Optimizing the design of acoustic surveys of Peruvian anchoveta

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Acoustic surveys of stocks of small pelagic fish, in particular the Peruvian anchovy or anchoveta (*Engraulis ringens*), have been carried out off the coast of Peru since the late 1970s. In all, 51 of these have been carefully archived since 1983. The surveys provide a wealth of data on the distribution and abundance of pelagic fish in the most productive of the world's upwelling ecosystems. The data comprise integrated acoustic data at a resolution of 1 or 2 nautical miles along the cruise tracks, and trawl data, which include catch-by-species and catch-by-length information for anchoveta. Data since 1992 are sufficiently complete to allow a full re-evaluation of the surveys to determine their precision, taking account of the spatial variability of the catch and acoustic data. The methods used include bootstrap by trawl sample and transect segment, geostatistical simulation, and simulated surveys. The results reveal consistent spatial patterns of abundance with a more variable distribution of variance and a strong relationship between the local mean abundance and the variance. The temporal and spatial variabilities are considered in an evaluation of alternative survey designs, including pre-stratified and adaptive designs.

Keywords: acoustic survey, anchoveta, anchovy, Peru Humboldt Current system, survey design.

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Introduction

The Peruvian anchovy or anchoveta (*Engraulis ringens*) is a critical element of the Humboldt Current system (HCS) and supports the world's largest monospecific fishery. Anchoveta is fast growing, matures rapidly ($\sim$1 year), has a short lifespan ($<$4 years), and responds rapidly to environmental variability (Valdivia, 1978; Buitrón and Perea, 2000; Alheit and Niquen, 2004; Bertrand *et al.*, 2004, 2008a, b; Gutiérrez *et al.*, 2007; Espinoza and Bertrand, 2008). Stock biomass and catches have exceeded 15×10^6 t; hence, anchoveta plays a crucial ecological and socio-economical role in the HCS. It is therefore important to acquire data on anchoveta distribution and abundance for the purposes of managing the Peruvian fishery.

Stocks of small pelagic fish, in particular the Peruvian anchoveta, have been surveyed acoustically off the coast of Peru since the late 1970s. In all, 51 surveys since 1983 provide a wealth of data on the seasonal distributions and abundances of pelagic fish in the area. The surveys involve up to four vessels and last between one and two months. The survey-track densities are variable from survey to survey; most span the area uniformly, but some are limited to the central-coast area. The current survey design has been adapted only slightly and in an *ad hoc* manner since it was adopted in 1983. The objective of our study was to identify the major sources of variability in the population estimates and evaluate the possibilities for pre-stratification of effort, among either areas or activities, and to investigate whether adaptive effort allocation is useful.

Data

Acoustic data were collected from 1983 to 2006 by the Instituto del Mar del Peru (IMARPE) on a variety of vessels, most commonly the RV "Humboldt" (76 m long), the RV "Olaya" (41 m long), and the RV "SNP-2" (36 m long). In most years, the surveys comprised parallel transects, $\sim$100 nautical miles (185 km) long, with nearly a 15-nautical-mile spacing (Figure 1). Biological data were collected using a midwater trawl with a fine-mesh codend.

Simrad scientific echosounders (EK, EKS, EK400, EY500, EK500, and EK60) were used. From 1983 to 1991, and after 1997, measurements at 120 kHz were made for abundance estimation, whereas between 1992 and 1997, measurements at 38 kHz were taken. The echosounders were calibrated before each survey, using hydrophones until 1992; thereafter a standard sphere was used (Foote *et al.*, 1987). Extensive midwater-trawl sampling accompanied the acoustic surveys for species identification and biological samples (Figure 1).

Nautical-area-backscattering coefficients (s_A) were recorded in each georeferenced elementary distance sampling unit (EDSU; Simmonds and MacLennan, 2005) equal to one or two nautical miles (1994–2006 and 1983–1993, respectively). The volume-backscattering strengths were thresholded at -65 dB.

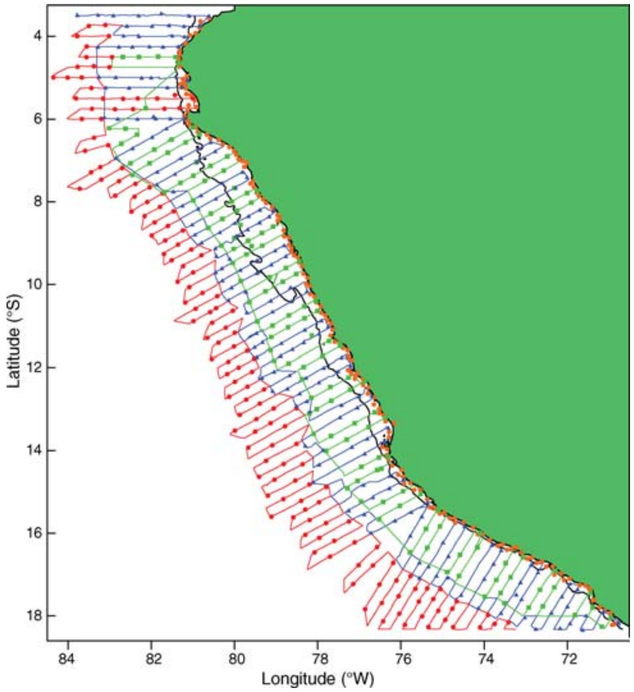

Figure 1. A systematic parallel grid as used on a Peruvian survey from 7 October to 9 November 2001 involving three research vessels. Transects are normal to the run of the coast in three sections. The offshore legs (red) are surveyed by RV "Olaya" and the inshore legs (interlaced in pairs) by RV "SNP-2" (green) and RV "Humboldt" (blue). Symbols mark the locations of pelagic-trawl stations and identify the vessel involved. A fourth vessel (FV "IMARPE") provided additional trawl samples very close to inshore (orange).

Table 1. Survey estimates: year, time-in-year (to the nearest half month), number of hauls, length of cruise track, and estimates of total biomass and spawning-stock biomass (SSB; 10^6 t).

Cruise	Year	Month	Number of hauls	Number of EDSUs	Total biomass	SSB	*CV* (%)
0602-04	2006	3.5	282	8 052	7.59	6.18	9
0511-12	2005	12	158	4 006	5.81	5.56	10
0508-09	2005	9	61	5 582	7.06	5.08	14
0502-04	2005	3.5	106	8 296	16.40	8.70	12
0411-12	2004	12	66	2 740	3.77	2.85	28
0408-09	2004	9	85	5 537	7.15	6.67	13
0402-03	2004	3	152	9 403	12.43	4.69	15
0310-12	2003	11.5	176	11 112	3.14	2.51	20
0308-09	2003	9	103	6 542	8.65	4.27	18
0302-03	2003	3	248	7 085	6.41	4.44	16
0210-11	2002	11	167	10 690	4.69	4.61	8
0208	2002	8.5	100	4 735	4.70	4.10	11
0202-03	2002	3	233	6 081	20.15	9.27	12
0110-11	2001	11	539	16 008	5.77	5.54	9
0108-09	2001	9	169	4 255	4.18	4.13	8
0107-08	2001	8	409	9 232	5.39	5.23	5
0102-04	2001	3.5	452	9 357	13.67	10.98	8
0010-11	2000	11	353	7 942	5.35	4.76	15
0008-09	2000	9	110	3 455	4.19	4.02	10
0006-07	2000	7	309	6 671	9.02	8.99	8
0001-02	2000	2	447	8 801	14.11	14.06	6
9911-12	1999	12	139	4 844	6.51	6.28	15
9908-09	1999	9	24	5 150	3.42	2.83	33
9906	1999	6.5	170	4 092	2.72	1.64	16
9902-03	1999	3	168	6 681	4.41	3.15	11
9811-12	1998	12	100	3 225	1.69	1.47	18
9808-09	1998	9	272	7 499	0.92	0.00	149
9805-06	1998	6	82	3 338	0.98	0.93	17
9709-10	1997	10	51	5 183	3.13	3.07	17
9704	1997	4.5	54	2 434	1.88	1.83	74
9611-12	1996	12	90	5 560	0.47	0.17	13
9602-04	1996	3.5	133	7 392	0.87	0.79	11
9502-04	1995	3.5	129	6 344	2.21	1.84	14
9401-03	1994	2.5	96	3 914	10.96	8.26	21
9301-03	1993	2.5	80	3 901	3.41	2.77	25

SSB is defined as the biomass of anchoveta ≥ 12 cm; *CV*s are approximate—see text, estimates do not compensate for occasional reduced-area coverage.

Identification of echoes is accomplished using metrics of the echoes and the catches from associated fishing trawls.

A list of surveys conducted between 1992 and 2006, by year and month, and a number of EDSUs and hauls are given in Table 1. Archived data from 1992 include s_A per EDSU, catches by species by station, length (L) distributions of anchoveta and other species by station, and the target strength (TS) vs. L relationship used.

Methods

These parallel-transect data are fully reanalysed using the general methods described in Simmonds and MacLennan (2005) and further detailed in Simmonds and Fryer (1996). For surveys before 1992, full reanalysis is impossible, because TS and s_A were not recorded separately. However, the relative magnitudes of their spatial-sampling errors attributable to the corresponding acoustic and catch data are evaluated and included in the estimates of spatial abundance and variance.

Abundance

Fish abundance is estimated as the mean of observations within 10 × 30 nautical-mile strata formed by 30-min intervals of latitude and lines of 10, 20, 30, etc. nautical miles from the coast. The strata boundaries and areas are estimated from the coastline data using a geographic information system. The quantity of fish Q in stratum i is estimated from s_A, the area (A), L, and the mean backscattering-cross-sectional area ($\bar{\sigma}_{\mathrm{bs}}$) in stratum i (Simmonds and MacLennan, 2005):

$$Q_i = \bar{\sigma}_{\mathrm{bs}i}\bar{s}_{Ai}A_i, \tag{1}$$

where

$$\bar{\sigma}_{\mathrm{bs}i} = \sum_j P_{ij}10^{((b+m\log(L_{ij}))/10)}, \tag{2}$$

where P is the fraction of fish of length j in stratum i, and $b = -88.57$ and $m = 30.05$ are from the mean of the TS vs. $\log(L)$ relationships used from 1992 to 2006. Inter-transect tracks are included because an examination of the full dataset indicated that they do not cause bias, but probably represent useful additional sampling.

Variance

Throughout these analyses, the estimation variance (Rivoirard *et al.*, 2000) describes the uncertainty because of sampling. Ideally, the variability for each survey is described using

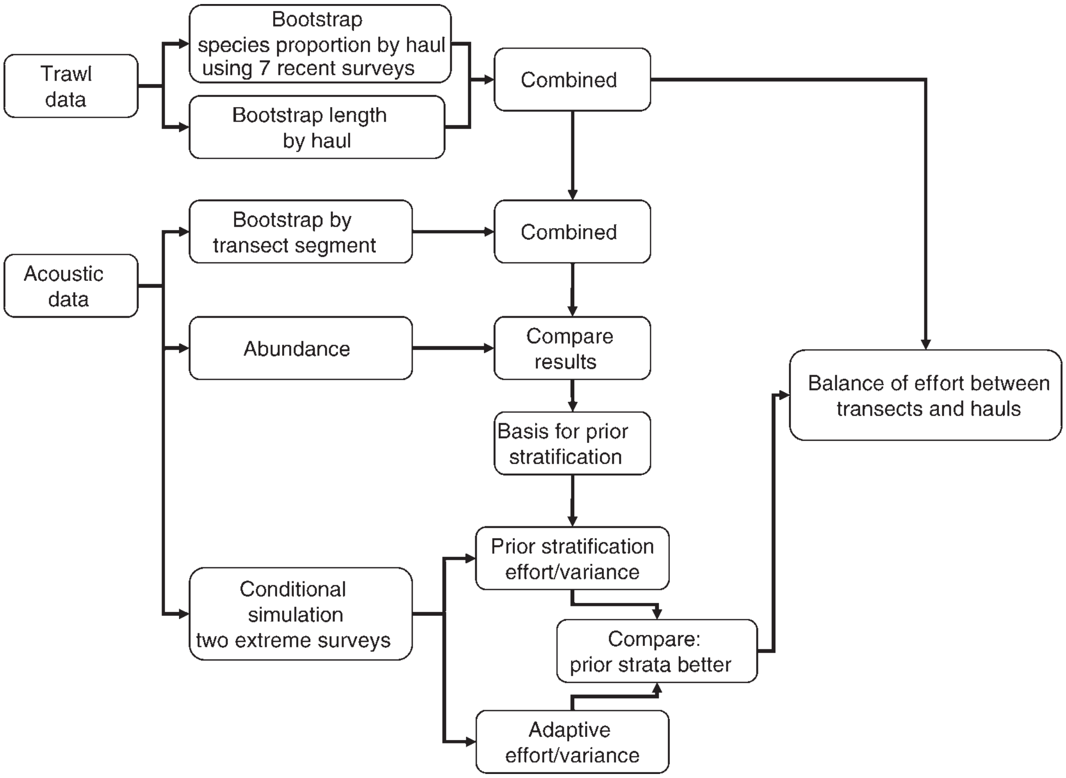

Figure 2. Flow diagram of the analysis procedure used to evaluate the survey-design options.

conditional simulations, including acoustic and trawl data (Woillez, 2007; Woillez *et al.*, 2009). However, this type of analysis is not feasible for all the surveys because of the requisite computing time (see below). Instead, a series of approximations elucidates the main sources of variability. The approach is summarized in the flow diagram in Figure 2 and discussed in detail below. A key assumption is that the spatial distribution of the variance is derived from the variance at the scale of the stratum; the sill of the stratum variogram. Because all the surveys are normalized and combined to give a mean distribution of variability, this approach captures all the main features of the spatial distribution of variability and is sensitive only to the assumption that the range of the spatial correlation does not depend on the sill. To evaluate variance–effort relationships further and also different strategies where spatial autocorrelation must be included, six conditional simulations are used to generate suitable distributions to quantify the dependence of variance on sampling effort.

Stratum variance (V_i) is estimated by bootstrap resampling with replacement (Efron and Tibshirani, 1986) of transect segments (mean values of each sequence of EDSUs that intersect a stratum) T_{ik},

$$V_i = \frac{\mathrm{var}(\sum_k T_{ik})}{n_i}. \tag{3}$$

The number of resamples, n_i, is equal to the number of segments in stratum i. Segments are not all of equal length, because small segments intersect the corners of the strata. Therefore, the probability that a value is drawn is made proportional to the number of EDSUs in the segment. This method gives unbiased abundance, but poor precision for variance estimates, because of the small number of segments per stratum. It assumes independence of segments from different transects. This assumption is investigated by a classical geostatistical-structural analysis. Because the characteristics of survey data, such as acoustic backscatter, often make the inference of the variogram difficult, the log back-transformed variogram (Rivoirard *et al.*, 2000) is more robust and is used as an alternative. It indicates that most of the structure is at ranges of < 10 nautical miles (Figure 3). This supports the assumption of independence between transects required by the bootstrap analysis. A second more precise method using EDSUs as the sampling unit was tested, but this required bias correction for variance, taking into account spatial autocorrelation of the alongtrack EDSU values; it gave similar results, so only the unbiased transect method is used in the final analysis.

Trawl sampling and biological data

There are two main purposes for sampling by trawl: to identify the echoes and to obtain biological samples of length, and weight-at-length.

The influence of echo identification on the precision of estimated abundance is difficult to estimate, because in practice it involves the subjective judgement of echo classifications and fishing data. Most anchoveta echoes are associated with catches with >85% anchoveta, suggesting good identification. However, echoes may not always be adequately validated with samples; the fishing operation may catch something different from that insonified on the survey track. Only data from the seven most recent surveys are analysed, because it is complicated and time-consuming to evaluate error in echo classifications across all surveys. The requirement of the bootstrap analysis that the fraction of anchoveta by haul can be regarded as independently distributed,

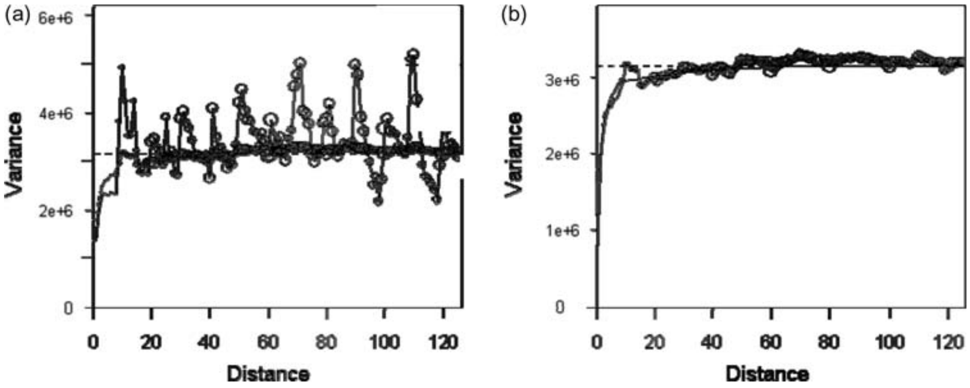

Figure 3. Example variograms of s_A values for cruise 06020-04. (a) original-untransformed model compared with (b) transformed-and-back-transformed-and-fitted model. Circles indicate the relative number of points for each point on the variogram (3400 in total). Horizontal scale is in nautical miles. Most of the structure is in a range of <10 nautical miles. This compares with transect spacings of 15 nautical miles.

is supported by variogram analysis (Rivoirard *et al.*, 2000), which demonstrates that the variability with short distance is high, and has only a small, positive, linear component as distance increases.

The following procedure is used to evaluate the influence of echo identification on the variance. The acoustic data are linked to hauls based on collocation in the same stratum or, if unsampled, adjacent strata. Acoustic data from >30 nautical miles (two transects) from a haul are classed as unallocated. Using the proportions by haul, the "total" biomass to be allocated is obtained by dividing s_A by the fraction of anchoveta in the strata, based on the mean of one or more haul observations. The observation data on fraction of the anchoveta-by-haul are bootstrapped with replacement. The species-allocation process is repeated with the new haul set by multiplying the "total" by the bootstrap-estimated fraction, by strata. For unallocated values of $s_A > 30$ nautical miles from a haul, a random choice is mimicked, because the initial allocation is assumed to represent 50% of the "total", and the bootstrap fraction of anchoveta is then drawn randomly from a uniform 0–1 distribution.

A comparison of within-haul-sampling precision with between-haul variability indicates that estimates of length and weight-at-length at a location are precise, because of the large number of fish measured at each station. Within-sample variance for estimates of the mean length and mean weight is ignored, but some part of this variability is implicitly included as part of the within-strata variance, if multiple hauls are available. The survey-analysis procedure weights multiple hauls in a stratum by the mean s_A of the nearest six EDSUs to each haul. If a stratum had no anchoveta samples, the closest haul is used to define the anchoveta size. The influence of this process on variance is evaluated through a three-stage bootstrap of the haul data:

(i) draw hauls at random from the set;

(ii) weight each haul by the values of the closest EDSUs, displaced randomly by up to three EDSUs in either direction along the transect; and

(iii) weight each haul by the mean s_A from a number (between 2 and 10) of EDSUs drawn randomly.

Combination of sources of variance

The spatial distribution of estimation variance of the biomass of mature anchoveta (≥ 12.0 cm) is approximated by combining the spatial variabilities estimated by the simultaneous bootstrap of haul and acoustic data described above for all the surveys.

Geostatistical-conditional simulation

Geostatistical-conditional simulation was developed to evaluate the uncertainty in abundance estimates from acoustic surveys of herring (Gimona and Fernandes, 2003; Woillez *et al.*, 2009) and is applied here to acoustic data on anchoveta. Such conditional simulations reproduce the spatial variability of a variable, while honouring the measurement data. However, the highly skewed distributions and many zeroes of the acoustic variables must be taken into account (see details in Woillez *et al.*, 2009).

The simulations depend on the assumed spatial properties of the anchoveta abundance. The datasets with 4000–8000 values per survey give information on longer ranges, but the nugget is difficult to estimate. Following a method similar to that proposed by Demer (2004), the relationship between point estimates of anchoveta at 120 and 38 kHz was used to establish variability at the points. This approach assumes that two acoustic systems located close together, but operating at different frequencies, obtain independent estimates of acoustic backscatter at a point, so the variability between them is a measure of variability at that point. This approach estimates the local variability in the observation location, the effect of fish orientation on *TS*, and the stochasticity of the acoustic measurements of multiple targets. It does not account for errors correlated across frequencies, such as the effects of ocean conditions on sound speed. Nevertheless, because the factor is used as a proportion of variance and the nugget is scaled to the long-range variance of the sill, it is considered a good measure of point variability. Figure 4 shows a plot of the natural logarithm of s_A at 120 kHz plotted against the s_A at 38 kHz. The variability around the line expresses the point variability, or the nugget that is used in the conditional simulations, and it represents ~15% of the overall variance.

Although 1-nautical-mile data are available, they are too many for the available computing resources and a 2-nautical-mile grid is used; the simulated fields have around 400 000–500 000 nodes and each surface takes >24 h to generate. However, the number is insufficient for resampling the field by transects because the simulated surfaces must have hundreds more points than samples, else the variances are in error. To create enough samples, additional short-range samples, located in-between the 2-mile-transect spacing, are generated from the local-simulated value by adding a multiplicative random factor equivalent to the nugget of 15%. This approach has negligible influence on the variance of a random sample, because it preserves the simulated patchiness in the field, and quickly generates sufficient nodes for sampling of the simulated fields.

Acoustic-sampling strategies

The summer 2002 survey exhibited reasonably smooth anchoveta distributions over the typical area (Figure 5). In contrast, the winter 1998 survey, at the end of the 1997/1998 *El Niño*, identified small, dense patches in coastal-refuge areas (Bertrand *et al*., 2004; Gutiérrez *et al*., 2007) and a few dense offshore patches in deeper water. Three simulated fields (Figure 5) from each survey were used for the evaluation. Then, three-survey strategies all using the same number of transects, estimating biomass as the mean of the transects in the stratum, were compared.

(i) Parallel: transects placed randomly throughout the area in one stratum.

(ii) Systematic: evenly spaced transects located with a single random starting point; 15-nautical-mile strata.

(iii) Adaptive: mean abundance is estimated with one pass with half of the effort. Then 50% of the area, based on the greatest abundance values, is selected for an additional two transects placed randomly in the 30-nautical-mile strata. The Rao–Blackwell estimator (Thompson and Seber, 1996) attempts to correct for bias.

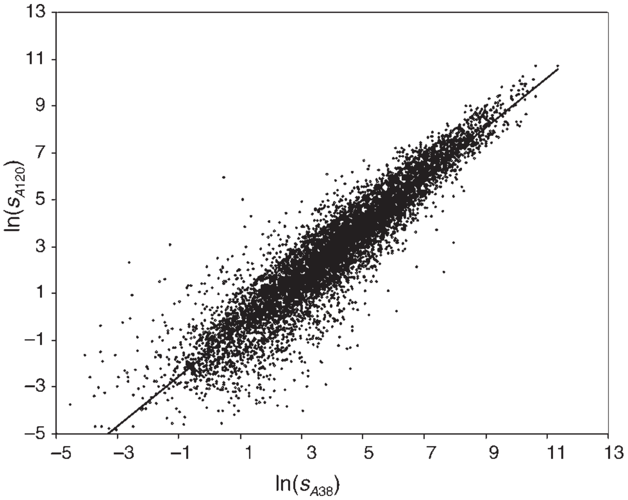

Figure 4. Relationship between EDSU estimates of anchoveta at 120 and 38 kHz. The variability around the line expresses the point variability or the nugget used in the conditional simulations and is around 15% of the overall variance.

In addition to the sampling simulations, the conditional-simulation fields are evaluated for spatial autocorrelation on a strata basis. The "between-transect" correlation for distances of between 2 and 28 nautical miles are given in Table 2.

Variance vs. effort allocation

The same simulated fields (1998 and 2002) are resampled with a stratified survey design based on the high- and low-density areas described in Figure 6. The number of nautical miles required for the different transect spacing, including inter-transect sections, is established, and this is used as the measure of effort. The estimates from 100 surveys at each track density are used to estimate measurement precision.

The variances resulting from these simulations, and from the trawl data, are evaluated separately to allow examination of the allocation of resources. These are combined to provide optimal solutions for a given total effort by minimizing the *CV* through allocation of a fixed time between the two activities. The methods employed are similar to those proposed by Simmonds (1995) and documented in Simmonds and MacLennan (2005).

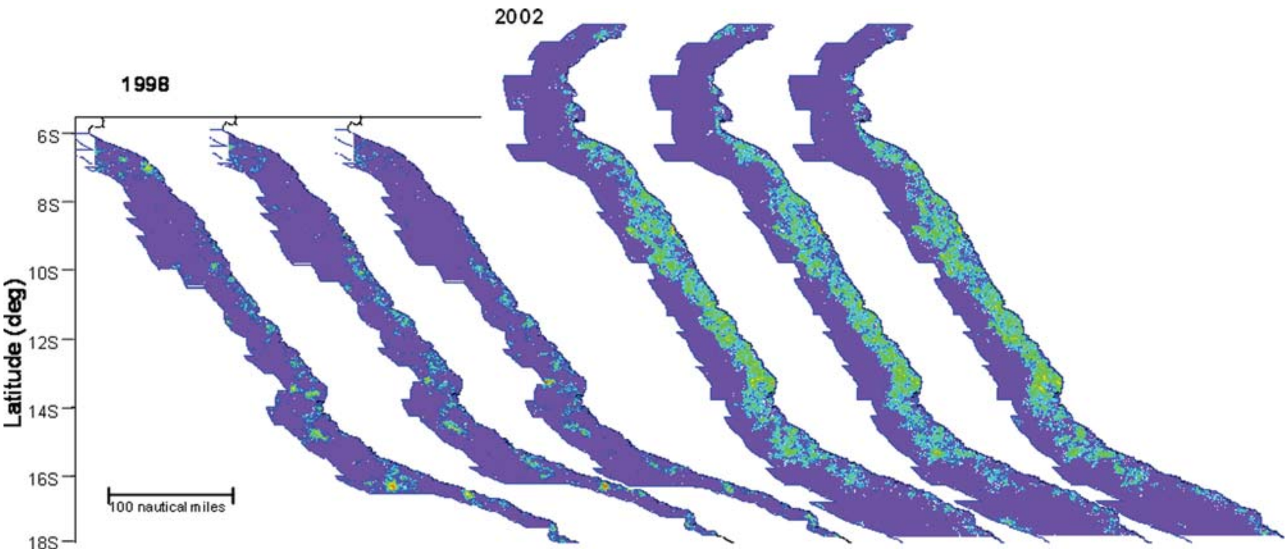

Figure 5. Three conditionally simulated surfaces from both 1998 and 2002 surveys, used for evaluation of sampling. Note the contrasting distributions and variability between distributions, especially for 1998.

Table 2. Correlation between "transect" estimates by strata for two simulated surveys for transect spacings of 2–28 nautical miles.

Survey distance	2	4	6	8	10	12	14	16	18	20	22	24	26	28
0202-03	0.93	0.85	0.77	0.68	0.61	0.53	0.48	0.43	0.40	0.37	0.34	0.34	0.34	0.33
9811-12	0.81	0.68	0.53	0.40	0.30	0.22	0.15	0.11	0.08	0.05	0.04	0.01	0.03	0.00

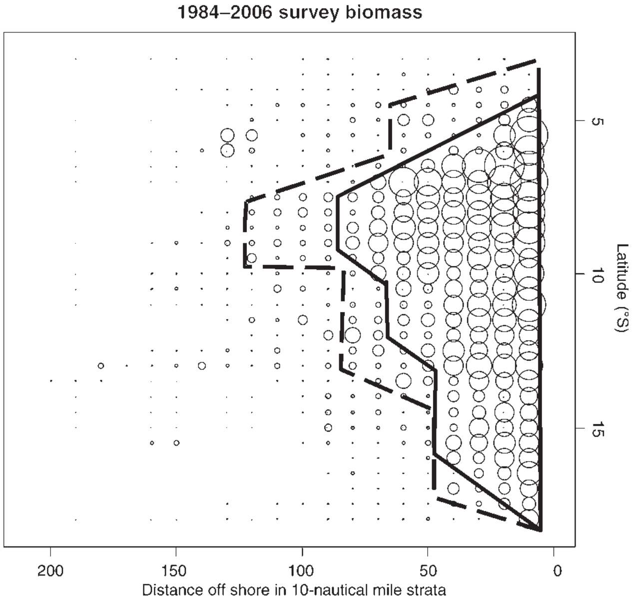

Figure 6. Average spatial distribution of biomass of anchoveta from acoustic surveys in 1984–2006 from estimates of the average biomass for each stratum surveyed. Selected areas for higher- and lower-intensity survey track are displayed as solid and dotted lines, respectively.

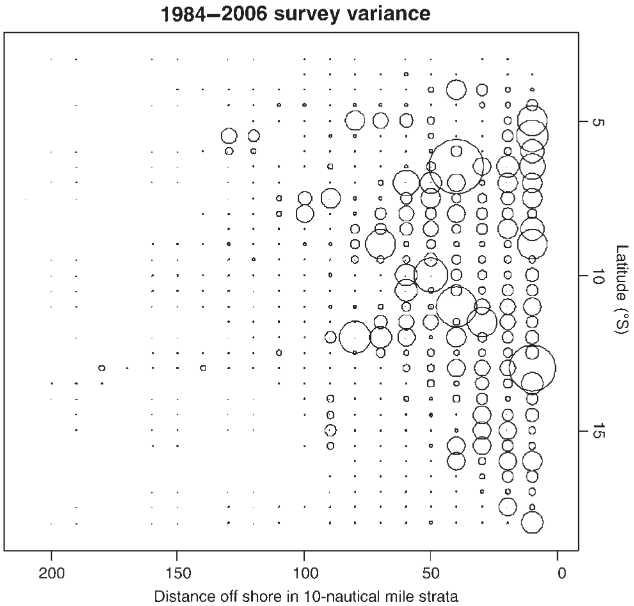

Figure 7. Average spatial distribution of estimates of within-strata variance of biomass from acoustic surveys 1984–2006 from estimates of the average variance over surveys for each stratum surveyed.

Results

Abundance

On average, anchoveta abundance is concentrated in a region close to the coast, extending between 20 and 100 nautical miles from the coast (Figure 6). The entire observable range of anchoveta distribution appears to be covered. The biomass and spawning-stock biomass (SSB) by survey are presented with approximate *CV*s, based on strata sills, bootstrap of length, and precision of identification, for all surveys (Table 1). Anchoveta biomass varies between 0.5×10^6 t in 1997, during an *El Niño* event—Bertrand *et al.* (2004) discusses the representativeness of the survey—and 20×10^6 t in 2002.

Variance estimated by strata from the trawl and acoustic data

Spatial distribution of variance

The mean estimation variance by strata (Figure 7) reveals consistent spatial patterns similar to those for abundance, but with a more variable distribution. Strata estimates from all surveys demonstrate a strong relationship between abundance and variance (Figure 8).

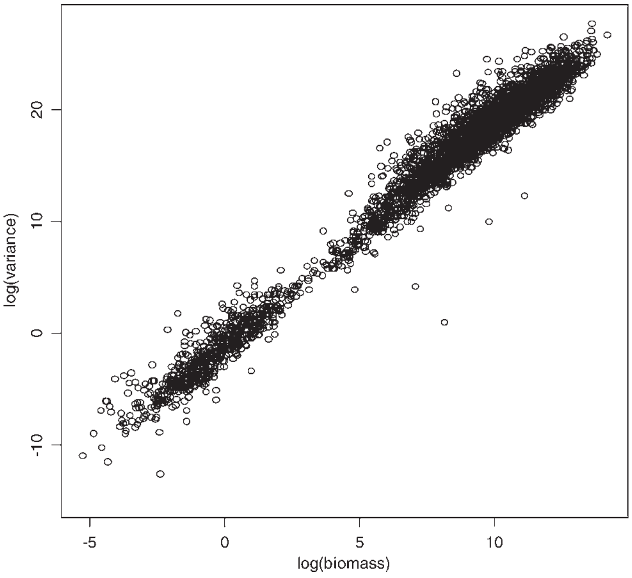

Figure 8. The relationship between estimated strata variance and estimated strata biomass across all surveys.

The geostatistical conditional simulations reveal that this patchy distribution of variance is not just observed among surveys, but also seen when comparing the estimates of strata variance between simulated surfaces. A variance map derived from local abundance through a mean–variance relationship may therefore be a more reliable guide to the underlying spatial variability than the variance calculated from the samples. The presence of a high-variance area confirms that effort stratification is likely to be beneficial.

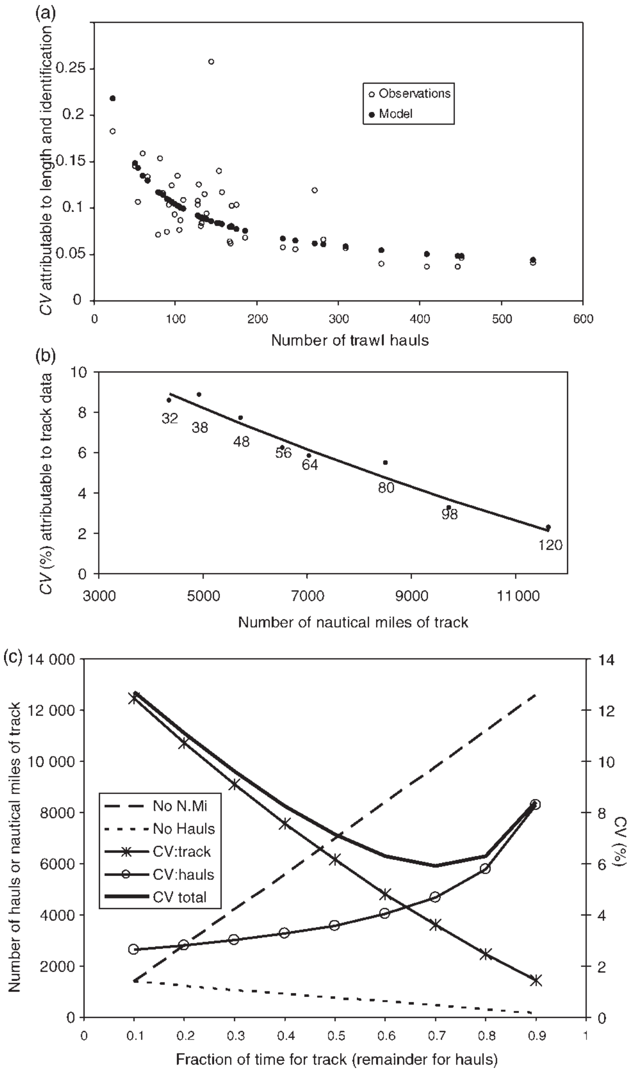

Figure 9. Dependence of *CV* (biomass) from 1986 to 2006 on (a) length sampling and identification of a number of trawl hauls, (b) the number of nautical miles of track on a survey, and (c) the allocation options based on a 60-daytime allocation with vessel speed of 10 knots and haul time of 2 h.

Net sampling for identification and fish size

The results for the bootstrap analysis of seven recent surveys indicate that the allocation is very local and misallocation using haul proportions may be problematic. By 20 nautical miles, any indication of the small amount of local continuity seen in some surveys (not presented) has dissipated.

The sampling variability from length data is a small source of variability in biomass estimates. The use of trawl data for identification of echoes dominates the contribution that fishing makes to the variance. The results of sampling for identification and length combined, plotted against effort, and including a fitted power relationship using least-square regression are presented in Figure 9a.

Acoustic sampling for distribution and abundance

The two sets of simulated surveys covering the extremes of the distribution have different *CV*s, but reveal similar dependences of *CV* on effort (not presented). The combined results and the fitted relationship are given in Figure 9b.

Acoustic-survey strategies

Correlation between strata observations by "transect" from the simulated fields is illustrated in Table 2. In 2002, correlation falls to 50% by 12 nautical miles; in 1998, it falls to 50% in half that distance. This indicates that with an average transect spacing of 15 nautical miles, little can be inferred about the next transect.

For this part of the analysis, only the acoustic data are simulated and sampled. Therefore, the conclusions are limited to considerations of the spatial patchiness of anchoveta aggregations. Nevertheless, because it is this patchiness which dominates the sampling variance through both abundance and identification, the results are considered informative.

The results of the three-survey methods are given in Table 3. Always, the "random transect placement" is the most ineffective, and the systematic survey performs the best. The differences between the adaptive and systematic survey designs are small. The *CV*s on the adaptive survey are slightly higher and there is a small negative bias, despite the use of bias correction.

However, the adaptive survey may be even poorer in practice, because the simulations do not account for additional practical aspects. The two-pass strategy reported here assumes that the area is spanned with low-density transects before selecting areas for higher density transects. In practice, this would be time-consuming, and meanwhile the fish distribution may change. Adaptive methods, where decisions are taken during the survey, would be logistically more practical, though likely to give even poorer performance, because of suboptimal selection of a two-pass threshold.

Optimal surveys from combined sources of variance

The precision of the surveys resulting from track line and trawl effort are shown in Figure 9a and b, respectively. The fitted

Table 3. Results of simulated surveys on simulated fields using three different parallel-transect strategies (random, systematic, and adaptive) on two types of spatial distribution [smoother with larger patches (0202-03) and small, widely distributed patches (9811-12)].

Survey Strategy	0202-03 (estimate = 38 492)			9811-12 (estimate = 4 590)		
	Random	**Systematic**	**Adaptive**	**Random**	**Systematic**	**Adaptive**
Mean	38 171	38 559	36 477	4 568	4 639	4 150
Maximum	62 855	44 936	43 296	11 952	8 100	7 148
Minimum	22 102	33 569	29 720	864	2 740	2 223
s.d.	6 173	1 859	2 192	1 665	798	795
CV (%)	16	4.8	6.0	36	17	19

Results are from 100 surveys on each of three surfaces for each type of spatial distribution.

models are used to estimate the optimal proportions of time to be allocated to each type of sampling effort, assuming that operational resources include 60 24 h periods, ship speed = 10 knots, and 1 h per haul. Under these conditions, 68% of the resources should be allocated to sampling along the track lines (Figure 9c).

Discussion

Given an objective, there is a basis for allocating effort between the major data-collecting processes: the length of cruise track and the number of fishing trawls. There is scope for prestratification of effort around the area. For instance, twice the effort is recommended in areas with greater abundance and variance. The analyses depend on a number of assumptions, but not critically so. Despite the obvious along-coast distribution, the anchoveta are assumed isotropic because the patchiness that dominates the variability appears to be isotropic.

The *CV*s given in Table 1 are approximate. They overestimate variability because they do not fully account for short-range (<10 nautical miles) spatial autocorrelation. They underestimate variability, because they do not account for variation in oceanography and uncertainty in the mean *TS* function.

Instead of optimizing for fixed effort, the derived relationships could be used instead to estimate the effort necessary to achieve a required *CV*. However, in practice, the variability in the *CV* around the modelled curves is considerable (Figure 9a, Table 3), because of differing spatial distributions among surveys. Neither the abundance nor the patchiness can be predicted in advance; therefore, designing the survey for a required precision is not straightforward.

Adaptive methods are affected by the strong correlation between the mean and the variance. Allocating more effort to areas with high variance has some potential for biasing the results. Therefore, a planned systematic survey appears to be the best trade-off between bias and precision.

The results presented here depend on the choice of survey objective, and different conclusions may be reached if optimization is required to meet other objectives, such as estimates of other species.

Some care must be taken during years when the distribution is patchier and the anchoveta could be distributed in areas near the coast; the prime example of this is the *El Niño* period of 1997/1998 (Bertrand *et al.*, 2004; Gutiérrez *et al.*, 2007). By monitoring the large-scale climatic forcing, specifically the coastally trapped Kelvin waves, it is possible to predict the state that would dominate the HCS over the following 2–6 months (Bertrand *et al.*, 2008b). In such cases, a single level of stratification effort might be better, because the distribution may not conform to the otherwise typical expected distribution.

Because of the high variability of the system and its low predictability, successful management cannot only rely on mid- or long-term policies. In Peru, fishery management is necessarily adaptive, and decisions are taken in real time, based on the most recent ecosystem observations. Therefore, the proposed improvements are important for the provision of reliable indicators to support the decision-making process.

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