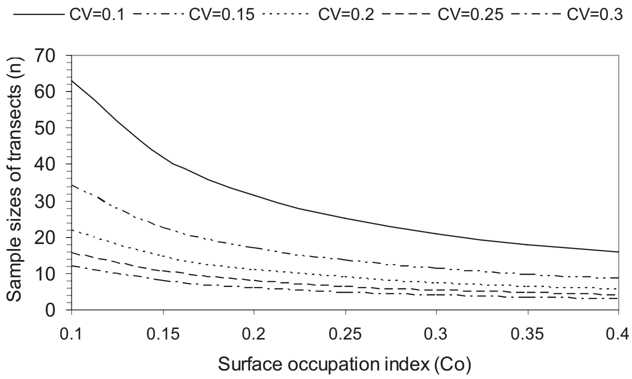

Fig. 4. Curves of sample sizes of transects (n) as a function of the coefficient of variation (CV) of the estimated density and surface occupation index (Co), for the acoustic data obtained from seven seasonal surveys in northern Chile during the period 1984-1990.

In addition to the surface occupation index (Co) and the coefficient of variation (CV) inter-transect distance is an important reference to considerer when the sample size must be chosen, even though it is not a parameter in the sample size equation. The number of transects sampled is limited by the restriction on minimum separation which will allow for independence among transect densities. Information about the correlation structures of the various fish species is unknown prior to carrying out an acoustic survey for many fish populations. The probability of observing inter-transect correlation decreases with increasing distance among transects. Determining an inter-transect distance for assessing several species simultaneously with different long-range correlations may present

Table 3. Parameters of the normalized variogram models fitted for acoustics data of sardine off northern Chile during the period 1984-1990.

Year	Model	Nugget	Sill	Range (km)
1984	Exponential	0.2736	0.9575	18.5
1985	Exponential	0.3757	0.9018	33.3
1986	Spherical ($\log(1 + z)$)	0.5573	0.5573	33.3
1987	Spherical ($\log(1 + z)$)	0.3631	0.7322	27.8
1988	Exponential ($\log(1 + z)$)	0.3454	0.6909	18.5
1989	Exponential ($\log(1 + z)$)	0.5182	0.5959	33.3
1990	Spherical ($\log(1 + z)$)	0.4642	0.3979	27.8

significant practical problems. Barange and Hampton (1997) suggested that the ideal inter-transect distance would be driven by the range of the highest density indicator for the sardine, approximately 19 km. In their paper two species, sardine and anchovy, were assessed simultaneously. The inter-transect distance used in a survey may not be adequate for all species, and therefore the survey may not be efficient for all species (Barange and Hampton 1997; Barange et al. 2005).

Using the data from the north of Chile as an example, we estimated the number of transects. As we do not know the autocorrelation ranges of the all species exactly, we assumed that the most important species, the sardine, had the highest autocorrelation range, with a maximum range of approximately 33 km (Table 3). For a inter-transect distances larger than this autocorrelation range, the number of transects in the study area will have an upper limit of 20 transects or less. In this framework, for a level of CV between 0.21 and 0.33 and a Co index equal to 0.1, the optimal number of transects ranged between 10 and 20. For the same number of transects, when the Co index is equal to 0.3, the CV ranges between 0.10 and 0.16. Clearly, when Co decreases, CV increases. As a general criterion a CV less than or equal to 0.2 is assumed to be a reasonable level of precision, while Co has an unknown magnitude that needs be estimated.

Given that the surface occupation index showed significant year-species interaction and is a value which is unknown prior to carrying out an acoustic survey, it is proposed to estimate Co by measuring spatial occupation over some testing transects (supplementary transects) during the initial activity of the survey. The number of transects used for the testing phase depends on the budgetary considerations of the study and the targeted species in the area. Another procedure to estimate Co is to conduct a rapid acoustic survey with several fishing vessels simultaneously. The feasibility of the second procedure depends on the incentives to fishing vessel operators, including enlarged quotas. The empirical approach to defining an optimal sample effort (number of transects) can be generalized for other multispecies assessments, if the information is available from previous studies, since the approach requires repeated echo integrator surveys. Clearly in order to obtain the required estimates of the parameters α and β in the Eq. (5), we need several previous surveys with varying values of Co and CV. In future work, it would be possible to incorporate into the sample size formula other alternative forms of measuring the spatial structure that have been shown to be less variable than Co at different population abundances.

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APPENDIX

The empirical approach to obtain the precision-effort relationship, Eqs. (1) and (2), and the sample size of transects, Eq. (5), can be applied to different estimator of fish density as the mean and ratio estimators. Both estimators had been used in acoustic surveys (Simmonds et al. 1992; ICES 2005).

In Aglen (1989), the precision was measured by the coefficient of variation of mean density estimator per transect, where the transect is assumed as a single sample and the density of schools summed over the transects is assumed independent and identically distributed throughout the survey area. Serial correlation within transects had no effect since only transect density sums are used in variance estimation.

In this context, let y_i the density of schools summed over the i-th transect ($i = 1, ..., n$) and n the number of transects of the systematic sample. The variance of the mean sample $\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$ without considering the finite correction factor is

$$V(\bar{y}) \approx \frac{S^2}{n} + \frac{(n-1)}{n} Cov(y_i, y_j) \quad ; \quad i \neq j \tag{8}$$

where S^2 is the variance of the cumulated densities of transects (inter-transect variance) and $Cov(y_i, y_j)$ is the term of covariance between transect densities ($i \neq j$). Assuming the density of schools summed over the transects are independent, $Cov(y_i, y_j) = 0$, the variance and the coefficient of variation are, respectively

$$V(\bar{y}) \approx \frac{S^2}{n} = \frac{1}{n} \frac{\sum_{i=1}^{N} (y_i - \bar{Y})^2}{N-1} \tag{9}$$

$$CV(\bar{y}) \approx \sqrt{\frac{1}{\bar{Y}^2} \frac{\sum_{i=1}^{N} (y_i - \bar{Y})^2}{(N-1)}}\, n^{-1/2} \tag{10}$$

where $\bar{Y}$ is the mean fish density per transect to estimate. From this last equation Aglen, (1989) studied the relationship (Eq. (1)) between coefficient of variation (CV) of mean fish density per transect and the degree of coverage (DC) from repeated surveys. The coefficient of variation (CV) is a measure of the relative standard error, defined as a ratio between the standard error of the estimator and the estimator itself.

In this paper, the precision of the relationship studied was measured by the coefficient of variation of the ratio estimator (density relative per ESDU). The ratio estimator was used because the transect (as sample unit) is not always exactly the same length and the coefficient of variation of transect sizes in the number of ESDU is less than 0.2 (Kish 1965; Williamson 1982). The approach that developed in this study for the ratio estimator is applicable to mean estimator.

To estimate the relative density per ESDU the ratio estimator r was used, expressed as:

$$r = \frac{\sum\limits_{i=1}^{n} y_i}{\sum\limits_{i=1}^{n} x_i} \tag{11}$$

where n is the number of transects, y_i is the density of schools summed over the i-th transect and x_i is the total number of ESDU on the i-th transect ($i = 1, ..., n$). An approximate variance of the r estimator, without considering the finite correction factor, is given by

$$V(r) \approx \frac{1}{n} \frac{\sum\limits_{i=1}^{N} (y_i - Rx_i)^2}{(N-1)\,\bar{X}^2} \tag{12}$$

where R is the relative density per ESDU to estimate, N is the total number of transects in the study area and $\bar{X}$ is the mean number of ESDU per transect. The variance expression assumed that each transect cumulated densities through the area is independent. If there is a dependence between transects estimates, the covariance between transects will introduce an additional term in the variance expressions.

From the Eq. (12) a possible approximate expression for the coefficient of variation of the r estimator without considering the finite correction factor (details of the derivation are in Cochran 1977).

$$CV(r) \approx \sqrt{\frac{1}{\bar{Y}^2} \frac{\sum\limits_{i=1}^{N} (y_i - Rx_i)^2}{(N-1)}}\; n^{-1/2}. \tag{13}$$

The number of transects n can be expressed as a ratio between the total modified degree coverage (MDC) and the modified degree coverage represented by one transect (Aglen 1989):

$$n = \left(\frac{D}{\sqrt{A}} Co / \frac{\bar{D}}{\sqrt{A}} Co \right) \tag{14}$$

where $\bar{D} = D/n$ is the average distance covered per transect. Derived from the Eq. (14), $n^{-1/2}$ is equal to

$$n^{-1/2} = \left(\frac{D}{\sqrt{A}} Co \right)^{-1/2} \left(\frac{\bar{D}}{\sqrt{A}} Co \right)^{1/2} \tag{15}$$

making the first term in CV (Eqs. (13) or 10) equal to L. Hence,

$$CV \approx L\ n^{-1/2}. \tag{16}$$

By replacing $n^{-1/2}$ an equivalent equation is obtained by

$$CV \approx L \left(\frac{\bar{D}}{\sqrt{A}} Co \right)^{1/2} \left(\frac{D}{\sqrt{A}} Co \right)^{-1/2}. \tag{17}$$

This can be approximated for the power model given by

$$CV = \alpha \left(\frac{D}{\sqrt{A}} Co \right)^{-1/2} \tag{18}$$

where $\alpha = L(\bar{D}Co/\sqrt{A})^{1/2}$ is equal to CV when the modified degree of coverage ($MDC = (DCo/\sqrt{A})$) is equal to 1. By definition, MDC is always greater than zero. In the equation, CV decreases with the increase of MDC. Equation (18) simplified is

$$CV = \alpha\,(MDC)^{\beta}. \tag{19}$$

Note that the power model in Eq. (1), fitted by Aglen (1989) is similar to Eq. (19) where the degree of coverage (DC) is replaced by a modified degree of coverage (MDC). The expected value for theβ parameters is –0.5, which is the theoretical value assuming independent transect estimates, otherwise a covariance term must be included in the Equations (10) and (13).

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