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Use of a shoal analysis and patch estimation system (SHAPES) to characterise sardine schools

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Abstract — The use of a shoal analysis and patch estimation system (SHAPES) to analyse hydro-acoustic data is discussed. SHAPES was used to detect and characterise sardine schools from four echo integration surveys off the coast of South Africa. Methods of school detection and characterisation, assumptions made and corrections applied to school variables are presented. Measurements of school morphology and internal school features are discussed and compared to other relevant works. Significant relationships were established, both between measures of school morphology and internal density structure. Several variables showed significant differences between surveys. Composite factors derived from principle component analyses showed that morphological variables are the most important school descriptors. No differences in the loading of composite factors between surveys are evident. This suggests an inherent spatial and temporal stability in sardine school characteristics. This fact may prove beneficial for comparisons of school structure between co-occurring fish species and possibly aid fish school identification in the future. © 2000 Ifremer/Cnrs/Inra/Ird/Cemagref/Éditions scientifiques et médicales Elsevier SAS

Acoustic surveys / school detection / school characterisation / SHAPES / sardine

Résumé — Utilisation d’un système d’analyse des bancs et d’estimation des concentrations de poissons (SHAPES) pour caractériser des bancs de sardines. L’utilisation d’un système d’analyse des bancs de poissons et d’estimation des concentrations (SHAPES) est discutée. SHAPES est utilisé pour identifier et caractériser les bancs de sardines observés au cours de quatre campagnes océanographiques d’écho-intégration au large de l’Afrique du Sud. On présente les méthodes de détection et caractérisation des bancs, les hypothèses de travail et les corrections appliquées aux variables du banc. Des mesures de la morphologie et des caractéristiques internes du banc sont discutées et comparées à d’autres travaux du même ordre. Des relations significatives ont été établies, à la fois entre les mesures de morphologie du banc et sa structure interne. Plusieurs variables montrent des différences significatives entre les campagnes. Des facteurs composites, dérivés d’analyses en composantes principales, montrent que les variables morphologiques sont les descripteurs les plus importants du banc. Aucune différence dans le chargement de facteurs composites n’est évident entre campagnes. Ceci laisse supposer une stabilité inhérente spatiale et temporelle dans les caractéristiques des bancs. Ceci pourrait être bénéfique pour les futures comparaisons de structures de bancs entre espèces de poissons d’un même habitat et apporter une aide à l’identification des bancs dans l’avenir. © 2000 Ifremer/Cnrs/Inra/Ird/Cemagref/Éditions scientifiques et médicales Elsevier SAS

Campagnes océanographiques d’acoustique / détection de bancs / caractéristiques des bancs de poissons / sardine

1. INTRODUCTION

Traditionally, hydro-acoustic stock estimation surveys have mainly provided information on the distribution and relative abundance of fish species. The typical scale of one to five nautical miles, imposed by the echo integrator, limited extracting further detailed information from the acoustic data or echo charts [28]. Consequently, studies of fish aggregating patterns in situ at a scale allowing for measurements of school dimensions have been limited. Azzali et al. manually determined basic school characteristics such as height, width and volume of 500 sardine schools in the Adriatic [1]. This approach is, however, extremely time consuming and would rule out the processing of large volumes of data such as that collected during routine acoustic surveys.

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Recently, though, advances have been made in fisheries science, acoustic technology, digital signal processing and digital image processing. These enable the use and interpretation of information present in the acoustic signal at a much finer scale. Several authors have recently used the information present in the digitised back-scattered signal to analyse schooling characteristics of fish and even to discriminate between different species, with varying success [15, 30, 31].

Off the west and south coasts of South Africa, four pelagic fish species co-occur in varying degrees at different times of the year. These include anchovy (*Engraulis capensis*), sardine (*Sardinops sagax*), round herring (*Etrumeus whiteheadi*) and juvenile horse mackerel (*Trachurus trachurus capensis*). Acoustic assessments of the biomass of both anchovy and sardine off the coast of South Africa have been carried out since the mid 1980s [13].

Accurate hydro-acoustic assessment of the biomass of a particular species has been limited, however, by the difficulty to objectively differentiate among taxonomic groups of sound-scatterers [28–30]. Identification methods most commonly used include trawl sampling close to the acoustic targets and visual interpretation of the echograms based on previous knowledge of a species' shoaling patterns. Often, however, these techniques have not enabled unbiased discrimination between co-occurring fish species [30]. Catchability of different species may vary and the trawl cannot achieve a spatial and temporal sampling comparable with that of acoustic sampling. In addition, identifying species based on echogram characteristics remains subjective. Species mixing in aggregations may therefore lead to biases in the proportion of the measured acoustic energy allocated to a particular species. Hampton concluded that the error due to incorrect acoustic energy allocation could be as large as 10 % for the South African anchovy during some surveys [14].

This paper describes the use of a shoal analysis and patch estimation system (SHAPES) to characterise sardine schools. In addition, a principal component analysis (PCA) is used to reflect on the descriptive importance of school characteristics. If such school characteristics are species specific, their use in the future to differentiate between schools of various species in an automated and objective manner may complement traditional methods of fish identification.

2. MATERIALS AND METHODS

2.1. Data collection and equipment

Acoustic data of fish density were used for this study. The data were collected during four meso-scale acoustic surveys according to standard echo integration methodology [17]. All surveys were conducted on the western Agulhas Bank of South Africa between Cape Point and Cape Agulhas (*figure 1*). The surveys

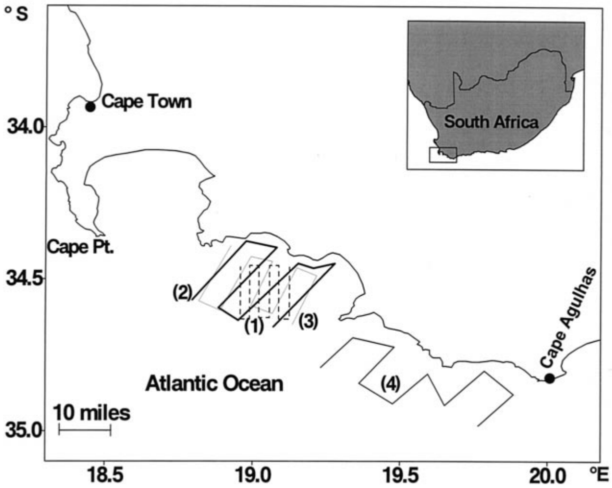


Figure 1. Geographic location of the four meso-scale acoustic surveys.

were carried out in September 1994, October 1994 and February 1995. Equipment used for these purposes included a sphere-calibrated 38-kHz EK400 echo sounder and a custom-built digital echo-integrator [13]. A mid-water trawl (Engels 308) fitted with an anchovy cod-end liner of 8-mm mesh was used to identify acoustic targets.

Halldórsson and Reynisson's expression for the weight-normalised target strength of herring (*Clupea harengus*) at 38 kHz as a function of length was used to convert back-scattering strengths (S_A) to density ($g{\cdot}m^{-3}$ and $g{\cdot}m^{-2}$) [11]. The expression was the following:

$$\text{Density}\ (g{\cdot}m^{-3}) = \frac{S_A}{4\pi{\cdot}10^{0.1{\cdot}TS{\cdot}kg^{-1}}{\cdot}1\,852^2{\cdot}\Delta R}{\cdot}1\,000 \quad \text{or}$$

$$\text{Density}\ (g{\cdot}m^{-2}) = 10^{0.1[(10\log S_A\ -\ 76.34)-TS{\cdot}kg^{-1}]}{\cdot}1\,000$$

where ΔR is the width of the vertical integration channel and

$$TS_{dB{\cdot}kg^{-1}} = -\,10.9\log L - 20.9$$

This is the target strength expression used routinely in South Africa for stock assessment of pelagic fish. Hampton supplies background information for using this particular target strength function [12]. Preliminary in situ measurements of the target strength of sardine in South Africa are available [4] but not as yet implemented during stock assessment surveys. These results suggest a higher sardine target strength per kg ($TS{\cdot}kg^{-1} = 14.9\log L - 13.21$) and therefore a decrease in fish density compared with that obtained from the herring expression. As all data were collected in areas where trawls indicated the presence of sardine only, applying weighting factors for proportional allocation of the acoustic energy between species was not necessary. A mean fish total length of 17.2 cm and weight of 35.8 g was calculated and used for all surveys.

2.2. School detection and description

School analyses were performed using SHAPES (shoal analysis and patch estimation system). This is a Sea Fisheries Research Institute (SFRI)-developed software capable of detecting, extracting and statistically characterising fish schools in an automated and objective manner from acoustic data. SHAPES provides statistics for up to 17 school descriptors. These descriptors are divided into three main groups.

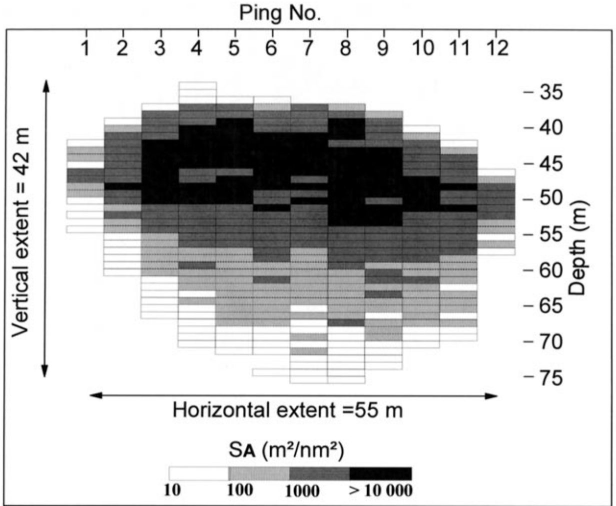
The first set of descriptors includes size and shape variables such as length, height, area (cross-sectional), volume, perimeter and fractal dimension. Variables describing internal features and energetic characteristics of the schools (i.e. mean and standard deviation of the acoustic intensity, horizontal and vertical roughness, skewness and kurtosis of the acoustic energy) make up the second set of descriptors. The third set includes relational statistics such as distance and angle relative to the nearest neighbour school. This third set was not utilised during this study.

SHAPES processes the raw acoustic data in four steps, as follows. First, a matrix consisting of *n* columns (one per echo return) and *m* rows (one per 1-m vertical depth channel) is generated, from the first accepted channel depth (5 m from the transducer) to the last (2 m above the sea bed). In this study, the horizontal resolution varied from approximately 2.4 to 4.5 m depending on the vessel speed and ping rate.

Second, applying a threshold reduces the matrix to eliminate any unwanted noise. This threshold is applied interactively, and a graphic interface is used to ensure accurate filtering and school definition. In this study, a threshold of 10 S_A units ($m^2 \cdot$nautical mile^{-2}) was applied, which is equivalent to S_V = –66 dB. This corresponds to a minimum fish density of 0.02 fish$\cdot m^{-3}$ for a 17-cm fish.

In the third step, schools are detected from the filtered matrices using routines based on the principle that a school is composed of a number of super-threshold adjacent cells. A continuity factor accommodates ‘empty’ cells within a school (vacuoles, sensu [9]) and helps to smooth the small-scale variability between successive echo returns. A minimum number of rows and columns are set to discard any aggregations smaller than a predetermined size. In this case a length of 10 m (calculated from number of pings and ping length and uncorrected for beam width effects) and height of 2 m (uncorrected for pulse length effects) was used. Vessel speed during the survey was quite constant (10–12 knots). The ping rate and therefore the length of each ping, however, varied somewhat depending on the range selected. At a vertical range of 100 m and a vessel speed of 10 knots, the ping rate was 128 pings$\cdot$min^{-1} and the horizontal length of each ping 2.4 m.

The fourth step involves the extraction of school characteristics. Morphological variables based on earlier definitions were used [2, 24, 28]. The basic assumption is that the horizontal projections of the schools are circular [27]. It is assumed that schools are intercepted at random so that only a few would be intercepted through the centre. A correction factor of $4/\pi$ is therefore applied to estimate the expected school length [17].



Height (m)	41.3	SA ($m^2 nm^{-2}$)	20 546
Length (m)	57.1	Density ($g.m^{-2}$)	1307.8
Area (m^2)	7409	Packing density ($fish.m^{-3}$)	31
Volume (m^3)	105 758	Horizontal roughness	26 453
No of cells (n)	353	Vertical roughness	18 147
Perimeter (n)	87	Skewness	1.4
Depth (m)	57	Fractal Dimension	1.05

Figure 2. An example of a sardine school detected according to specified criteria by SHAPES, with an example of the statistical output of selected variables.

Corrections to school shape variables, to account for pulse length effects, are performed prior to the calculation of averaging parameters. In addition, artefacts due to beam width are corrected for by removing those pings in which the acoustic axis was outside the edge of the school (on both sides). This was done according to procedures described in Barange et al. [3] and assumed a beam width of 5° (the approximate position of the –3 dB points). Formal definitions of the variables and corrections used during this study were presented by Barange [3] and are included (*table I*). An example of one school extracted by SHAPES, along with selected calculated parameters is shown (*figure 2*). The variables were then used in a number of statistical analyses to detect any differences or similarities between school parameters during the various surveys. All statistical tests were according to methods described by Zar [34] or by using STATISTICA© data analysis software.

Sardine tend to disperse in layers at night, making it very difficult to accurately delineate separate schools particularly when they are within a dense sound-scattering layer. Only distinct schools recorded during

Table I. Definitions of variables calculated by SHAPES and corrections made for beam width and pulse length effects.

Variable		Definition	Notes
Nearest neighbour angle	(°)	$\tan^{-1}(\lvert i_1 - i_2\rvert/(\lvert j_1 - j_2\rvert)k)$	where k is the number of metres per ping (calculated using vessel speed and ping rate)
Nearest neighbour distance	(m)	$((i_1 - i_2)^2 + ((j_1 - j_2)k)^2)^{0.5}$	and i are rows and j are columns of school 1 and its nearest neighbouring school 2
$\text{Height}_{(\text{apparent})}$	(m)	Number of 1 m depth cells at max. vertical extent of school	
$\text{Length}_{(\text{apparent})}$	(m)	Number of pings × k	where k is as above
$\text{Height}_{(\text{real})}$ (H)	(m)	$\text{Height}_{\text{appar}} - (c\gamma/2)$	where c = sound speed ($m \cdot s^{-1}$), γ = pulse length (ms), θ = half angle of the beam,
$\text{Length}_{(\text{real})}$ (L)	(m)	$[\text{Length}_{\text{appar}} - (2 \times \tan\theta \cdot D)]4/\pi$	assumed to be 5°, D = shoal mean depth (m) and k as above
Area (A)	(m^2)	$L \cdot H \pi$	cross-sectional
Volume (V)	(m^3)	$(\pi . L^2 \cdot H)/4$	
Number of cells (n)		Σ(cells)	
Perimeter (P)		Σ(side-cells)	
Fractal dimension		(Ln (P/4) × 2)/Ln(n)	where P = perimeter
Pings to discard (each side)		(tan θ × D)/k	where θ, D and k are as above
Mean echo intensity (E_m)		$(\Sigma E_{ij})/(n)$	
Sandard deviation of echo intensity (E_s)		$[(\Sigma(E_{ij} - E_m)^2)/(n - 1)]^{0.5}$	
Coefficient of variation of echo intensity (E_{cv})		E_s/E_m	
Coefficient of horizontal roughness		$(Rh)^2/E_m$	where $(Rh)^2 = \Sigma[(E_{i,\,j} - E_{i,\,j+1})^2/(n - 1)]$
Coefficient of vertical roughness		$(Rv)^2/E_m$	where $(Rv)^2 = \Sigma[(E_{i,\,j} - E_{i+1,\,j})^2/(n - 1)]$
Skewness (g_1)		$K_3/(E_s)^3$	where $K_3 = N \times \Sigma(E_{ij} - E_m)^3/(n - 1)(n - 2)$
Kurtosis (g_2)		$K_4/(E_s)^4 - 3$	where K_4 is calculated as defined in Zar [34]

daylight hours were therefore included in the analysis. A total of 572 schools was eventually extracted after all selection criteria had been satisfied.

2.3. Principal component analysis

A principal component analysis (PCA) was applied to the data of all schools. This was so as to reduce the number of variables and to identify composite factors which best explain a large fraction of the observed variability, thereby making it possible to describe differences between the data sets.

The frequency distributions of most variables were positively skewed. All variables except fractal dimension, skewness and kurtosis were therefore log-transformed to assist in the normalisation of their distributions. To maximise the variance explained by the PCA and ease interpretation, a varimax-normalised rotation was applied to the data. After computation of eigenvalues, a graphical screen test was performed to establish the number of factors to extract.

3. RESULTS

3.1. School statistics and description

3.1.1. School morphology

Summary statistics of selected variables describing the size and shape of sardine schools recorded during each of the four acoustic surveys are presented (*table II*). All variables except fractal dimension were positively skewed and therefore log-transformed. This provided more symmetrical distributions of all the variables, most of which were log-normally distributed.

Results of this study suggest a general trend in which the horizontal dimensions are larger than the vertical extent. The mean school height varied from a minimum of 2 m (corrected) to a maximum of 69 m. The mean height of schools recorded during surveys 3 and 4 was significantly less ($P < 0.0001$) than the schools recorded during the first two surveys. The mean school length also varied greatly from less than 10 m (corrected) to a maximum of 250 m. No significant differences in mean school length were noted between the surveys (ANOVA).

The cross-sectional area of schools analysed varied from 10 m^2 to a maximum of almost 35 000 m^2. The data were strongly positively skewed with schools less than 1 000 m^2 accounting for 70 % of the schools. The difference in mean area between surveys is significant ($P < 0.0005$). Schools recorded during the first and second surveys had a larger mean and maximum area than the remaining two surveys. The volume of schools ranged from a minimum of 10 m^3 to more than 2 000 000 m^3. Generally area and volume behaved similarly as a significant difference in mean volume was also noted between surveys with the mean school volume being larger for the first two surveys ($P < 0.0005$).

The mean perimeter of all the schools was 35.9 m and varied significantly between surveys ($P < 0.0005$). The second survey had the highest mean perimeter and

Table II. Summary statistics of selected variables describing sardine school morphology for each survey. CV reflects the coefficient of variation of the mean.

Variables	Survey no. 1		Survey no. 2		Survey no. 3		Survey no. 4		All surveys	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Height (m)	13.1	0.9	16.1	0.9	6.6	0.6	7.3	0.7	11.4	1.0
Length (m)	32.8	1.1	30.3	1.0	19.6	0.8	25.8	0.8	28.4	1.0
Area (m^2)	1 867.0	2.0	2 132.7	1.9	468.9	1.2	868.5	1.4	1 468.0	2.1
Volume (m^3)	44 823.8	4.1	43 308.9	2.8	3 921.1	2.0	9 238.4	1.8	29 577.5	4.3
Perimeter (n)	38.6	1.0	52.2	1.0	17.8	0.6	28.0	0.8	35.9	1.1
FD	1.0	0.2	1.0	0.1	0.9	0.2	1.0	0.2	1.0	0.2
No. schools	213		134		99		126		572	

the largest range in perimeter. The mean, standard deviation and range of the perimeter of schools recorded during the third survey were the lowest. The fractal dimension (FD), calculated from the perimeter to area relationship, is a measure of school shape complexity. A fractal dimension value of one represents a square outline shape while a value of two denotes the most complex outline shapes. FD calculated for all schools, was generally low (< 1.4) suggesting that the shape of the schools was quite regular. The mean fractal dimensions of the individual surveys were compared by an analysis of variance and this showed a significant difference ($P < 0.0005$) between the survey means. A Tukey test [34], however, showed that the only significantly different mean was that of the third survey. These schools were the most regular in shape.

3.1.2. School energetic features

A summary of selected variables describing internal energetic features of the sardine schools is provided (*table III*). The average biomass per unit volume of the schools varied from 0.1 to 127.9 $g{\cdot}m^{-3}$. The mean school density for all surveys was calculated to be 16.7 $g{\cdot}m^{-3}$. The distribution of mean school density is highly positively skewed ($g_1 = 2.18$) and schools with a mean density per unit volume of less than 40 $g{\cdot}m^{-3}$ accounted for more than 75 % of the total. The log-transformed data are normally distributed ($P < 0.05$). The average density per unit area for all schools was 170.7 $g{\cdot}m^{-2}$. The distribution was also positively skewed ($g_1 = 2.08$) and although the log-transformed data were more symmetrical, a Chi-squared test showed that the distribution was far from normal ($P < 0.001$). At least 50 % of the schools had a mean biomass per unit area of less than 100 $g{\cdot}m^{-2}$. Packing density (fish per cubic metre) derived from the density per unit volume, varied from less than 1 to 4 $fish{\cdot}m^{-3}$. The mean packing density for all surveys is 0.5 $fish{\cdot}m^{-3}$.

Acoustic roughness, which is a measure of the dispersion pattern of acoustic intensity within schools, generally indicated larger vertical than horizontal within-school variability. This was most pronounced for the fourth survey. Both horizontal and vertical roughness was least for the third survey, possibly

Table III. Summary statistics of selected variables describing the internal energetic features of sardine schools for each survey. CV reflects the coefficient of variation of the mean.

Variables	Survey									
	1		2		3		4		All surveys	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Density ($g{\cdot}m^{-2}$)	150.4	1.3	233.9	1.2	119.6	1.4	178.3	0.9	170.7	1.2
Density ($g{\cdot}m^{-3}$)	12.2	1.3	15.8	1.4	17.7	1.3	24.3	0.9	16.7	1.2
Horizontal roughness	8 720.7	1.4	8 797.1	1.2	4 741.7	1.4	6 585.4	1.0	7 584.5	1.3
Vertical roughness	7 116.4	1.2	10 428.9	1.5	5 698.1	1.5	8 879.7	1.0	8 033.7	1.3
Skewness	2.3	0.6	2.1	0.6	1.8	0.6	2.1	0.5	2.1	0.6
No. schools	213		134		99		126		572	

Table IV. Correlation matrix for selected school variables.

Variables										
Height (H)	m	H								
Length (L)	m	**0.47**	L							
Area (A)	m^2	**0.74**	**0.77**	A						
Volume (V)	m^3	**0.49**	**0.74**	**0.87**	V					
Perimeter (P)	n	**0.84**	**0.75**	**0.88**	**0.69**	P				
Fractal dimension (FD)		**0.61**	**0.58**	**0.49**	**0.33**	**0.66**	FD			
Density (D)	$g \cdot m^{-3}$	**0.46**	**0.14**	**0.25**	**0.10**	**0.34**	**0.28**	D		
Horizontal roughness (HR)		**0.48**	**0.23**	**0.29**	**0.14**	**0.36**	**0.31**	**0.65**	HR	
Vertical roughness (VR)		**0.30**	**0.19**	**0.20**	**0.08**	**0.27**	**0.30**	**0.73**	**0.65**	VR
Depth (D)	m	0.01	0.01	0.02	0.05	0.04	**0.09**	–0.07	**–0.14**	**–0.20**

Bold text indicates significant correlations at $P < 0.05$.

indicating a more homogeneous spread of fish in both dimensions within schools during this survey compared to the other three surveys.

3.1.3. Relationships between school morphology and energetic features

Schools from all surveys were merged and a correlation matrix of the variables produced (*table IV*). Significant correlations are observed amongst all morphological variables. Variables describing the internal energetic features are also significantly correlated. In addition, significant correlations exist between morphological and internal energetic variables. Shoal depth, however, is only correlated with fractal dimension and horizontal and vertical roughness. Shoal depth along with length and height are the only independently measured variables. Still, a relatively strong correlation was found between length and height (r = 0.47). This correlation coefficient is significant when tested using a Student's *t*-test ($P < 0.001$). Correlation between length and height was highest for the second survey (0.61) and very similar between the other three surveys (0.41, 0.33, 0.40).

Significant correlations existed between school area (m^2) and school biomass (kg) for all schools analysed (*figure 3a*). The correlation was strongest for the second survey (*table V*). All other surveys showed a correlation between school area and school biomass greater than 0.56 ($P < 0.001$ for all surveys). When comparing school volume to school biomass (*figure 3b*), significant correlations were also found for all surveys. Again the correlation was strongest for the second survey (r = 0.83). The correlation coefficients between school volume and school biomass were greater than 0.42 for all surveys ($P < 0.001$).

3.2. Principal component analysis

For extraction of the principal components, the schools from all surveys were pooled and the distributions of the variables describing them normalised. The first component explained 43 % of the total variance, the second explained 26 % of the variance and the third explained 19 % of the variance. Together the first three components explained 88 % of the total variance.

When the maximised factor loadings are compared (*table VI*) it is clear that the first factor is highly correlated with the variables describing the size and shape of the schools such as length, area and perimeter. This suggests the importance of school morphology in the classification of school types. The second factor mainly reflected those variables relating to the spatial distribution within schools (horizontal and vertical roughness) and the mean acoustic intensity. The third factor was highly correlated to variables describing the distribution of the acoustic intensity such as skewness and kurtosis. It is therefore apparent that the variables describing school characteristics are grouped into three distinct sets of school descriptors.

The distribution of the schools' characteristics, classified according to the first two factors did not show clear differences between surveys (*figure 4*). Variation

Table V. Correlation (r) with estimated standard error (s_r) between school area, school volume and school biomass for each survey. The correlations represent log-transformed data.

Survey	n	School area to biomass		School volume to biomass	
		r	s_r	r	s_r
1	213	0.72	0.047	0.60	0.055
2	134	0.80	0.053	0.83	0.049
3	99	0.61	0.080	0.65	0.077
4	126	0.56	0.075	0.83	0.051
All surveys	572	0.77	0.027	0.63	0.033

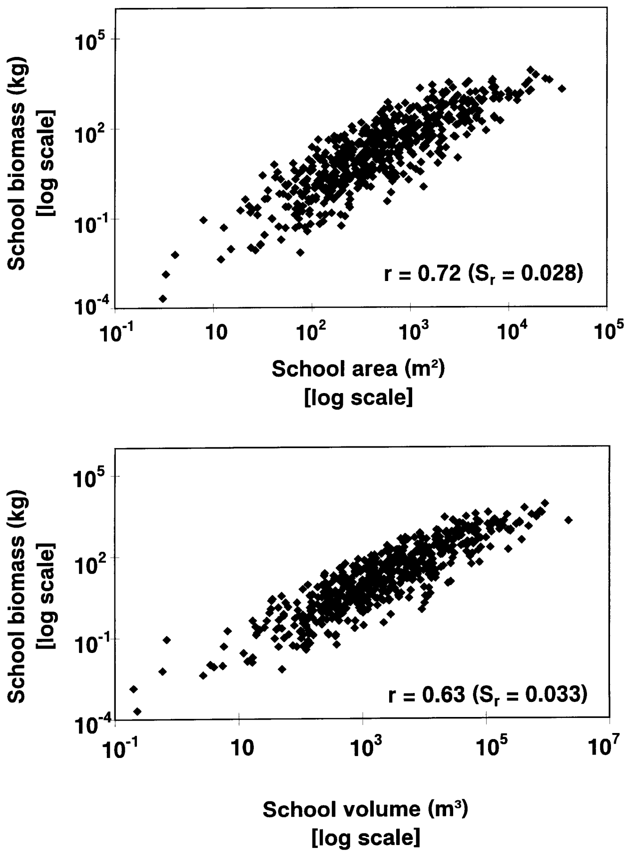


Figure 3. Correlation (r) with estimated standard error (s_r) between school biomass and corresponding school area and school volume.

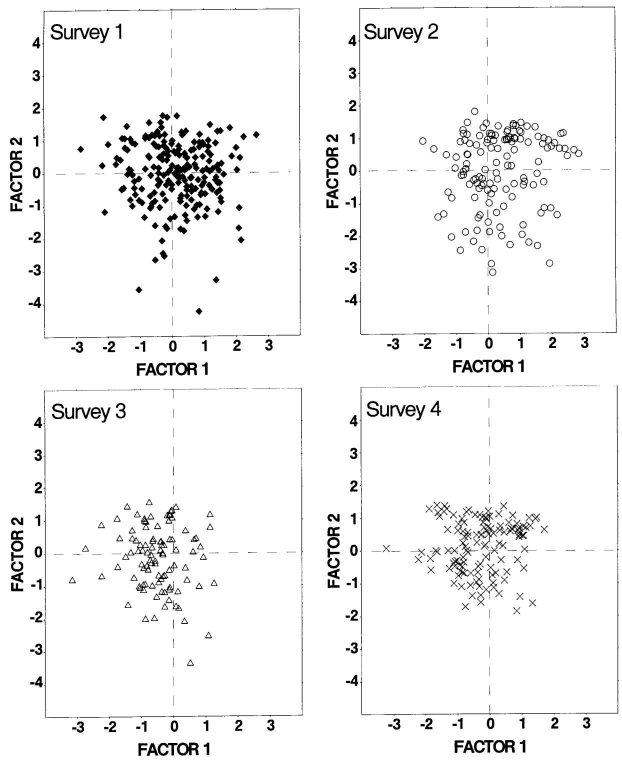


Figure 4. Scattergrams of the schools detected in each survey according to the first two components of the PCA.

along both the x-axis and y-axis was similar with few outliers observed, indicating just as much variability in morphological characteristics as internal school characteristics. This also indicated that neither one of the two components separated the four surveys in any significant manner. Overall, these observations suggest that sardine schools are variable as the individual parameters differed between surveys, but that there is a consistency in the composite factors defined through the PCA. This may be characteristic of the species, which is independent of the time and area of the surveys.

Table VI Factor loadings of the first, second and third principal components.

Variable	Factor loadings (Varimax-normalised)		
	Factor 1	Factor 2	Factor 3
Height	0.77	0.31	0.10
Length	0.78	0.09	0.30
Area	0.92	0.23	0.25
Volume	0.89	0.17	0.27
Perimeter	0.88	0.24	0.21
Fractal dimension	0.85	0.11	0.16
Acoustic intensity	0.23	0.93	–0.03
Horizontal roughness	0.18	0.88	0.24
Vertical roughness	0.19	0.92	0.21
Skewness	0.34	0.25	0.88
Kurtosis	0.29	0.10	0.91
Variance explained	4.70	2.84	2.03
% of total	42.80	25.85	18.53

4. DISCUSSION

The occupation of space by fish may not always be the same. The shape, size and density of schools may vary appreciably from species to species and within species, from age class to age class. Within species, school characteristics might also be dependent on external factors such as hydrological features and the presence or absence of predators and prey. The species composition of schools might also influence both the vertical distribution and schooling behaviour of pelagic fish [18]. Internal and external factors may therefore interact in a complex manner, making the modelling of school structures and behaviour difficult.

The general trend observed here in which the horizontal dimensions of schools are significantly larger than the vertical extent is in accordance with previous findings for herring [8, 27]. During the present study, it was presumed that schools have a circular shape and therefore only the ratio of length to height is of relevance for comparisons to earlier studies. In this study length to height ratios varied between surveys (survey 1 = 3:1; survey 2 = 2:1; surveys 3 and 4 = 4:1) with an average ratio for all surveys of 3:1 (SE = 0.12). The fractal dimension revealed that sardine schools had a regular shape.

Of the factors which may affect school shape, one study suggested that faster swimming schools would be more elongated than slower swimming schools [7], whilst another found that schools became more spherical with an increase in swimming speed [26]. During this study, swimming speed of schools was not measured and therefore determining directly whether it was a factor contributing to the variability of school shape is not possible. A factor that may have played a role in the variability of elongation between surveys is the difference in size of the fish. During the third and fourth surveys, the mean length of fish was larger than during the first and second surveys. If the swimming speed of sardine is proportional to body length as suggested by studies on other schooling fish species [6, 16, 20], this would explain the greater elongation of schools during the third and fourth surveys.

Investigations into the relationships between school geometry and school biomass revealed significant relationships between the back-scattered echo energy and the area or volume of the schools during all surveys. An underlying principle for the existence of such relationships is that individuals performing synchronised and polarised swimming, must form compact high-density units [26], which create proportionality between the biomass and geometric dimensions. School dimension to school biomass relationships found during this study are in accordance with a previous finding [27] in which it was concluded that school volume is proportional to the number of individuals in a school. The existence of such relationships also supports the ‘behavioural rules’ that apply to schooling individuals [25, 26]. This ‘rule’ states that individuals in a school maintain a minimum approach distance to each other and prefer a certain distance and direction to their neighbours. It is therefore obvious that proportionality must exist between the total volume occupied and the number of fish in a school.

The variations seen in the relationship between school geometry and school biomass are probably to some extent because of the positions of transects through schools that were not circular [19]. In addition, large variations in packing density exist between schools because of the internal dynamics of a moving mass of individuals [21]. The fact that the area to biomass and volume to biomass relationships are equally strong indicates that both the horizontal and vertical dimensions are important determinants of school size. In a similar analysis of herring, sprat and saithe schools, the horizontal dimension was the most important determinant of school size [19]. In a recent study focusing on sardine schools, stronger relationships between school volume and school biomass than school area and school biomass were established [23], indicating the importance of the vertical dimension on the size of schools. The existence of relationships between school geometry and school biomass is of significance if comparative echo sounder and sonar studies are performed in the future, as planned in the Southern African region.

Mean packing densities measured during this study are much lower than those measured for herring [21, 22]. If packing density is inversely related to fish length according to the relationship established for free-swimming herring schools [10], a mean packing density for sardine of between 10 and 20 fish·m^{-3} should be expected. Indeed, another study of sardine packing density off South Africa [23] indicated a mean density of 29.5 fish·m^{-3}. These fish were only slightly smaller (15 cm), but threshold values for shoal recognition were higher. Furthermore, density was measured using a SIMRAD EK500 echo sounder rather than the older EK400 model used during the present study. The EK500 has a wider dynamic range than the older EK400 model, which did not respond linearly to high voltages and saturated. This level of receiver saturation has been estimated at around –29 dB [5] and could easily account for a decrease in mean back-scattered energy of up to 90 % in a dense sardine school. The packing density estimates presented in this study are therefore too low and current studies using data collected with an EK500 echo sounder show much higher estimates.

The comparison of school characteristics in this study has allowed for the determination of those acoustic variables which best describe the nature of sardine schools. In this study, it was apparent from multivariate analyses that school description was dominated by two composite descriptors, the morphology and energetics, the former being the most dominant. Other studies concerning the characterisation of patches have shown similar results with geometry and echo intensity being the principle factors [3, 32–33].

5. CONCLUSION

The fact that sardine school characteristics in this study did not differ between surveys could indicate an inherent temporal and spatial stability in sardine school structure. It is noted that all surveys were carried out during the same season, in similar areas with no strong hydrological features and where sardine were the dominant species present. It is therefore essential that this study be expanded to cover wider geographic and hydrological ranges and situations where species compositions are different in order to validate the results. Future work addressing the problem of species identification could also benefit by concentrating efforts on establishing differences of a morphological nature between schools of co-occurring fish.

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