Assessment of anchovy spawner biomass off South Africa through combined acoustic and egg-production surveys

Ian Hampton, Michael J. Armstrong, George M. Jolly, and Peter A. Shelton


The abundance of spawning Cape anchovy (Engraulis capensis) on the South African continental shelf in 1985 and 1986 has been assessed through combined acoustic and egg-production surveys from a single vessel. The two surveys are complementary, and their combination is a natural and efficient means of improving estimates of spawning biomass. Acoustic estimates were obtained by stratified random-sample surveys using a multi-channel digital echo integrator. Egg counts at regular intervals on the acoustic grid, together with estimates of spawning fraction obtained from midwater-trawl identification hauls, allowed the mean daily egg production to be estimated in both years, from which alternative estimates of spawning biomass were derived. Agreement between estimates obtained by the two methods was acceptable in both years. A spawning-biomass estimator based on the acoustic and egg-production estimates from both the current year and previous years has been developed. The estimator is considered to be less susceptible to bias than one obtained from acoustic and egg-production estimates from the current year only, although it will be less precise. Weighting factors for minimizing the variance in the former estimate are developed and applied to the 1985 and 1986 estimates to give a spawning biomass in 1986 of 1.37 million tonnes, with a coefficient of variation of 27%. All the estimates indicate that the anchovy spawning stock is considerably greater than was previously believed to be the case on the basis of virtual population analysis (VPA) of age data from commercial catches. Application of the survey estimates has led to the anchovy quota being more than doubled since the inception of the survey programme.

Introduction

The anchovy (Engraulis capensis) has been a major contributor to the South African purse-seine fishery since 1966, with annual catches ranging from 138 thousand tonnes in 1968 to 350 thousand tonnes in 1974 (Armstrong et al., 1985). Egg and larval surveys (Shelton, 1986) have established that spawning occurs predominantly over the continental shelf east of Cape Point in summer, and that the ichthyoplankton is subsequently transported around Cape Point into the Benguela Current system, resulting in recruitment to the West Coast fishing grounds in autumn and winter (Crawford, 1981; Shelton and Hutchings, 1982; Shelton, 1986; Hampton, 1987). The recruits move south along the West Coast in winter (Crawford, 1981; Hampton, 1987), rounding Cape Point towards the end of their first year of life (Armstrong et al., 1985), at which stage they are sexually mature and ready to initiate the next spawning/recruitment cycle.

Attempts have been made (e.g., by Armstrong et al., 1983, and Butterworth, 1983) to estimate annual fluctuations in spawning biomass by virtual population analysis (VPA) of the age structure in commercial catches. The estimates range from 80 thousand tonnes in 1968 (Armstrong et al., 1983) to 460 thousand tonnes in 1979 (Butterworth, 1983). On the basis of the VPA estimates the stock was considered to be overexploited.

In 1983 an acoustic survey programme on anchovy was introduced (Hampton et al., 1985), using the Sea Fisheries Research Institute's new research stern-trawler RV "Africana", which was specifically designed for such acoustic work (Anon., 1986). Acoustic estimates have subsequently been made of spawning biomass in November 1984, 1985, and 1986, and of recruitment in the autumn of 1985 and 1986 (Hampton, 1987).
As from 1984, estimates of anchovy spawning biomass have also been made from contemporaneous estimates of daily egg production, according to the methodology developed for the northern anchovy (E. mordax) off California (Parker, 1980). It has been found that the requirements of the acoustic and egg-production sampling can be easily accommodated within the same cruise, and that the methods are in many ways complementary. For example, trawls necessary for identifying acoustic targets provide samples for the estimation of the biological parameters (spawning fraction, sex ratio, fecundity, etc.) necessary to derive a stock estimate from egg counts, while acoustic estimates of density in the vicinity of a trawl can be used to weight estimates of these parameters obtained from the trawl (Armstrong et al., 1988). In a typical survey, the addition of the egg sampling increases survey time by only some 15%, and additional information, for example on vertical temperature structure, is collected at no extra cost in time by sensors attached to the net.

In this paper we present the acoustic and egg results from the 1985 and 1986 spawning surveys and, in particular, investigate ways in which estimates of spawning biomass derived from the two methods can be combined into a single estimate with minimum variance and reduced bias. The acoustic and egg-production methodologies per se are described only briefly. For further details on these, consult Hampton (1987), Jolly and Hampton (1990), and Armstrong et al. (1988).

Methods

Acoustics

A 38 kHz Simrad EK-S echo sounder interfaced to a custom-built digital integration and logging system (Anon., 1986; Hampton, 1987) was used. The system integrates echoes in real time with a vertical resolution of 1 m, and outputs the mean volume backscattering strength (MVBS) in selected channels at the end of each logging/integration cycle, permitting densities to be estimated directly. The 1-m integrals for each echo return exceeding a selectable threshold for longer than a preset time at any point with a chosen depth range are stored on tape for subsequent analysis on board or ashore.

Primary calibration of the echo sounder was performed by the standard sphere method (Foote et al., 1981) before each of the cruises. The calibration was regarded as accurate to within about 0.5 dB. In addition, secondary calibrations were carried out before, during, and after every cruise using a built-in hydrophone monitor (Anon., 1986). These measurements indicated that the combined Source Level and Voltage Receiving Sensitivity (SL+VRS) during both of the cruises reported here was stable to better than 0.5 dB. Receiver gain and TVG characteristics were checked before each cruise. Appropriate corrections (amounting to between -0.5 and -1.5 dB depending on range) were applied to correct for TVG imperfections.

A typical set of calibration data (in this case for the survey in November 1986) is shown below. Note that the equivalent beam factor was taken from the manufacturer's specifications for the Simrad 38–29/25 E (8x8 degree beamwidth) transducer used.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source Level + Voltage Receiving Sensitivity (dB)</td>
<td>127.75</td>
</tr>
<tr>
<td>Pulse duration (ms)</td>
<td>0.86</td>
</tr>
<tr>
<td>Equivalent ideal beam factor (dB)</td>
<td>-19.6</td>
</tr>
<tr>
<td>Absorption coefficient (dB/km)</td>
<td>10.5</td>
</tr>
</tbody>
</table>

*From manufacturer's specifications.

Acoustic targets were identified by aimed trawling with an Engels 308 commercial midwater trawl, fitted with an 8-mm anchovy mesh codend liner. The measured backscatter was apportioned between the various species in the trawl according to a general relationship between weight-normalized target strength and length Equation (1). The fact that anchovy was by far the most abundant pelagic species encountered greatly facilitated target identification and apportionment of the backscatter. Identification of anchovy was also facilitated by characteristic patterns in their shoaling behaviour, and by the presence or absence of anchovy eggs in the vicinity.

A stratified random-sample design was used in both surveys to enable the sampling variance to be estimated rigorously, without recourse to assumptions regarding the distribution of the fish (Jolly and Hampton, 1990). The stratification in each year was based on the density distribution observed in the previous year's survey. In both years a two-phase approach was used, in which density information obtained from the outward (eastward-going) phase was used to allocate transects on the return (westward-going) phase to areas of greatest density. This approach was effective in 1985, but not in 1986, when the information gained from the second phase transects had to be discarded because of, *inter alia*, equipment problems towards the end of the cruise. The transects in both phases were drawn from a single set of transects, randomly spaced within limits by a two-stage randomization procedure which effected a compromise between strict randomization and an even distribution of effort, while still permitting valid estimates of sampling variance to be made (Jolly and Hampton, 1990).

The survey grids for the two years (excluding the Phase 2 grid in 1986), and the various strata adopted, are shown in Figures 1 and 2. In 1986 an additional stratum, inshore of the survey grid, was added to make
Figure 1. Anchovy distribution, November 1985, derived from acoustic data. Strata A to F in Table 1 are marked.
Figure 2. Anchovy distribution, November 1986, derived from acoustic data. Strata A to F in Table 2 are marked.
some allowance for fish too close inshore to be surveyed. This was not considered necessary in 1985 as the densities on the inshore ends of the transects in that year were generally low.

The MVBS for each interval of track between egg-sampling stations (situated either 5 or 10 nautical miles apart along the transects, depending on the presence of eggs) was converted to area density using Halldörsson and Reynisson's (1983) relationship for the weight-normalized target strength of herring (*Clupea harengus*) at 38 kHz, viz:

\[ TS_k = -10.9 \log L - 20.9, \]  

(1)

where \( L \) is the total length of the fish in cm. This expression was chosen as (a) we do not yet have an expression for *E. capensis* target strength, (b) it was obtained from *in situ* measurements at 38 kHz, and (c) the fish on which it was based covered a wide size range (9.4 to 32.8 cm total length), which encompassed most of the fish in our surveys. Although a specific expression for *E. capensis* would obviously have been preferable, it will be seen later that the combined acoustic/egg-production estimator which we have developed requires in theory no knowledge of actual target strength, but only that the target-strength/length relationship remains constant from survey to survey.

The mean anchovy density for a stratum was computed from the estimated densities for all the intervals within it, weighted by interval length, excluding those intervals for which the fish were too close to the surface for reliable detection, judged by a comparison between echo-sounder and sonar records. The mean density for the inshore stratum in 1986 was similarly estimated from the intervals falling on the inshore transit lines between the transects. Sampling variance for a stratum was estimated from the mean densities for each of the transects falling within the stratum, through the expression

\[ \text{Var} (\hat{o}_h) = \frac{K}{K-1} \left( \frac{\sum_{k=1}^{K} (\hat{o}_k - \hat{o}_h)^2 L_k^2}{\sum_{k=1}^{K} L_k^2} \right), \]  

(2)

where \( \hat{o}_h \) is the estimated mean density for stratum \( h \), computed from the \( K \) transects falling within it through the expression

\[ \hat{o}_h = \frac{\sum_{k=1}^{K} L_k \hat{o}_k}{\sum_{k=1}^{K} L_k}, \]  

(3)

and \( \hat{o}_k \) is the estimated mean density for transect \( k \) of length \( L_k \). The expression is derived from the standard expression for the variance of a ratio estimator (e.g., Cochran, 1977), where the variates are \( \hat{o}_k L_k \) and \( L_k \). Total sampling variance in the biomass estimate, \( \hat{B} \), for a survey was obtained from

\[ \text{Var} (\hat{B}) = \sum_{h=1}^{H} A_h \text{Var} (\hat{o}_h), \]  

(4)

where \( A_h \) is the area of stratum \( h \), \( H \) the total number of strata in the survey, and

\[ \hat{B} = \sum_{h=1}^{H} A_h \hat{o}_h. \]  

(5)

In both surveys there were some strata in which the number of transects was regarded as too low for the reliable estimation of \( \text{Var} (\hat{o}_h) \). These strata were amalgamated in each case into a single stratum through an adaptation of the method given in Cochran (1977, p. 165) for combining ratio estimates. The principle of the method is described in Armstrong et al. (1988).

**Egg production**

The egg-production method of estimating anchovy spawning biomass (Parker, 1980) is based on estimates of the mean daily egg production, and estimates of the number of eggs produced per unit mass of fish per day. The spawning biomass is estimated from the expression

\[ \hat{B}_s = \frac{\hat{P}_0 A \hat{\bar{W}}}{\hat{R} \hat{F} \hat{S}}, \]  

(6)

where

- \( \hat{P}_0 = \) estimated daily production of eggs per unit area,
- \( A = \) area for which \( \hat{P}_0 \) was estimated,
- \( \hat{\bar{W}} = \) estimated mean mass of female fish,
- \( \hat{R} = \) estimated ratio (by mass) of females to all fish,
- \( \hat{F} = \) estimated mean batch fecundity,
- \( \hat{S} = \) estimated fraction (by number) of females spawning per day.

\( \hat{P}_0 \) was estimated from anchovy egg counts in a CALCOFI Vertical Egg Tow (CalVET) net (Smith et al., 1985) hauled at regular intervals along the acoustic transects (Armstrong et al., 1988). The use of the acoustic transects ensured, *inter alia*, that the egg production samples were randomly selected at the transect level. Station spacing was 5 nautical miles in regions where eggs were found and 10 nm elsewhere. The eggs were aged and the mean and variance of the hourly instantaneous mortality rate, \( Z \), estimated by regressing abundances of eggs against age, assuming exponential mortality. This value was used to raise the station values of egg abundance to numbers of eggs per unit area at age zero, which were then averaged, with weights proportional to the length of transect represented by the station, to provide estimates of \( P_0 \) for each transect.
Estimates of the spawning parameters \((W, R, F, \text{ and } S)\) were obtained from samples of anchovy taken by midwater trawl. (These trawls also served to identify acoustic targets.) Batch fecundity \(F\), defined as the number of eggs released by a female during a spawning event, was estimated from a linear regression of the number of hydrated eggs against body mass, obtained from a subsample of females with hydrated (but not yet ovulated) eggs taken during the hydration period (approximately 18:00 to 24:00). The spawning fraction, \(S\), was estimated from histological examination of the ovaries of sampled fish, based on the finding of Moser (1967) that post-ovulatory follicles can be recognized and aged according to the stage of follicular degeneration.

Estimates of the spawning parameters were obtained for each transect as weighted means of station values. The weighting factor for sex ratio, \(R\), was derived for each trawl as the product of the mean anchovy density (estimated acoustically) for the segment of transect to which the trawl was assigned for target-identification purposes, and the segment length. Similar weightings were used for estimates of \(W, F, \text{ and } S\), except that acoustic density was first converted to fish numbers by multiplying by the associated station value of \(R/W\). The acoustic weightings represent an extension of Parker's (1980) original method, in which no specific weighting is applied to the spawning parameters, reliance being placed on the greater frequency of trawls in the more abundant regions to supply a natural weighting. We believe that the acoustic weightings are more exact and less biased. It would, for example, be difficult to conduct sufficient trawls to give a proper natural weighting to a region in which the density was many times greater than the average. (Regions such as this are common.) It should be noted that as only the relative densities are needed, the weightings can be obtained with uncalibrated equipment and without knowledge of target strength. It is demonstrated in Appendix A that the introduction of the acoustic weightings introduces no additional covariance between the acoustic and egg estimates.

Mean values of \(P_n\) and the spawning parameters, and the variance in these estimates, were obtained from the transect means for the same strata used in analysing the acoustic data (see Figs. 1 and 2). In both years, a number of strata in which there were insufficient transects to yield reliable variance estimates were amalgamated, in a manner similar to that adopted for the acoustic data. In estimating mean spawning parameters for a stratum, the weighting factors for the transect means were taken as the product of the transect length and the mean anchovy density along the transect (estimated acoustically), multiplied by the ratio \(R/W\) for the transects to convert to a weighting by number for the parameters \(W, F, \text{ and } S\).

Final estimates of the parameters for substitution in Equation (6) were calculated as weighted averages of stratum estimates, with weights equivalent to stratum area for \(P_n\), and to the acoustic estimates of stratum biomass (or numbers of fish, where appropriate), for the spawning parameters. Covariances between the egg and acoustic estimates of density, which are needed in the combination of the two methods (see following section), were estimated from covariances between the mean acoustic density and each of the egg-production parameters for each transect.

All expressions used for deriving stratum variances and covariances, the procedure used for stratum amalgamation, and details of a final adjustment made to compensate for small-sample bias are given in Armstrong et al. (1988).

Combination of acoustic and egg-production estimates

Since there was no a priori reason to prefer either of the methods to the other, a method of combining the egg and acoustic estimates into a single estimate, having greater accuracy than either estimate separately, was sought. The usual approach of computing a weighted mean with inverse variance weightings was considered inappropriate, primarily because the acoustic estimate is thought to be much more susceptible to bias (e.g., from target-strength and calibration errors) than the egg estimate. Inverse variance weighting would therefore have given undue weight to the acoustic estimate. Instead, the acoustic estimates in 1985 and 1986 (\(A_{85}\) and \(A_{86}\)) were used to form an indirect estimate for 1986 which was expected to be less biased than \(A_{86}\) and could therefore more properly be combined with \(E_{85}\). The estimate was

\[
E_{86}' = \frac{E_{85} A_{86}}{A_{85}},
\]

where \(E_{85}\) is the 1985 egg estimate. Note that this estimate does not involve \(E_{86}\). The assumption is that the bias in \(A_{85}\) is constant and proportional to \(A_{86}\), as would tend to be the case for target-strength and calibration errors in particular. In this case, if \(E_{85}\) is unbiased, the ratio \(E_{85}/A_{85}\) corrects for bias in \(A_{86}\), and \(E_{86}'\) is unbiased. Even if there is bias in \(E_{85}\), it is likely to be of the same order as the bias in \(E_{86}\), so that no undue weight is given to either \(E_{85}\) or \(E_{86}\) when combining the two estimates.

The required combined estimate for 1986, \(C_{86}\), is a weighted combination of \(E_{85}\) and \(E_{86}\), with weights chosen to minimize \(\text{Var}(C_{86})\). In Appendix B, the general problem of minimizing \(\text{Var}(\hat{C})\) for \(n\) years' data is investigated. From this, the optimum value of \((\hat{C}_{86})_{\text{opt}}\) can be seen to be

\[
(\hat{C}_{86})_{\text{opt}} = \left( \frac{a - c}{a + b - 2c} \right) E_{85} + \left( \frac{b - c}{a + b - 2c} \right) E_{86},
\]
with minimum variance,
\[ \text{Var}(\hat{C}_{\text{m}})_{\text{min}} = \frac{ab - c^2}{a + b - 2c} . \]  
(9)

where
\[ a = \text{Var}(\hat{E}_{66}) = (\hat{E}_{66})^2 \times \]
\[ \times \left\{ \frac{\text{Var}(\hat{A}_{66})}{A_{66}} + \frac{\text{Var}(\hat{A}_{55})}{A_{55}} \times \frac{\text{Var}(\hat{E}_{55})}{E_{55}} - \frac{2\text{Cov}(\hat{A}_{55}, \hat{E}_{55})}{A_{55} E_{55}} \right\} , \]
\[ b = \text{Var}(\hat{E}_{66}), \]
\[ c = \text{Cov}(\hat{E}_{66}, \hat{E}_{55}) = \frac{E_{55} \text{Cov}(\hat{A}_{66}, \hat{E}_{55})}{A_{55}} . \]
(10)

In evaluating these expressions, \( A_{55}, A_{66}, E_{55}, \) and \( E_{66} \) were replaced by their estimates. Note that only covariance between acoustic and egg estimates in the same year is included, as the expected covariance between estimates in different years is zero because of the independence of the two surveys. Within-survey covariances would be expected to be positive, as the egg and acoustic data were collected simultaneously from the same sample transects. These covariances could nevertheless be small, since the distribution of eggs may be substantially different from that of the fish.

In the situation where egg and acoustic estimates are available for more than one previous year, a combined ratio, \( \hat{R} \), of egg to acoustic estimates from the previous years can be estimated, and the biomass for the current year (\( n \)) estimated from
\[ \hat{E}_n = \hat{R} \hat{A}_n . \]

It is shown in Appendix B that
\[ (\hat{C}_n)_{\text{opt}} = \left( \frac{a - c}{a + b - 2c} \right) \hat{E}_n + \left( \frac{b - c}{a + b - 2c} \right) \hat{E}_n' \]

with
\[ a = \text{Var}(\hat{E}_n) = \hat{A}_n^2 \text{Var}(\hat{R}) + \hat{R}^2 \text{Var}(\hat{A}_n) \]
\[ b = \text{Var}(\hat{E}_n') \]
\[ c = \text{Cov}(\hat{E}_n, \hat{E}_n') . \]

and that
\[ \text{Var}(\hat{C}_n)_{\text{min}} = \left( \hat{A}_n^2 \text{Var}(\hat{R}) + \hat{R}^2 \text{Var}(\hat{A}_n) \text{Var}(\hat{E}_n) - \text{Cov}(\hat{E}_n, \hat{A}_n)^2 / \hat{A}_n^2 \right) / \left( \hat{A}_n^2 \text{Var}(\hat{R}) + \text{Var}(\hat{R}_n) \right) . \]

These expressions contain elements from the current year only, except for \( R \) and \( \text{Var}(\hat{R}) \), which introduce the information from the previous years. \( \hat{R} \) can be optimized independently of year \( n \) by minimizing \( \text{Var}(\hat{R}) \). The derivation and resultant expressions for \( (\hat{R})_{\text{opt}} \) and \( \text{[Var}(\hat{R})]_{\text{min}} \) are given in Appendix B.

**Results**

Anchovy distribution in 1985 and 1986, ascertained from the acoustic data, is shown in Figures 1 and 2 respectively. Egg distributions for the two years are shown in Figures 3 and 4. The egg boundaries are superimposed on Figures 1 and 2 to facilitate comparison with the fish distribution. It can be seen that while there are some marked differences in distribution between the years, in both years the fish and egg distributions correspond reasonably well with one another, which lends credence to their validity. The greatest discrepancy lies in the area northwest of Cape Point where the eggs tend to be displaced northwards of the fish, particularly in 1985. This is expected as it is known that the eggs are transported rapidly northwards in this area by a frontal jet current (Shelton and Hutchings, 1982). Also, between Cape Point and Cape Agulhas in both years, the eggs tended to lie farther offshore than the fish, suggesting offshore and/or westward transport in this area. East of Cape Agulhas, the correspondence between eggs and fish is particularly good in both years.

Tables 1 and 2 summarize the acoustic results per stratum and the egg-production results (in parentheses) for 1985 and 1986 respectively. Note that in both years, all strata with fewer than seven transects were amalgamated into a single stratum for reasons previously discussed. The estimated coefficients of variation for all strata were obtained by combining the variances in these strata with those in the remaining single strata, through Equation (4). (The respective coefficients of variation for 1985 and 1986 without combination of strata are 0.151 and 0.146.)

It can be seen that the agreement between the overall acoustic and egg estimates in both years is reasonably good. The estimates in each year are clearly not significantly different, given the variances in them.

From Tables 1 and 2, \( \hat{E}_{55} = 0.62, \hat{A}_{55} = 0.97, \) and \( \hat{A}_{66} = 1.75 \) million tonnes. Substitution in Equation (7) gives \( \hat{E}_{66} = 1.12 \) million tonnes. From the analysis of the covariance between acoustically determined densities and the spawning parameters,

\[ \text{Cov}(\hat{E}_{55}, \hat{A}_{55}) \]
\[ \hat{E}_{55} \hat{A}_{55} = 0.013 \]

and

\[ \text{Cov}(\hat{E}_{66}, \hat{A}_{66}) \]
\[ \hat{E}_{66} \hat{A}_{66} = -0.09 . \]
Figure 3. Anchovy egg distribution from November 1985 survey.
Figure 4. Anchovy egg distribution from November 1986 survey.
Table 1. Acoustic results from the survey in November 1985. Values in parentheses were obtained from the egg data for the same survey.

<table>
<thead>
<tr>
<th>Stratum</th>
<th>Area (km²×10^4)</th>
<th>No. of transects</th>
<th>( \hat{\theta}_h ) (tonnes/km²)</th>
<th>( \hat{B} ) (tonnes×10^5)</th>
<th>CV (( \hat{B} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>18.6</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0.36</td>
</tr>
<tr>
<td>B</td>
<td>14.4</td>
<td>7</td>
<td>23.65</td>
<td>340</td>
<td>0.19</td>
</tr>
<tr>
<td>C</td>
<td>24.7</td>
<td>9</td>
<td>15.27</td>
<td>777</td>
<td>0.18</td>
</tr>
<tr>
<td>D</td>
<td>21.5</td>
<td>5</td>
<td>3.70</td>
<td>80</td>
<td>0.28</td>
</tr>
<tr>
<td>E</td>
<td>19.6</td>
<td>6</td>
<td>2.92</td>
<td>61</td>
<td>0.20</td>
</tr>
<tr>
<td>F</td>
<td>21.0</td>
<td>2</td>
<td>4.15</td>
<td>258</td>
<td>0.21</td>
</tr>
<tr>
<td>D+E+F</td>
<td>62.1</td>
<td>13</td>
<td>4.15</td>
<td>258</td>
<td>0.21</td>
</tr>
<tr>
<td>All strata</td>
<td>119.8</td>
<td>33</td>
<td>8.14</td>
<td>(616)</td>
<td>(0.40)</td>
</tr>
</tbody>
</table>

Table 2. Acoustic results from the survey in November 1986. Values in parentheses were obtained from the egg data for the same survey.

<table>
<thead>
<tr>
<th>Stratum</th>
<th>Area (km²×10^4)</th>
<th>No. of transects</th>
<th>( \hat{\theta}_h ) (tonnes/km²)</th>
<th>( \hat{B} ) (tonnes×10^5)</th>
<th>CV (( \hat{B} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>14.0</td>
<td>5</td>
<td>8.40</td>
<td>117</td>
<td>0.43</td>
</tr>
<tr>
<td>B</td>
<td>12.6</td>
<td>10</td>
<td>66.93</td>
<td>842</td>
<td>0.14</td>
</tr>
<tr>
<td>C</td>
<td>10.4</td>
<td>8</td>
<td>24.25</td>
<td>732</td>
<td>0.51</td>
</tr>
<tr>
<td>D</td>
<td>22.0</td>
<td>5</td>
<td>10.75</td>
<td>236</td>
<td>0.63</td>
</tr>
<tr>
<td>E</td>
<td>23.6</td>
<td>5</td>
<td>6.01</td>
<td>142</td>
<td>0.52</td>
</tr>
<tr>
<td>F</td>
<td>24.4</td>
<td>5</td>
<td>1.99</td>
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<td>0.36</td>
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<td>Inshore</td>
<td>1.0</td>
<td>10</td>
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<td>109</td>
<td>0.41</td>
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<tr>
<td>A+D+E+F</td>
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<td>20</td>
<td>6.48</td>
<td>544</td>
<td>0.32</td>
</tr>
<tr>
<td>All strata</td>
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<td>38</td>
<td>16.17</td>
<td>(2 001)</td>
<td>(0.35)</td>
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</table>

The fact that these covariances are small indicates that at the transect level, the acoustic and egg-production data are essentially independent, despite the fact that they were collected on the same transects. This is probably due to the displacement of fish from their eggs caused by fish movement and egg dispersal, which can be considerable during the two-to-three-day period required for the eggs to hatch.

Substituting the above covariances into Equation (10) and taking \( \hat{E}_{90} \) as 2 million tonnes gives \( a = 0.20 \times 10^{12} \), \( b = 0.49 \times 10^{12} \), and \( c = 0.20 \times 10^{12} \) tonnes². Substitution in Equations (8) and (9) gives

\[
(\hat{C}_{90})_{opt} = 0.30 \hat{E}_{90} + 0.70 \hat{E}_{so} = 1.37 \text{ million tonnes},
\]

and

\[
[\text{Var}(\hat{C}_{90})]_{\text{min}} = 0.133 \times 10^{12} \text{ tonnes}^2.
\]

The coefficient of variation in \( (\hat{C}_{90})_{opt} \) is therefore 0.27.

Discussion

It will be noted that \( (\hat{C}_{90})_{opt} \) is substantially lower than either \( E_{90} \) or \( \hat{A}_{90} \), which is a consequence of the fact that \( \hat{E} \) was lower than \( \hat{A} \) in 1985, but \textit{vice versa} in 1986. With only one previous year's data \( (\hat{C})_{min} \) is very sensitive to the ratio of \( \hat{E} \) to \( \hat{A} \) in that year. As estimates from more years become available, the estimator should become more robust.

The acoustic and egg-production estimates for 1985 and 1986 are similar in magnitude to an acoustic estimate of 1.07 million tonnes obtained for the anchovy spawning biomass in 1984 (Hampton, 1987), but run five to ten times higher than typical levels estimated by VPA in the past (Armstrong et al., 1983; Butterworth, 1983). It is now apparent, partly from information on population age structure and distribution derived from the current survey programme (Armstrong et al., 1985; Hampton, 1987), and partly from new aging studies (Prosch, 1986), that the VPA estimates were essentially spurious. It would therefore seem clear that the resource is less seriously threatened than was previously believed to be the case, and that it may in fact have been considerably underexploited in the past.

Since 1984, management of the resource has been almost entirely based on the direct estimates of spawning biomass and, from 1985, acoustic estimates of recruitment strength (Hampton, 1987). The biomass estimates and associated variances obtained from the surveys have been used to predict safe levels of harvest in 1985, 1986, and 1987 (e.g., Armstrong and Butterworth, 1986; D. S. Butterworth, pers. comm.). This
work has led to a progressive increase in quota from 225 thousand tonnes immediately prior to the introduction of the survey programme, to 600 thousand tonnes in 1987. The estimated variances have had a major influence on the quota recommendations, which emphasizes the importance of both reducing the variance and estimating it as accurately as possible. In 1987, for the first time, separate quotas were recommended for the 0-year-old and the older fish, based on perceptions of the population age structure derived from the surveys. This approach is expected to lead to more efficient utilization of the resource than has hitherto been possible.

Direct combination of the 1986 acoustic and egg estimates with inverse variance weightings (assuming no bias in either estimate) would have given a combined estimate of 1.78 million tonnes, with a coefficient of variation of 0.13. The indirect combined estimate \( \hat{C}_{\text{opt}} \) is however regarded as more reliable, as it does not assume the acoustic estimate to be unbiased. In effect, a reduced sensitivity to bias has been achieved at the expense of an increase in the variance. On the other hand, if only a relative estimate is required, for example for estimating biomass changes between two years, it would probably be preferable to average the ratio of the acoustic and egg estimates in the two years with appropriate inverse variance weightings, as bias would be of lesser importance.

The reasonable agreement between the acoustic and egg estimates in both years does not of course establish that the acoustic method is unbiased, because of the variances in both estimates, but it does suggest that the method is probably not severely biased. In particular, it suggests that the target-strength expression assumed was at least realistic.

An advantage of the indirect estimate is that it can be made with no knowledge of target strength, provided that the same target-strength/length expression holds for the different surveys. Likewise, the echo sounder need only be calibrated in relative terms, removing, for example, the need for absolute calibration of hydrophones. Alternatively, the egg estimate enables the mean target strength during a survey to be estimated. This value could then be used in acoustic surveys for which there is no corresponding egg estimate, for example, in surveys on pre- and post-spawning fish. Allowance would have to be made for differences in fish size between the spawning and the other surveys, but target-strength/length relationships such as in Equation (1) for similar species may be adequate for this.

In regions where the displacement of eggs from the fish is small, and one or the other of the methods is suspected to be biased, the methods can be used to supplement one another. For example, acoustic estimates could replace egg-production estimates in regions where fish are present but not spawning, and vice versa in regions where acoustic estimates are suspect (e.g., where the fish are shallow or detection conditions poor), but the egg data reliable.

It is instructive to investigate the relative precision of the indirect estimate compared with that of a direct estimate obtained from the average of \( \bar{E} \) and \( \bar{A} \), were \( \bar{A} \) to be unbiased. (This represents the lower bound on the absolute error.) Making the simplifying assumptions that \( \text{Var}(\bar{A}) = \text{Var}(\bar{E}) \), \( R = R_n = 1 \), and that \( c = 0 \), the estimated variance in the direct estimate would be \( \frac{n}{2} \), and

\[
[\text{Var}(\hat{C}_n)]_{\text{lim}} = \frac{(n + 2) b}{2(n + 1)}
\]

(See Equation (B.9), Appendix B.) The relative precision of the two estimates (i.e., the inverse ratio of their variances) would then be \( \frac{n + 1}{(n + 2)} \), which would approach 1 as \( n \to \infty \). With one previous year (the present case), the relative precision is 2/3, which means that the standard error is about 18% higher than that achievable for a direct estimate in the ideal situation of no bias in \( \bar{E} \) and \( \bar{A} \), and zero covariance between them.

It is noted that if the bias in \( \bar{A} \) is not constant, but fluctuates about some mean \( R \), the combination method could still be used by replacing the theoretical variance \( \text{Var}(\bar{R}) \) with the actual variance among the \( R \). Several years’ data would be required, and the actual variance could be tested against the theoretical \( \text{Var}(\bar{R}) \) before deciding on which method to use.

Finally, it is noted that in situations where bias is of little or no concern, and the precision of the acoustic estimate is good (as in the present case), the egg estimate may be of little value because of its comparatively low precision. Unless this precision can be substantially improved, for example by major reduction of the variances in \( \bar{P} \) and \( \bar{S} \), which are the chief sources of error (Armstrong et al., 1988), investment in egg surveys in such situations may not be warranted. Estimates of error in both types of survey, such as those developed here, allow an objective decision to be made on the value of incorporating egg surveys.
Appendix A
Covariance introduced by acoustic weighting of spawning parameters

We demonstrate here that, in principle, acoustic weighting of the spawning parameters introduces no additional covariance between the acoustic and egg-production estimates of spawning biomass. We consider as an example of one of the more complex cases, the covariance between \( \hat{q} \), the estimated mean density for a stratum, and \( \hat{F} \), the estimated mean batch fecundity for the stratum. \( \hat{q} \) and \( \hat{F} \) are given by

\[
\hat{q} = \frac{\sum_{k=1}^{K} L_k \hat{o}_k}{\sum_{k=1}^{K} L_k}
\]

and

\[
\hat{F} = \frac{\sum_{k=1}^{K} L_k \hat{o}_k \hat{R}_k \hat{F}_k / W_k}{\sum_{k=1}^{K} L_k \hat{o}_k \hat{R}_k / W_k}
\]

where \( k \) is the transect index, \( K \) the number of transects in the stratum, and the other symbols have the meanings ascribed to them in Equations (3) and (6).

For convenience we write

\[
\alpha_k = \frac{\hat{o}_k \hat{R}_k}{W_k}
\]

giving

\[
\begin{align*}
\text{Cov}(\hat{q}, \hat{F}) &= \text{Cov}\left(\sum_{k=1}^{K} L_k \hat{o}_k, \frac{\sum_{k=1}^{K} L_k \hat{F}_k}{\sum_{k=1}^{K} L_k} \right) \\
&= \hat{o} \hat{R} \left[ \frac{\text{Cov}(\sum_{k=1}^{K} L_k \hat{o}_k, \sum_{k=1}^{K} L_k \hat{F}_k)}{\sum_{k=1}^{K} L_k \hat{o}_k \sum_{k=1}^{K} L_k \hat{F}_k} \right] \\
&\quad - \frac{\text{Cov}(\sum_{k=1}^{K} L_k \hat{o}_k, \sum_{k=1}^{K} L_k)}{\sum_{k=1}^{K} L_k \hat{o}_k \sum_{k=1}^{K} L_k} + 0 - 0
\end{align*}
\]

All summations run between \( k = 1 \) and \( K \). The above expansion, and those which follow, are straightforward approximations to the first term of a Taylor's series. The last two terms are zero since they involve a covariance with \( \sum L_k \) which, it is easy to show, can be treated as a constant in this argument.

Expanding the above expression further, and re-substituting for \( \alpha_k \) from Equation (A.2), gives

\[
\begin{align*}
\text{Cov}(\hat{q}, \hat{F}) &= \frac{\hat{o} \hat{R} \hat{F}}{W(\sum_{k=1}^{K} L_k \hat{o}_k) (\sum_{k=1}^{K} L_k \hat{o}_k \hat{R}_k / W_k )} \times \\
&\quad \left[ \frac{\sum_{k=1}^{K} \text{Cov}(L_k \hat{o}_k, L_k \hat{F}_k)}{\hat{o}} + \frac{\sum_{k=1}^{K} \text{Cov}(L_k \hat{o}_k, L_k \hat{R}_k)}{\hat{R}} \right] \\
&\quad + \frac{\sum_{k=1}^{K} \text{Cov}(L_k \hat{o}_k, L_k \hat{F}) - \sum_{k=1}^{K} \text{Cov}(L_k \hat{o}_k, L_k \hat{W}_k)}{\hat{F} + \frac{\sum_{k=1}^{K} \text{Cov}(L_k \hat{o}_k, L_k \hat{R}_k)}{\hat{R}} - \frac{\sum_{k=1}^{K} \text{Cov}(L_k \hat{o}_k, L_k \hat{W}_k)}{\hat{W}}}
\end{align*}
\]

The replacement of covariances of sums by sums of covariances is legitimate because of the zero covariance between transects resulting from the randomization (and hence independence) of the transects.

Using Equation (A.1) to equate the denominator of the first group of terms to that of the second group, and grouping similar terms gives

\[
\begin{align*}
\text{Cov}(\hat{q}, \hat{F}) &= \frac{\hat{o} \hat{R} (\sum_{k=1}^{K} L_k \hat{F}_k)}{W(\sum_{k=1}^{K} L_k \hat{o}_k) (\sum_{k=1}^{K} L_k \hat{o}_k \hat{R}_k / W_k ) \hat{W}}.
\end{align*}
\]

This can be rewritten:

\[
\begin{align*}
\text{Cov}(\hat{q}, \hat{F}) &= \frac{\hat{o} \hat{R} \sum_{k=1}^{K} L_k \hat{o}_k \hat{R}_k}{W (\sum_{k=1}^{K} L_k \hat{o}_k) (\sum_{k=1}^{K} L_k \hat{o}_k \hat{R}_k / W_k )} \\
&\quad \times \left( \frac{\sum_{k=1}^{K} L_k}{\sum_{k=1}^{K} L_k \hat{o}_k \hat{R}_k} \right)^2 \frac{\sum_{k=1}^{K} L_k \hat{o}_k}{\sum_{k=1}^{K} L_k \hat{o}_k \hat{R}_k / W_k} \\
&\quad \times \frac{\hat{o} \hat{R}}{W} \text{Cov}(\hat{q}, \hat{F}) \left( \frac{1}{\hat{o}} \right)^2 \frac{1}{\hat{R}} \hat{W} \\
&\quad = \text{Cov}(\hat{q}, \hat{F})
\end{align*}
\]
where \( \text{Cov}(\hat{q}^F, \hat{F}) \) is the covariance between \( \hat{q}' \) and \( \hat{F}' \), the estimates of \( \hat{q} \) and \( \hat{F} \) obtained with only \( L_k \) as weights, i.e., with no acoustic weighting.

The above argument has demonstrated that acoustic weighting does not affect the covariance between \( \hat{q} \) and \( \hat{F} \) at the transect level. Repeating the procedure at the station level shows that the covariances within transects (which could affect the intertransect covariance indirectly through the different \( F_k \) values which would result) are also independent of the chosen acoustic weightings.

It can readily be seen that applying the whole argument \textit{ab initio} to any of the other spawning parameters gives the same result.

### Appendix B

**Use of previous egg and acoustic estimates to improve the current egg estimate**

We assume the egg estimate, \( \hat{E}_i \), for year \( i \) to be unbiased, and the corresponding acoustic estimate, \( \hat{A}_i \), to have an unknown bias which is a constant proportion of \( A_i \). Suppose we have egg and acoustic estimates for \( n \) previous years, \( 0, 1, \ldots, n-1 \), year \( n \) being the current year. It is then possible to make an unbiased estimate for year \( n \):

\[
\hat{E}_n' = \hat{R} \hat{A}_n,
\]

where \( \hat{R} = \hat{E}/\hat{A} \), and \( \hat{E} \) and \( \hat{A} \) are estimated means of \( E_i \) and \( A_i \) for the \( n \) previous years. \( \hat{E}_n \) and \( \hat{E}_n' \) can then be combined to give a single estimate \( \hat{C}_n \):

\[
\hat{C}_n = w \hat{E}_n + (1 - w) \hat{E}_n',
\]

with weighting factor \( w \) chosen to minimize the variance in \( \hat{C}_n \). To obtain \( w \) we define, for convenience,

\[
a = \text{Var}(\hat{E}_n) = A_i^2 \text{Var}(\hat{R}) + \hat{R}^2 \text{Var}(\hat{A}_n)
b = \text{Var}(\hat{E}_n')
c = \text{Cov}(\hat{E}_n, \hat{E}_n') = \hat{R} \text{Cov}(\hat{E}_n, \hat{A}_n).
\]

Then

\[
\text{Var}(\hat{C}_n) = w^2 b + (1 - w)^2 a + 2w (1 - w) c.
\]

Differentiating \( \text{Var}(\hat{C}_n) \) with respect to \( w \) and setting to zero gives

\[
w = \frac{a - c}{a + b - 2c}
\]

for minimum \( \text{Var}(\hat{C}_n) \). Substituting in Equation (B.1) gives

\[
[\text{Var}(\hat{C}_n)]_{\text{min}} = \frac{ab - c^2}{a + b - 2c} = (A_i^2 \text{Var}(\hat{R}) \text{Var}(\hat{E}_n) + \hat{R}^2 \text{Var}(\hat{A}_n) - \text{Cov}(\hat{E}_n, \hat{A}_n)^2) / \{A_i^2 [\text{Var}(\hat{R}) + \text{Var}(\hat{A}_n)]\}. \quad (B.2)
\]

Equation (B.2) only involves parameters from year \( n \) except for \( \text{Var}(\hat{R}) \) which accounts for the variance in the data from the previous years. The only element that changes with increasing \( n \) is \( \text{Var}(\hat{R}) \), since \( \text{Var}(\hat{R}) \propto 1/n \).

\( \text{Var}(\hat{R}) \) can be minimized independently of data from year \( n \) as follows. Let

\[
\hat{R} = \frac{\sum i=0 \text{n-1} w_i \hat{E}_i}{\sum i=0 \text{n-1} w_i \hat{A}_i}, \quad (B.3)
\]

where the \( w_i \) are weighting factors to be chosen to minimize \( \text{Var}(\hat{R}) \). Then

\[
\text{Var}(\hat{R}) = \frac{1}{\text{Var}(\hat{R})} \left[ \sum i=0 \text{n-1} w_i^2 \text{Var}(\hat{E}_i) - 2 \hat{R} \sum i=0 \text{n-1} w_i \text{Cov}(\hat{E}_i, \hat{A}_i) \right]. \quad (B.4)
\]

All summations run from 0 to \( n-1 \). Differentiating with respect to \( w_i \) using Lagrange’s method of undetermined multipliers conditional on \( \sum w_i = 1 \), and equating to zero gives

\[
w_i = \frac{1}{A_i^2 \text{Var}(\hat{R})}, \quad (B.5)
\]

where

\[
A_i^2 \text{Var}(\hat{R}) = \text{Var}(\hat{E}_i) - 2 \hat{R} \text{Cov}(\hat{E}_i, \hat{A}_i) + \hat{R}^2 \text{Var}(\hat{A}_i). \quad (B.6)
\]

Substituting for \( w_i \) in Equation (B.3) gives

\[
(\hat{R})_{\text{opt}} = \frac{\sum i \hat{E}_i / A_i^2 \text{Var}(\hat{R}_i)}{\sum i \hat{A}_i / A_i^2 \text{Var}(\hat{R}_i)}.
\]
From Equations (B.4) and (B.5), and the condition that
\[ \sum_{i} w_i = 1. \]
\[
[\text{Var}(\hat{R})]_{\text{min}} = \frac{1}{A^2 \sum_i [1/A_i^2 \text{Var}(R_i)]}.
\]

\( \text{Var}(R_i) \) is obtainable from Equation (B.6).

If, as in the present situation, data are only available
for one previous year (i.e., \( n = 1 \)), \( R = \hat{E}_{n}/\hat{A}_{n} \), and the
combined estimate for year 1 becomes
\[
\hat{C}_1 = w \hat{E}_1 + (1 - w) \hat{E}_i.
\]
with
\[
\hat{E}_i = \frac{\hat{E}_i}{\hat{A}_i} \hat{A}_n.
\]
As before, \( \text{Var}(\hat{C}) \) has minimum variance
\[
(n + 2) b + n c \]
where in this case,
\[
a = \text{Var}(\hat{E}_i) = A_i^2 \text{Var}(\hat{E}_n/\hat{A}_n) + (\hat{E}_n/\hat{A}_n)^2 \text{Var}(\hat{A}_n)
\]
\[
= (E_i)^2 \left[ \frac{\text{Var}(A_i)}{A_i^2} + \frac{\text{Var}(\hat{A}_n)}{A_n^2} + \frac{\text{Var}(\hat{E}_n)}{E_n^2} + \frac{2 \text{Cov}(\hat{A}_n, \hat{E}_n)}{A_n E_n} \right]
\]
\[
b = \text{Var}(\hat{E}_i)
\]
\[
c = \text{Cov}(\hat{E}_i, E_i) = \frac{E_n \text{Cov}(\hat{A}_n, \hat{E}_n)}{A_n}.
\]

The behaviour of \( [\text{Var}(\hat{C}_n)]_{\text{min}} \) with increasing \( n \) is of interest, and is best seen by setting \( \text{Var}(\hat{A}_n) = \text{Var}(\hat{E}_n) = b, \) and \( R = R_n = 1. \) Substitution in Equation (B.2) gives, assuming all \( \hat{E}_i \) and \( \hat{A}_i \) approximately equal,
\[
[\text{Var}(\hat{C}_n)]_{\text{min}} = \frac{b (2b - 2c) + n (b^2 - c^2)}{(n + 1) (2b - 2c)}
\]
\[
= \frac{(n + 2) b + n c}{2 (n + 1)}
\]
\[
\rightarrow \frac{b + c}{2} \quad \text{for large } n.
\]
If the covariance between \( \hat{E}_n \) and \( \hat{A}_n \) is zero (i.e., \( c = 0 \)),
\[
[\text{Var}(\hat{C}_n)]_{\text{min}} = \frac{(n + 2) b}{2 (n + 1)}
\]
\[
\rightarrow \frac{b}{2} \quad \text{for large } n.
\]

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