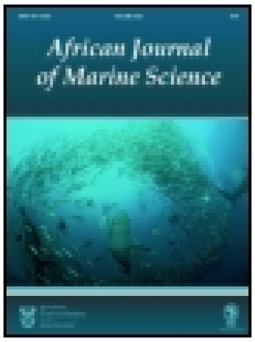

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Indicators of sustainable fishing for South African sardine *Sardinops sagax* and anchovy *Engraulis encrasicolus*

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Six indicators were investigated for South African sardine *Sardinops sagax* and anchovy *Engraulis encrasicolus*: mean length of catch, length-at-50% maturity, total mortality, exploitation rate, ratio of bycatch, and centre of gravity of commercial catches. Sardine length-at-50% maturity is the most promising as a descriptive indicator because it is positively correlated with population size for an extensive time period (1953–2005). The remaining indicators were limited by shorter data-series (1984–2005). However, mean length of catch, ratio of bycatch and exploitation rate were found to be useful when considered in conjunction with other indicators. The centre of gravity of commercial sardine catches has shown a significant eastward shift from the West Coast, whereas that of anchovy has remained off that coast. Ratio of bycatch indicates that school composition is a reliable descriptive indicator of relative abundance in the two species. Fewer indicators for anchovy were useful, which is attributed to this species' flexible life-history pattern.

Keywords: anchovy, biological indicator, exploitation, maturity, pelagic, sardine

Introduction

The importance of indicators in developing sustainable fisheries was acknowledged in 1992 at the United Nations Conference on Environment and Development (UNCED; United Nations1992) with the UN Commission on Sustainable Development emphasising that indicators should provide a basis for decision-making and thereby contribute to a self-regulating system of sustainable development (United Nations 1994). 'Indicators should reflect the state of the system with respect to societal goals and objectives' (Garcia *et al.* 2001 p 3) and should provide information about target species and the fisheries they support by communicating crucial technical information to non-technical users (Garcia and Staples 2000).

A range of population indicators derived from fishery-dependent and -independent data for sardine and anchovy in South African waters were investigated for their suitability for management purposes. This study was part of the EU INCO-DEV Knowledge base for fisheries management (KNOW-FISH) project (Degnbol 2005) whose objective was to understand the information needs for fisheries management in developing countries (Degnbol 2005, Fairweather *et al*. 2006). Indicators of resource or ecosystem health and exploitation status were developed to answer questions posed by fishery stakeholders during social analysis (Fairweather *et al.* 2006), and emphasis was placed on developing indicators that were robust, but less complex than stock assessment model-based indicators. In this context, the indicators discussed below were derived as part of an exploratory process rather than a structured process of deriving indicators with a specific management objective in mind.

South Africa has a large purse-seine fishery that harvests predominately sardine *Sardinops sagax* and anchovy *Engraulis encrasicolus*. Total catches have remained relatively stable over the past 50 years, at around 375 000 tons per annum, although the relative contribution by sardine and anchovy has fluctuated (van der Lingen *et al.* 2006b). Decadal-scale alternating periods of dominance of these two species has been observed in the southern Benguela, a phenomenon associated with all major eastern-boundary upwelling systems (Baumgartner *et al.* 1996, Schwartzlose *et al.* 1999). Together with high inter-annual variability in recruitment (Barange *et al*. 1999), this complicates management of the pelagic fishery.

Sardine are either canned or frozen for human (and pet) consumption and anchovy are reduced to fishmeal and oil. The anchovy fishery targets juvenile fish (~6 months old) in the nearshore waters of the West Coast (Figure 1), where most of the processing capacity is located. Because juvenile sardine shoal with anchovy up to approximately 6 months of age, bycatch of juvenile sardine in anchovy-directed fishing operations is a major complicating factor in the management of these resources.

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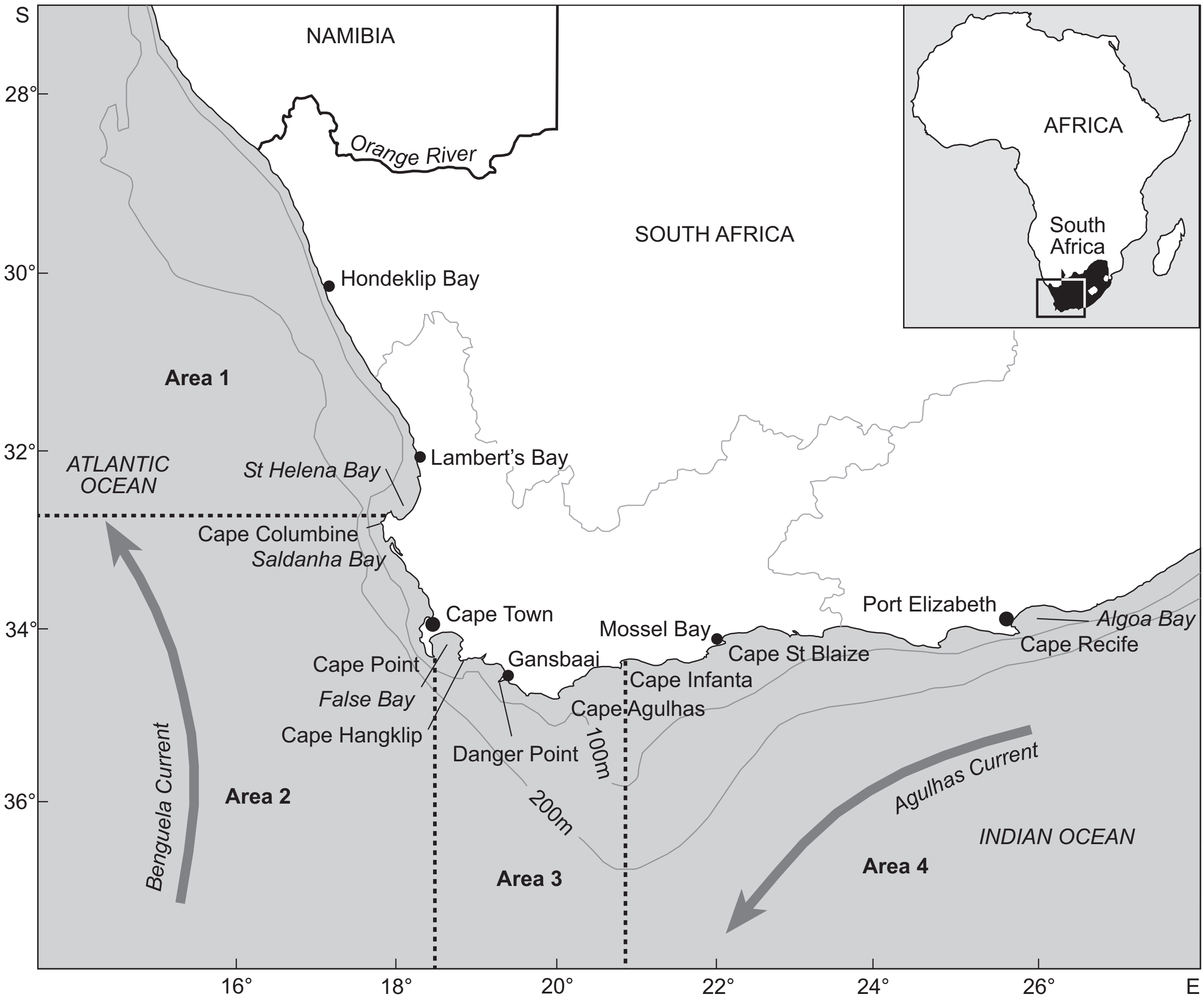

Figure 1: Map of South Africa showing the location of bays and capes along the coastline, the continental shelf and the Agulhas and Benguela currents (after van der Lingen and Hugget 2003). Commercial fishing areas are delineated by dashed lines. The West Coast is defined as extending from Cape Point northwards, the South Coast from Cape Point to Port Elizabeth and the East Coast from Port Elizabeth eastwards

South Africa's pelagic fishing sector is managed by catch control, and uses an Operational Management Procedure (OMP) to make recommendations regarding separate annual total allowable catch (TAC) levels for anchovy and sardine. The current operational management procedure (OMP-04) is tuned so as to avoid exposing the resources to undue risk of depletion. Undue risk is defined as the probability of adult biomass falling below the average adult biomass (1991–1994 for sardine and 1984–1999 for anchovy) at least once during the 20-year projection period. For sardine the probability must be <10% and for anchovy <30% (Cunningham and Butterworth 2006).

The sardine TAC applies to adult fish and is set at the start of the calendar year, as is an initial anchovy TAC which has an associated juvenile sardine total allowable bycatch (TAB). Should a right-holder catch either their anchovy TAC or sardine TAB they are required to stop fishing for the remainder of the calendar year. The initial anchovy TAC is based on an assumption of median recruitment strength and is revised to a final TAC with TAB midyear following the May recruit survey. The revised TAC is either equal to or greater than the initial TAC in order to facilitate industry stability.

Because OMP-04 has been designed to maximise catch while minimising the risk of overfishing, it is vital that catches are adequately monitored and accurately reported. Comprehensive monitoring of landings is expensive and may not necessarily be an effective measure of compliance (Cochrane *et al.* 2004). However, it may be possible to use data collected from commercial catch samples to provide further information on the status of the stocks.

The focus of this paper is on the development of six 'biological' indicators derived from commercial catch data and samples collected during research surveys that can be used as adjuncts to the management of South Africa's sardine and anchovy fisheries. These indicators are (1) mean length of the catch, (2) length-at-50% maturity, (3) total mortality, (4) exploitation rate, (5) centre of gravity of the catches and (6) ratio of bycatch in directed fishing. We describe the theoretical background underpinning each indicator and its mathematical derivation, provide time-series of each which are compared with annual landings or spawner-stock biomass, and discuss possible management implications of this suite of indicators.

Material and Methods

Commercial catch data

All commercial catch records reported are referenced to 10' x 10' grid blocks, which for the purpose of this study were grouped into four areas: Area 1 is north of Cape Columbine, Area 2 is between Cape Columbine and Cape Point, Area 3 is between Cape Point and Cape Infanta, and Area 4 is east of Cape Infanta (Figure 1). Vessel skippers are required to report the grid block in which each purse-seine set is located and estimate the tonnage of each species in catch. The total mass and species composition of the landed catch (which is usually from more than one setting of the net) is then collected by fisheries inspectors and/or monitors at designated landing points. The tonnage of each species per set is then estimated from the total tonnage landed and the skippers' estimate of the species composition of each set. For example, given a landed catch of 88.34 tons of anchovy and a skippers' estimate of 30 tons total catch from Grid 3465 and 80 tons from Grid 3466, the anchovy catch for Grid 3465 is calculated as:

$$\text{Anchovy catch}\left(\text{Grid 3465}\right) = \frac{30}{30+80} \times 88.34 = 24.09$$

These 'composition by set' data were used to investigate spatial and temporal variations in catch.

Commercial catches were sampled at field stations adjacent to factories where the majority of the catch is landed for processing: data on species and size composition and biological characteristics were collected. The number of fish in each 0.5cm length-group was recorded for the sample (n = 100), and length frequencies for the daily samples grouped by area, week and species. Landings were likewise grouped by grid block, week and species. Landings that were not sampled were assigned to the most appropriate grouped length frequency by target species by searching to within two weeks of the specified week and to within two grid blocks of the assigned grid block. Identification of the target species is crucial, because the length frequency of bycatch sardine would be dominated by small fish and it would therefore be inappropriate to assign to a sardine-directed landing of large fish. Once each landing was matched to the length frequency, the length frequency was raised to reflect the weight of the total catch landed and an annual raised length frequency (RLF) table was produced (De Oliveira 2002).

Biological samples (n = 25 of fish >10cm standard length [SL]) of sardine have been taken as subsamples from field station (FS) commercial catch samples since 1953 (excluding 1955 and 1995). Data collected included measurements of SL, mass, sex, gonad mass and macroscopic gonad maturity stage (Davies 1956). Smaller sardine taken as bycatch and anchovy were not similarly sampled because landed catches are generally in a partially decomposed condition — as they are processed as fishmeal, and hence are not refrigerated.

Acoustic survey data

The spawner-stock biomass of pelagic species off South Africa has been estimated annually since 1984 using acoustic survey data (Barange *et al.* 1999). Prior to those surveys, biomass estimates were derived (between 1953 and 1982) using virtual population analysis (VPA) (Butterworth 1983). Although these time-series are not strictly comparable, they are combined to illustrate trends in population size (Table 1). VPA is also likely to have underestimated biomass because the age-length key used at the time has since been considered to be incorrect (Beckley and van der Lingen 1999).

Biological data collected during the spawner biomass surveys (SBS) conducted in November of each year (excluding 1985 owing to paucity of data) include measuring each fish (measured in 0.5cm SL groups) and assigning it a macroscopic maturity stage into one of four categories: immature and female Stage 1; female Stages 2, 3 and 7; female Stages 5 and 6; and males (Davies 1956).

Mean length of catch

Mean length of the catch ($\bar{L}$) was estimated from samples of commercial landings for sardine ($\bar{L}_S$) and anchovy ($\bar{L}_A$). Crawford (1981) suggested that the availability of sardine of different ages (i.e. different sizes) varies both spatially and temporally; hence annual $\bar{L}$ for each area (spatial variability) and a monthly $\bar{L}$ for each year (temporal variability), in addition to a total annual $\bar{L}$ calculated over all months and areas, was estimated for both species.

Annual RLF tables have been produced since 1984. However, because data from 1984 to 1986 are not area specific, they were omitted from the analysis. The RLF data-series is relatively easily collected, is likely to be continued into the future, and is ideally structured for use in calculating a weighted mean length of catch:

$$\bar{L} = \frac{\sum_{i=1}^{L} C_i L_i}{\sum_{i=1}^{L} C_i} \qquad (1)$$

where L_i is the length of length-class i and C_i is the catch in numbers for each length-class i. Trenkel and Rochet (2003) included discard estimations in total catch, but for the purpose of this study it is assumed that fish were not discarded because there are no estimates that can be used with certainty, particularly at the level of length-frequency

Table 1: Spawner biomass estimates for sardine (1950–1982 from Butterworth 1983), anchovy and round herring (all estimates post 1984 are derived from hydroacoustic surveys); annual catch totals for sardine, anchovy and round herring (from MCM); and the total allowable catch (TAC) and bycatch allowance for the pelagic fishery (1987–2005)

	Spawner biomass estimates (thousand tons)			Annual catch totals (thousand tons)				TAC (thousand tons)				
								Anchovy*		Sardine		
Year	Sardine	Anchovy	Round herring	Anchovy	Sardine directed	Sardine bycatch	Round herring	Season 1	Season 2	Direct	Bycatch 1	Bycatch 2
1949					19.86							
1950	850				85.30							
1951	855				101.90							
1952	675				170.00							
1953	635				132.50							
1954	535				88.30							
1955	620				121.90							
1956	840				76.60							
1957	1 200				109.50							
1958	1 480			0.20	194.40		0.80					
1959	1 700			1.40	260.20		2.60					
1960	1 615			0.00	318.00		0.10					
1961	1 385			0.00	402.20		0.10					
1962	1 050			0.00	410.20		0.10					
1963	730			0.30	390.10		0.20					
1964	500			92.40	256.10		2.70					
1965	260			171.00	204.50		8.20					
1966	115			143.90	118.00		15.40					
1967	120			270.60	69.70		32.00					
1968	140			138.10	107.80		30.30					
1969	145			149.20	56.10		23.30					
1970	150			169.30	61.80		23.70					
1971	155			157.30	87.60		21.60					
1972	110			235.60	104.20		20.60					
1973	120			250.90	69.00		28.70					
1974	180			349.80	16.00		1.30					
1975	230			223.60	89.20		23.60					
1976	120			218.30	176.40		11.70					
1977	110			235.50	57.80		35.00					
1978	105			209.50	97.00		67.00					
1979	75			291.40	52.90		21.00					
1980	55			315.50	50.40		14.10					
1981	50			292.00	46.20		24.30					
1982	50			306.10	35.20		31.20					
1983				235.00	65.40		68.50					
1984	32	1 067		268.90	29.50		27.00					
1985	54	975		277.00	29.60		37.70					
1986	160	1 747		303.80	35.40		52.30					
1987	129	1 456	749	595.90	23.55	10.79	33.30	600		26		
1988	113	1 104	463	570.00	26.23	10.00	62.60	600		26		
1989	286	536	1 036	294.00	19.34	15.40	44.60	300		20		
1990	263	469	700	150.00	41.44	15.50	44.70	150		42		
1991	441	1 682	971	150.70	38.77	13.16	33.40	150		37		
1992	327	1 501	1 180	347.40	31.97	21.43	47.40	350		32		
1993	464	800	717	235.82	29.41	21.29	56.33	360		27		
1994	597	476	518	155.55	48.95	44.48	54.14	150		50	45	
1995	620	432	857	170.27	72.71	42.48	76.66	210		75	42	
1996	505	143	984	40.71	76.26	28.94	47.11	70		76	29	
1997	792	919	984	60.10	89.74	27.15	92.20	60		88	50	
1998	1 442	897	1 977	107.55	104.08	24.10	52.48	175		106	34.6	
1999	1 338	1 355	2 250	180.54	117.93	14.13	58.86	146	85	136	24.4	2
2000	1 361	3 308	2 327	268.00	123.00	11.80	37.00	191	100	126	26.2	2
2001	1 586	4 393	1 381	287.19	172.37	18.96	55.33	371	80	182	38.4	2
2002	2 543	2 555	1 421	213.44	244.00	16.60	54.80	260	100	258	42.5	2
2003	2 215	2 557	2 757	258.95	274.10	15.90	42.50	185	100	280	22.5	2
2004	1 920	1 313	2 516	190.09	365.81	8.03	47.21	273	150	457	57.2	2
2005	640	1 795	2 544	282.72	240.23	6.41	28.39	215	100.89	397	48.5	2

* Season 1 is the main anchovy TAC allocated in January with associated sardine Bycatch 1. The anchovy TAC for Season 2, with associated sardine Bycatch 2, was introduced in 1999 to take advantage of the 'clean' anchovy schools usually available to the fishery between August and September when the sardine have grown and formed their own schools

distribution. Fish discarded by the fishery are most likely to be small sardine because bycatch is limited and greater profit is achieved by landing large canning-size fish. Therefore, it is likely that $\bar{L}$ is larger than it would be if discards were included.

Because the variance of each length-class was not available, the standard deviation from grouped data (Fowler *et al.* 1998) was modified to account for large sample sizes:

$$SD = \sqrt{\frac{\sum_{i=1}^{L} C_i\left(\bar{x}_i - \bar{L}\right)^2}{\sum_{i=1}^{L} C_i}} \quad (2)$$

where C_i is the number of fish in the length-class i and $\bar{x}_i$ is the mean of the length-group range that encompasses the numbers of fish measured (i.e. $\bar{x}_i = \sum_{i=1}^{L} L_i / n$).

Length-at-50% maturity

In this study, length-at-50% maturity (L_{50}) is defined as the length-class at which 50% of female fish sampled are sexually mature. Davies (1956) found that the South African sardine spawning season extends mainly from September to February; active/ripe females were found to be present on the western Agulhas Bank from August 1993 to March 1994 (Akkers *et al.* 1996) and Armstrong *et al.* (1989) found no difference in sardine maturity patterns between sardine on the South and East coasts. Changes in L_{50}^{S} were examined for both the commercial field station (FS) and spawner biomass survey (SBS) datasets.

The commercial data, the longer time-series, were limited to samples collected between January and March in each year, because this period is more consistently fished than October–December and therefore has greater spatial coverage. Fish <12cm SL were considered immature (Armstrong *et al.* 1989) and were not included in the analyses.

Armstrong *et al.* (1989) calculated standardised gonad mass (SGM) to be ($10^3 \times W) \times L^{-3}$, where W is ovary mass in g and L is the standard length in cm. Those authors concluded that a SGM >0.25 could be used as a guideline in assuming maturity in sardine. This study followed their guideline for FS samples, but for SBS samples we considered all female fish having gonads in Stages 2–7 to be mature.

The predicted proportion of female fish mature, $\hat{p}_i$, at each 0.5cm length-group L_i was calculated from a logistic function as:

$$\hat{p}_i = \left(1 + \exp(-(L_i - L_{50})/\delta)\right)^{-1} \quad (3)$$

where δ is the inverse rate of maturity. The maximum likelihood estimates for the parameters were obtained by non-linear minimisation of the negative of a binomial likelihood of the form:

$$-\ln L = -\left[\sum_{n} m_i \ln\left(\frac{\hat{p}_i}{1 - \hat{p}_i}\right) + n_i \ln(1 - \hat{p}_i)\right] \quad (4)$$

where m_i = total number of mature females and n_i the number of immature females sampled in each length-class i, respectively.

Estimates of parameter variability were obtained through parametric bootstrapping with 450 re-samples (Efron and Tibshirani 1986). The pseudo-data were assumed to be binomially distributed, such that for each bootstrap iteration the pseudo-number of mature fish in each size-class was generated from the original number of fish sampled in each size-class and a random binomial variate given the model-predicted proportion of mature fish in that size-class. Confidence intervals were constructed from the sorted bootstrap results using the percentile method outlined by Buckland (1984).

Because the commercial anchovy catch is generally landed in a partially decomposed state, preventing biological sampling, L_{50}^{A} is based on gonad stage observations collected during the annual spawner biomass survey in November. It is assumed that all Stage 2–7 fish are mature. The formulae used to calculate the annual maturity ogives and standard deviation given above is without the assumption of minimum size as with sardine.

Total mortality

Die and Caddy (1997) suggest that monitoring total mortality (Z) would be more precise than monitoring fishing mortality (F) as a target reference point, because M and F are interrelated. They suggest the expression presented by Beverton and Holt (1957), relating total mortality and average size in the catch, is suitable for determining total mortality:

$$Z = \frac{\left(L_\infty - \bar{L}\right)K}{\bar{L} - L_c} \quad (5)$$

where K and L_∞ are the von Bertalanffy parameters of the species, $\bar{L}$ is the average length of fish in the catch, and L_c is the size at first capture calculated as the first 0.5cm length-group which accounted for at least 10% of the cumulative catch. Die and Caddy (1997 p 74) state that there is an assumption that 'on average a fish will be mature before it is caught', which is plausible for the sardine-directed fishery but not for the anchovy-directed recruit fishery.

An underlying assumption is that there is constant recruitment. It has been argued that higher M for recruits in years of larger recruitment reduces the variability (Macpherson *et al*. 1997), and the current stock assessment models for both sardine and anchovy use hockey-stick stock-recruit relationships (Cunningham and Butterworth 2004a, 2004b). In addition, this is the only option available for estimating Z from biological parameters and not using a model output.

Exploitation rate

To avoid stock collapse, fisheries management relies on maintaining a stable spawner-stock biomass (Patterson 1992, Trenkel and Rochet 2003). Patterson (1992) suggests that, where there are little or poor-quality data on spawner-stock biomass, the exploitation rate can be used to manage a fishery towards a stable spawner-stock biomass. Exploitation rate (E) is defined as the proportion of total mortality caused by fishing (Baranov 1918) and referred to as a measure of fishing intensity (Patterson 1992). Annual exploitation rate is calculated as:

$$E_i = \frac{F_i}{Z_i} \quad (6)$$

where

$$F_i = \frac{C_i}{N_i} \quad (7)$$

where N_i is the annual abundance estimates from the spawner biomass survey (Table 1) and C_i is the annual total commercial catch (Table 1). Including discard estimates would be ideal but this cannot be achieved with certainty. As such, it is assumed that there is no discarding of catches. Acoustic data (required for an accurate spawner biomass estimate) are only available from 1984 onwards, which restricts the time period analysed.

Centre of gravity of catches

The centre of gravity (CoG) can be considered as a spatial mean, and is typically represented by a centroid with minor and major axes (Bez and Rivoirard 2000). In this case, the centroid is the weighted mean position of all catches for a specific time period, and the axes represent the extent of the variance of those catches (i.e. quantifying the spatial dispersion).

The annual directed sardine catch at each catch (grid) position was calculated from 'composition per set' data (see above), which were only available from 1987 onwards. Directed sardine catch was defined as catches where sardine constituted 50% or more of the commercial landing by mass.

Given the topography of the South African coastline, with the West Coast being almost perpendicular to the South Coast, it was decided to linearise ('straighten') the coastline to aid both interpretation and explanation of the data. Using a non-linear coastline would result in the majority of CoG points being located inland.

A classical geometrical approach was used to linearise the coastline. The first step consisted of segmenting the coast into five distinct major coastal orientations.

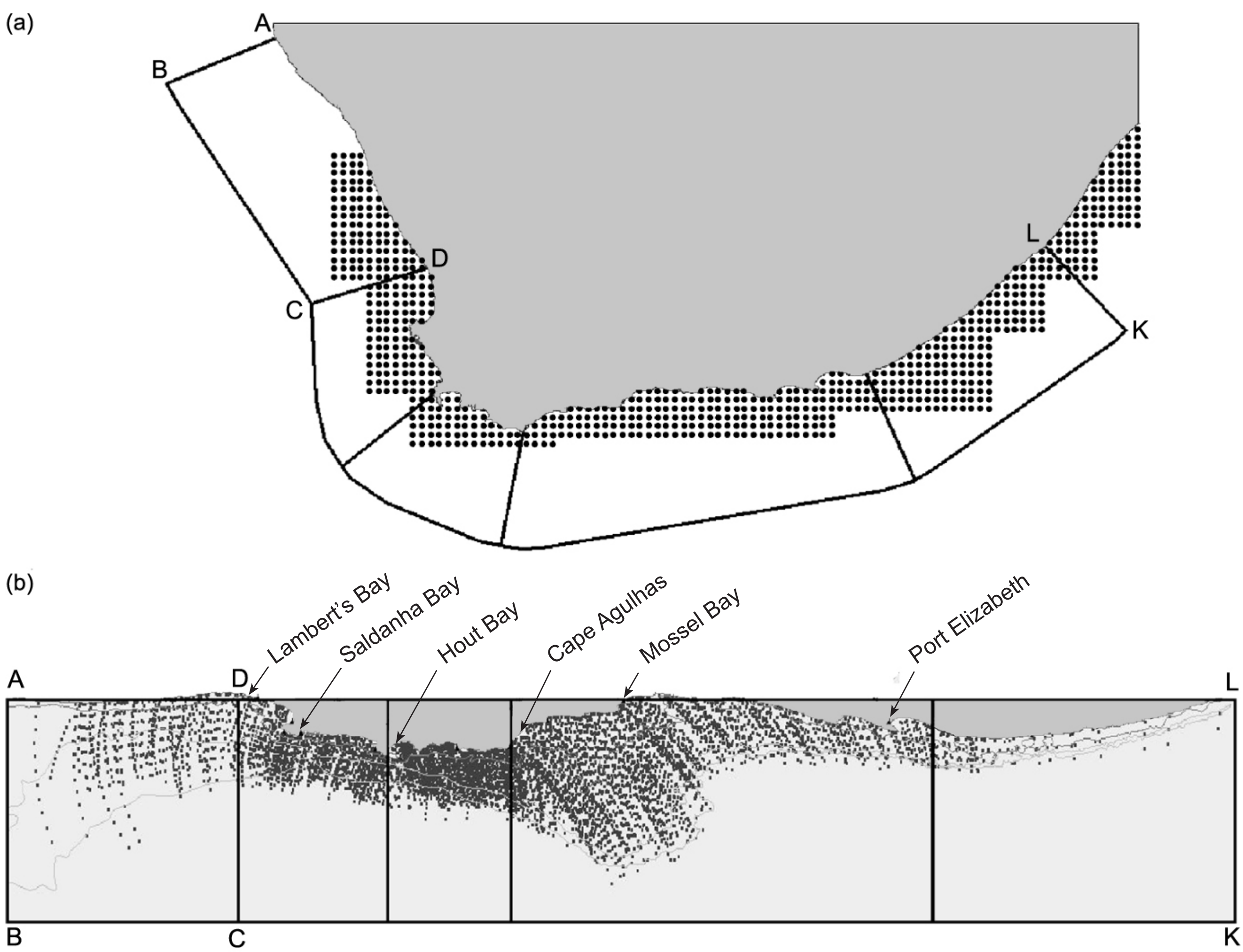

Figure 2: (a) South African coastline and pelagic commercial grid reference system, trapezoids (e.g. ABCD) segment the coast into a reasonable number of distinct lines which identify major coastal direction changes; (b) linearised coastline and pelagic commercial grid reference system

Trapezoids were delimited by the coastal segments, and bisectors associated with each angle and extended out to encompass the 200nm exclusive economic zone were created (Figure 2a). These areas (trapezoids) are homogeneous, and point locations can be transformed without major distortions.

Each area was geometrically transformed into a rectangle (Figure 2b) using a Lagrangian polynomial transformation (Séroul 2000). Such a transformation guarantees the precise transformation for each of the control points at the expense of straight line distortion. All areas are then combined into a complete linearised coastline and its associated offshore zone and can be analysed as a homogenous rectangle.

The transformation allows spatial analysis in a rectangular area where the horizontal direction is associated with longshore movement while the vertical dimension is associated with offshore movement. New co-ordinates for each pelagic commercial catch grid were used to calculate the CoG of the sardine catches on a linearised coastline.

The centroid of the centre of gravity of catches $\left(\bar{u}_{lat}, \bar{u}_{long}\right)$ was calculated as follows:

$$\bar{u}_{lat} = \frac{\sum_{i=1}^{n} p_i \times lat_i}{\sum_{i=1}^{n} p_i} \qquad (8)$$

and

$$\bar{u}_{long} = \frac{\sum_{i=1}^{n} p_i \times long_i}{\sum_{i=1}^{n} p_i} \qquad (9)$$

where p_i is the proportion of the total catch (C_i) of a species at a specific latitude lat_i and longitude $long_i$ (i.e. each catch record), $p_i = \frac{C_i}{\sum_{i=1}^{n} C_i}$ and n is the number of catch records.

The variance (σ^2) for each annual latitude and longitude is calculated as:

$$\sigma^2_{lat} = \frac{\sum\left[lat_i - \bar{u}_{lat}\right]^2}{N} \qquad (10)$$

and

$$\sigma^2_{long} = \frac{\sum\left[long_i - \bar{u}_{long}\right]^2}{N} \qquad (11)$$

The centroids and their coefficient of variation, mapped as perpendicular axes, were plotted against the linearised coastline using ArcGIS (v.9 www.esri.com) to determine if there were significant differences between annual centroids. The CV were calculated as:

$$CV_{lat} = \frac{\sqrt{\sigma^2_{lat}}}{\bar{u}_{lat}} \qquad (12)$$

and

$$CV_{long} = \frac{\sqrt{\sigma^2_{long}}}{\bar{u}_{long}} \qquad (13)$$

Ratio of bycatch

Bycatch is a crucial management issue for the South African pelagic fishery. Categorisation of catch was first formally attempted in 1998, by means of a flowchart that was distributed to landing points for use by inspectors and monitors (Payne 1998). This was initiated because the fishery was thought to be targeting adult sardine for bycatch and thus exceeding the sardine TAC (Anon. 2003). In September 2002 it emerged that vessels were possibly targeting juvenile sardine and landing them as directed catch. The flowchart was revised (Figure 3) and implemented in April 2003 (Anon. 2003). The crucial difference between the two flowcharts is that sardine were considered large (i.e. adult) if >16.5cm TL (13.4cm SL) in 1998 as opposed to >14cm TL (11.3cm SL) in 2003. Furthermore, in

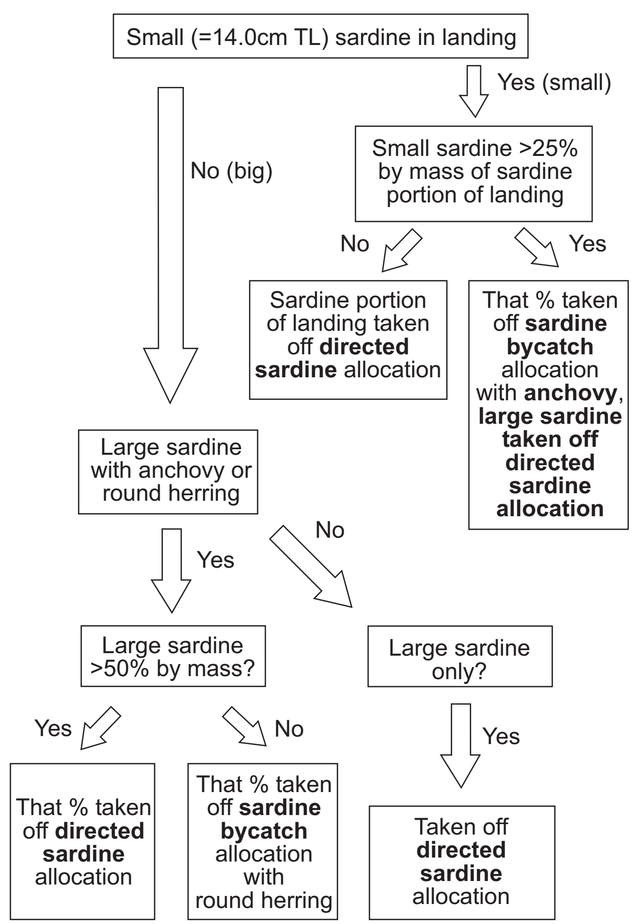

Figure 3: Sardine categorisation flowchart issued by Marine and Coastal Management for use at pelagic fishery landing points around the South African coastline (Anon. 2003)

1998 if more than 30% of the catch was sardine, it was considered sardine-directed; in 2003 this was changed to >50%.

What has remained consistent between iterations is that, if adult sardine catch is determined to be bycatch, it is taken off the round herring *Etrumeus whiteheadi* bycatch allocation. However, if juvenile sardine constitute >25% of the catch, the landing is taken off the anchovy bycatch allocation, regardless of whether the catch was directed at anchovy or not. There is an additional issue of whether the flowcharts have ever been properly implemented, which could not be resolved by this study and, thus, it is assumed that their implementation was successful.

The ratio of one species (x) caught in fishing effort directed at another species (i) was estimated separately for anchovy-directed fishing R_xB_A, sardine-directed fishing R_xB_S and round herring-directed fishing R_xB_R. Fishing was considered to be directed at a species when that species contributed >50% of the landing.

Table 2: Annual length-at-50% maturity (1999–2005) for sardine and the size constraints presented in the 1998 and 2003 categorisation flowcharts, rounded down to give the nearest 5mm length-group

Size constraint	Standard length (cm)	Nearest length-group
1999 L_{50}	19.90	19.5
2000 L_{50}	19.62	19.5
2001 L_{50}	18.96	18.5
2002 L_{50}	18.75	18.5
2003 L_{50}	20.45	20.0
2004 L_{50}	19.13	19.0
2005 L_{50}	16.95	16.5
1998 flowchart	13.40 (16.5 TL)	13.0
2003 flowchart	11.30 (14.0 TL)	11.0

The ratio of the three target species to the total catch of each throw was calculated as follows:

$$\text{Ratio of target species i} = \frac{\text{Target species i}}{(\text{Total catch} - \text{sardine bycatch})} \qquad (14)$$

Since the TAC system has been in place, the sardine catch has been allocated as either directed or bycatch, so it would therefore be illogical to include catches explicitly considered as bycatch with the total catch for a throw when determining the target species for each throw. Only 0.2% of the throws between 1987 and 2004 did not have a target species and were not used in the analysis. Once throws had been designated as anchovy-, sardine- or round herring-directed, the ratio of bycatch relative to those catches was calculated as an annual total. The ratio of bycatch (R_xB_i) was calculated as follows:

$$R_xB_i = \frac{\text{Non-target species x}(\text{tons})}{\text{Target species i}(\text{tons})} \qquad (15)$$

In addition, spatial (four areas, as in Figure 1) and temporal (quarterly time periods: January–March, April–June, July–August and September–December) variability in bycatch were investigated.

To determine what percentage of sardine catch was adult in sardine-directed, anchovy-directed and round herring-directed fishing, two possible cut-off points were compared. These were the annual sardine and the size constraints presented in the 1998 and 2003 flowcharts. These values were rounded down to the nearest 5mm length-class (Table 2), with the number of fish within each size range for each cut-off point calculated from catch length frequencies for each year.

Table 3: Monthly and annual mean standard length of sardine catch for the period 1987–2004

	Standard length (cm)													
Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual	L_{95}
1987	18.00	17.87	16.69	15.73	11.79	9.91	9.20	9.25	9.14				12.90	19.50
1988	17.98	16.89	16.52	18.52	10.70	10.58	11.42	12.86	11.90	10.52	13.73		12.48	20.50
1989	16.71	14.08	14.97	13.36	9.50	9.72	12.82	20.48					11.60	20.50
1990	15.57	18.55	14.03	10.07	10.15	9.25	18.70	19.94	19.76	19.59	18.87	17.71	11.77	21.00
1991	16.88	16.11	10.20	12.99	16.18	11.91	17.00	18.81	19.37	19.78	19.88	20.20	13.62	20.50
1992	15.89	17.39	17.07	9.61	9.39	10.20	9.35	10.79	16.27	18.07	19.05		10.92	20.00
1993	14.62	17.24	15.43	12.78	9.83	12.83	9.12	8.29	9.18	11.55	17.42	17.49	11.33	20.00
1994	12.38	13.00	15.31	12.54	11.73	11.10	18.65	12.98	17.81	18.91	18.51	17.99	13.02	19.50
1995	17.63	18.23	12.99	13.01	10.69	9.31	9.22	10.59	15.27	14.73	13.69	19.00	11.09	19.50
1996	11.88	14.34	14.85	13.78	12.80	11.24	18.34	18.90	18.57	17.71	18.39	18.50	14.65	20.50
1997	13.08	16.46	18.19	18.75	18.05	17.84	12.70	18.40	11.55	12.85	18.11	19.31	14.61	20.00
1998	16.32	17.31	17.29	11.18	9.63	10.88	14.13	16.11	13.38	18.81	19.13		13.06	20.00
1999	18.31	18.25	14.83	13.94	13.79	12.45	15.37	14.38	13.74	15.33	18.27	18.63	14.77	20.00
2000		17.80	12.91	12.72	14.76	15.04	13.98	15.73	11.48	14.80	18.05	18.00	14.30	19.50
2001	18.22	17.45	16.80	15.09	12.45	10.26	12.23	10.69	12.11	15.59	17.55	17.48	13.75	19.50
2002	12.49	16.73	16.79	15.88	15.04	11.52	10.59	10.20	13.96	16.86	16.77	16.92	13.84	19.00
2003	17.47	17.50	15.71	13.46	11.08	11.36	13.47	15.79	14.43	14.28	16.50	17.35	14.23	19.00
2004	17.25	16.51	16.70	14.18	12.87	15.02	13.82	14.20	15.89	17.27	16.90	17.32	15.34	19.00
2005	18.07	17.40	16.31	15.11	14.33	17.03	13.69	16.41	16.59	16.88	18.43	17.94	15.92	20.00

L_{95} = Length below which 95% of the catch is found

Results

Mean length of catch

Monthly and annual mean lengths of sardine were highly variable (Table 3). There were relatively few large sardine caught until 1991, and since 1999, the majority of large sardine have been caught in the last quarter of the year. Small sardine dominated the sardine catch in Area 1, following the dominant catch distribution of anchovy. The majority of the catch (including large sardine) was taken in Area 2 until 1999, coincident with an increasing proportion of the catch from Areas 3 and 4, which was dominated by large fish (Figure 4). Landing points/factories were built in locations central to catches in order to minimise fuel costs of the fishing vessels. The fishery follows the fish and in the case of sardine-directed fishing, vessels will search for large fish and thus will influence the mean size of the catch in different areas.

Monthly $\bar{L}_A$ for anchovy is variable, but has followed a relatively consistent pattern of being larger in the first and last quarters of the year (Table 4). This is more obvious in

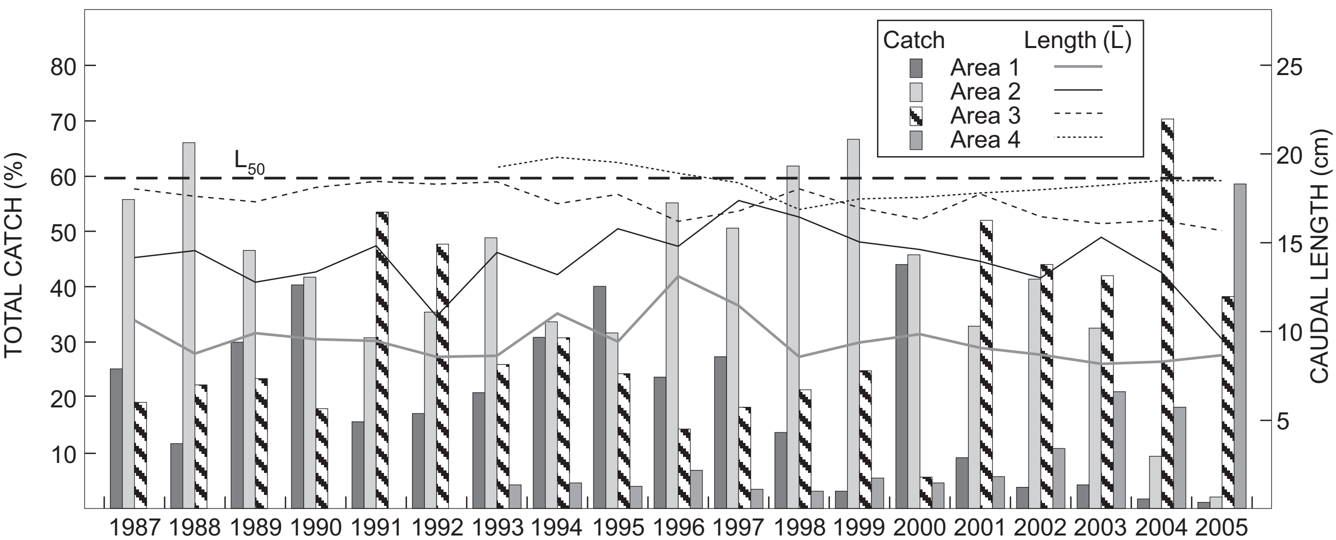

Figure 4: Annual mean standard length ($\bar{L}$) of sardine catch for the four fishing areas of South African coast (1987–2005) and the proportion of annual sardine catch taken in each area

Table 4: Monthly and annual mean standard length of anchovy catch for the period 1987–2005, and the annual mean standard lengths of anchovy catch per fishing area

	Standard length (cm)																
Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual	L_{95}	Area 1	Area 2	Area 3	Area 4
1987	9.13	9.90	10.28	10.03	8.28	8.81	8.83	8.78	8.63				9.31	11.50	9.18	9.61	9.57	
1988	10.58	10.46	10.47	10.47	8.62	8.20	8.21	8.57	8.67	8.59	10.25		8.88	11.50	8.59	9.41	10.17	
1989	10.20	10.42	10.18	9.43	9.16	8.41	7.86						9.25	11.00	9.16	9.16	9.95	
1990	10.01	7.54	7.18	7.35	7.06	7.46	7.31						7.29	9.00	7.06	7.70	9.94	
1991	9.50	6.69	7.77	7.98	8.73	8.00	7.27	7.79	7.39				7.95	9.50	7.78	8.30	8.87	
1992	10.09	9.55	9.37	7.76	7.52	7.35	7.12	7.41	7.75	7.30			7.63	10.50	7.20	8.58	9.65	
1993	9.54	9.90	10.12	10.13	8.64	7.52	8.03	7.15	7.04	7.21			7.89	10.50	7.86	8.02	8.82	
1994	9.09	9.94	10.26	8.10	7.16	7.04	7.59	8.39	7.96				7.89	11.00	7.42	7.93	10.01	
1995	9.56	8.45	8.54	8.39	6.71	7.24	7.17	7.21	7.59	7.88	8.21		7.39	9.00	7.18	8.49	8.46	
1996	9.41	9.42	8.30	7.87	7.77	7.49	7.81						7.99	10.50	8.75	7.58	7.99	
1997		8.83			8.62	7.91	7.37	7.66	7.92	9.15			7.69	9.00	7.61	7.84	7.91	
1998		10.19	8.54	8.29	7.52	7.27	7.13	7.31	7.84	8.09			7.51	9.50	7.39	8.00	8.84	
1999			9.36	7.63	8.37	7.91	7.74	7.35	7.43	7.65	8.25	8.42	7.65	9.00	7.58	7.99	8.35	
2000		10.61	7.75	8.30	7.85	7.92	7.44	7.58	7.34	7.37	8.95	11.92	7.65	9.00	7.54	7.76	8.39	
2001	10.07	9.80	8.67	8.36	8.05	7.62	6.58	7.63	7.62	7.65	8.16	9.34	7.74	9.00	7.54	8.09	8.37	
2002	10.19	10.11	9.16	8.59	8.85	7.04	6.85	8.09	7.35	7.96	10.62	10.12	7.36	9.50	7.11	8.17	7.99	
2003	6.16	9.31	9.30	7.91	6.63	7.37	6.75	7.38	7.02	7.17	7.68	7.12	7.10	9.00	6.96	7.42	8.11	
2004	7.69	7.58	8.79	8.06	8.37	7.36	7.39	7.45	7.54	8.53	9.89	9.45	7.65	8.50	7.08	7.12	7.88	
2005	9.73	9.21	9.28	9.11	8.26	7.86	7.46	8.08	8.45	8.26	9.98	9.80	8.26	10.00	7.95	8.59	8.78	10.23

L_{95} is the length below which 95% of the catch is found

Table 5: Annual length-at-50% maturity (L_{50}) and associated standard deviation (SD) calculated using fishery-dependent (FS) data for sardine and fishery-independent (SBS) data for sardine and anchovy. Sample size (n) is presented for each annual dataset

	Length-at-50% maturity (cm, SL)								
	Fishery-dependent (FS)			Fishery-independent (SBS)			Fishery-independent (SBS)		
	Sardine			Sardine			Anchovy		
Year	FS L_{50}	FS L_{50} SD	n FS	SBS L_{50}	SBS L_{50} SD	n SBS	SBS L_{50}	SBS L_{50} SD	n SBS
1953	19.79	0.367	512						
1954	20.15	0.192	452						
1955									
1956	20.81	0.128	391						
1957	19.46	0.107	1 022						
1958	18.78	0.093	852						
1959	19.56	0.116	458						
1960	20.02	0.189	848						
1961	18.92	0.077	1 301						
1962	19.53	0.050	1 526						
1963	18.78	0.085	804						
1964	18.31	0.060	1 286						
1965	17.84	0.071	1 077						
1966	16.76	0.339	700						
1967	16.66	0.306	90						
1968	17.65	0.088	684						
1969	16.94	0.115	390						
1970	16.39	0.192	269						
1971	17.86	0.133	508						
1972	16.94	0.088	538						
1973	16.67	0.193	722						
1974	15.32	0.702	266						
1975	16.84	0.235	794						
1976	17.82	0.135	1 156						
1977	16.06	–	245						
1978	16.07	0.110	571						
1979	16.23	0.128	669						
1980	16.11	0.112	752						
1981	16.69	0.150	687						
1982	15.70	0.139	444						
1983	16.55	0.109	885						
1984	17.78	0.117	715	13.61	0.40	148	8.88	0.08	5 212
1985	16.76	0.123	873				8.56	0.06	3 313
1986	17.53	0.107	752	15.37	0.10	502	8.66	0.04	2 686
1987	18.31	0.088	808	14.65	0.11	698	8.05	0.09	3 356
1988	18.23	0.098	645	14.80	0.23	375	7.37	0.23	1 804
1989	19.22	0.115	939	16.33	0.08	1 260	8.39	0.07	2 002
1990	19.15	0.074	1 122	16.00	0.13	646	7.99	–	1 585
1991	17.07	0.262	797	16.01	0.08	948	8.42	0.03	3 210
1992	17.51	0.145	321	16.96	0.15	1 675	8.41	0.03	3 446
1993	16.55	0.167	211	16.02	0.07	1 545	7.96	0.08	2 252
1994	16.68	–	74	15.77	0.07	1 210	8.31	0.07	2 123
1995				15.58	0.13	1 218	8.53	0.03	1 926
1996	18.86	0.090	687	16.36	0.09	434	9.13	0.08	386
1997	20.11	0.227	601	16.66	0.14	604	8.89	0.05	1 120
1998	18.66	0.087	538	17.16	0.08	1 022	9.09	0.04	1 304
1999	19.90	0.240	360	16.53	0.10	1 196	8.76	0.03	2 588
2000	19.62	0.181	195	15.71	0.12	830	7.64	0.15	1 484
2001	18.96	0.382	343	15.87	0.07	1 822	8.96	0.02	5 258
2002	18.75	0.237	297	16.19	0.08	1 406	8.70	0.03	2 683
2003	20.45	0.602	593	18.74	0.06	2 148	8.88	0.05	2 307
2004	19.13	0.289	466	15.30	0.10	1 445	8.06	0.07	1 452
2005	16.95	0.201	399	14.37	0.17	343	7.82	0.48	731

–: SD could not be calculated

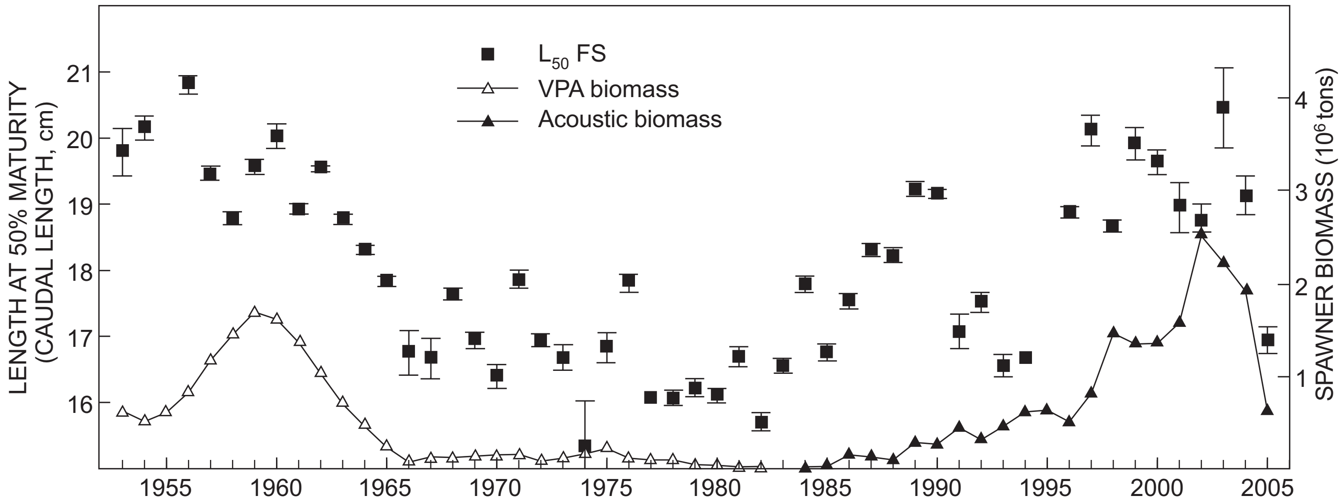

Figure 5: Sardine length-at-50% maturity estimated from fishery-independent Field Station (FS) data, and sardine spawner biomass; estimates for the period 1953–1982 are VPA-derived (Butterworth 1983) and those for the period 1984–2005 are derived from hydroacoustic surveys. Standard deviation is represented by error bars for length-at-50% maturity (L_{50} FS)

Table 6: South African sardine and anchovy von Bertalanffy parameters taken from the literature

	Sardine		Anchovy	
Parameters	Baird (1970)	Kerstan pers. comm. (Shin *et al*. 2004)	Prosch (1986)	Waldron *et al*. (1989)
K	0.2247	0.95	1.5858	1.367
L_∞	30.6	21.4	14.00 (fixed)	14.8
t_0	–1.505	–0.17	0.0012	–0.032

recent years when more fishing has taken place at the end of the year. Whereas most fish were historically caught in the second quarter of the year (April–June), the third quarter (July–September) has become the dominant catch period in recent years. Catches have been made predominantly in Area 1 throughout the study period, with the exception of 1996 when catches were more dominant in Area 2 (data not shown). There was no significant correlation between annual $\overline{L}_A$ and anchovy spawner biomass estimates.

Although there are clear trends in terms of where and when catches have been made for both species over the past two decades, there is no significant difference between of each area or each quarter.

Length-at-50% maturity

For sardine, annual L_{50}^{S} was calculated from the SBS and FS samples. The L_{50}^{S}, associated standard deviation, and sample size for both the SBS and FS annual ogives for sardine are presented in Table 5. There is a significant weak positive correlation ($r^2 = 0.23$, $p < 0.03$) between annual FS and SBS L_{50}^{S} values for the years the data-series have in common.

The L_{50}^{S} values estimated from the SBS data are consistently lower than those estimated from FS biological data (Table 5), by an average of 2.55cm. Although sample size varied extensively over the study periods for both data-series, only four years had samples of <200 fish and the standard deviation has been consistently small (Table 5). The FS data are likely to have a lower variance because measuring gonad weight is a less subjective process than assigning gonad stages, as was done for the SBS samples. In addition, the SBS samples are not collected in order to accurately determine maturity but rather as an aside, and accordingly the FS biological data are considered to be more precise despite the samples being collected from commercial catches.

Annual sardine FS L_{50}^{S} values and spawner biomass (Figure 5) appear to be related and were investigated. Those years that lacked an estimate for either parameter were omitted from the correlation analysis. There is a modest positive correlation between the FS values and sardine spawner biomass, which is highly significant ($r^2 = 0.45$, $p < 0.001$, $n = 50$). Because the two biomass series are not strictly comparable, the relationship of the VPA ($r^2 = 0.60$, $p < 0.001$, $n = 29$) and acoustic biomass ($r^2 = 0.31$, $p < 0.01$, $n = 20$) estimates to L_{50}^{S} were also investigated and both were found to have positive and significant correlations.

Annual maturity ogives were calculated for anchovy from the annual SBS. Annual L_{50}^{A}, standard deviation and sample size are presented in Table 5. Sample size is above 1 000 females and immature fish for all years except 1996 and 2005, but there is no obvious trend. There is no correlation between annual L_{50}^{A} and anchovy spawner biomass ($r^2 < 0.01$, $p > 0.9$, $n = 22$). Although the standard deviations are generally small for each annual estimate, it is difficult to assign the same

Table 7: Annual estimates of sardine fishing mortality calculated from catch and biomass estimates (F_S), extracted from the 2004 stock assessment model (F_{SM}) and computed in Ecopath with Ecosim (EwE) mass-balanced model of trophic flow through the southern Benguela ecosystem (F_{SE}) (Shannon *et al.* 2003), and annual estimates of sardine total mortality (Z_S) calculated using the von Bertalanffy parameters presented by Baird (1970) and Kerstan (Shin *et al.* 2004) and also from the EwE model (Z_{SE}; Shannon *et al.* 2003)

Year	F_S	F_{SM}	F_{SE}	Z_s Baird	Z_s Kerstan	Z_{SE}
1984	0.922	0.259	0.557	0.677	1.159	1.253
1985	0.548	0.225	0.820	1.338	3.235	1.504
1986	0.221	0.160	0.596	1.040	2.355	1.258
1987	0.266	0.135	0.327	0.736	1.494	1.017
1988	0.321	0.103	0.262	0.817	1.700	0.939
1989	0.121	0.093	0.199	1.042	2.272	0.905
1990	0.217	0.107	0.217	0.804	1.738	0.952
1991	0.118	0.089	0.178	0.679	1.316	0.909
1992	0.163	0.061	0.159	1.128	2.541	0.901
1993	0.109	0.051	0.132	1.001	2.211	0.942
1994	0.156	0.078	0.155	0.716	1.443	0.957
1995	0.186	0.083	0.156	1.071	2.392	1.006
1996	0.208	0.068	0.154	0.501	0.897	1.030
1997	0.148	0.090	0.172	0.506	0.908	1.027
1998	0.089	0.082	0.203	0.651	1.308	1.076
1999	0.099	0.042	0.152	0.490	0.867	0.988
2000	0.099	0.049	0.079	0.539	0.993	0.941
2001	0.121	0.038	0.150	0.602	1.154	1.088
2002	0.102	0.043	0.150	0.549	1.046	1.159
2003	0.131	0.049		0.547	1.012	
2004	0.195			0.468	0.785	
2005	0.385			0.445	0.702	

level of confidence in the data as with sardine because the maturity stages applied to anchovy have not been well researched and are possibly inconsistently applied.

Total mortality

Baird (1970) and Kerstan (pers. comm. in Shin *et al.* 2004) presented the only published von Bertalanffy parameters available for South African sardine (Table 6). The sardine Z estimates derived from Baird's parameters were lower than those from Kerstan (Table 7) and the two were positively correlated ($r^2 = 0.99$, $p < 0.001$). The sardine Z values computed in an Ecopath with Ecosim (EwE) mass-balanced model of trophic flow through the southern Benguela ecosystem (Z_{SE}) (Shannon *et al.* 2003) are more similar to those of the Baird Z values (Table 7), although they were uncorrelated ($r^2 = 0.08$). It is important to note that Z values produced by the EwE are not derived from von Bertalanffy parameters and can be considered absolute (L Shannon, Marine and Coastal Management, pers. comm.). Both the Z estimates derived from Baird and Kerstan show significant modest negative correlation (respectively $r^2 = 0.35$, $r^2 = 0.31$) to sardine spawner biomass estimates ($p < 0.01$).

Anchovy age and growth studies by Prosch (1986) and Waldron *et al.* (1989) included all three von Bertalanffy parameters (Table 6). However, the formulae presented by Sinovcic (2000) and Beverton and Holt (1957) yielded improbable estimates for anchovy Z, which precluded calculating E.

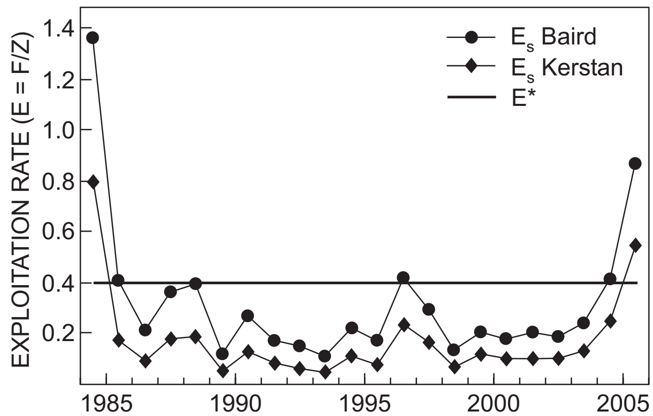

Figure 6: Annual sardine exploitation rates (E_S) calculated from two separate estimations of total mortality (Baird 1970 and Kerstan in Shin *et al.* 2004). The horizontal line (E*) at 0.4 represents the reference point recommended by Patterson (1992)

Exploitation rate

Annual sardine fishing mortality (F_S), total mortality (Z), fishing mortality estimates produced by the EwE model (F_{SE}) (Shannon *et al.* 2003) and the current stock assessment model (F_{SM}) for sardine (Cunningham and Butterworth 2004b) are presented in Table 7. These estimates were compared with the F_S estimates to establish if the values calculated were reasonable. Positive correlations between F_S and F_{SE}, and between F_S and F_{SM}, were highly significant ($r^2 = 0.55$, $p < 0.01$ and $r^2 = 0.81$, $p < 0.01$, respectively) Therefore, F_S can be used as a proxy for both F_{SE} and F_{SM}. It is, however, debatable which total mortality estimate may be more appropriate (see discussion).

With the exception of two of the 22 years of data available, the exploitation rate falls below the target reference point of 0.4 suggested by Patterson (1992) for both data-series (Figure 6), despite the Baird series reaching the reference point for three additional years. The particularly high F_S estimate for 1984, which would bias the calculation of E, could be attributed to the relatively small biomass estimate for that year (Table 1). However, F_{SE} is relatively high (Table 7) and it is not derived directly from the biomass or catch estimates. This implies that E_S for 1984 is not necessarily an outlier.

Centre of gravity of catches

The CoG of commercial sardine-directed catches has varied between Saldanha Bay and Cape Agulhas since 1987. Generally, years with smaller catches have had CoGs west of Hermanus (Figure 7a). In the past nine years (1997–2005), the annual CoG has successively and significantly shifted eastward from Saldanha Bay to past Cape Agulhas (Figure 7a).

The CoG of commercial anchovy-directed catches (Figure 7b) and sardine bycatch (Figure 7c) has fallen between

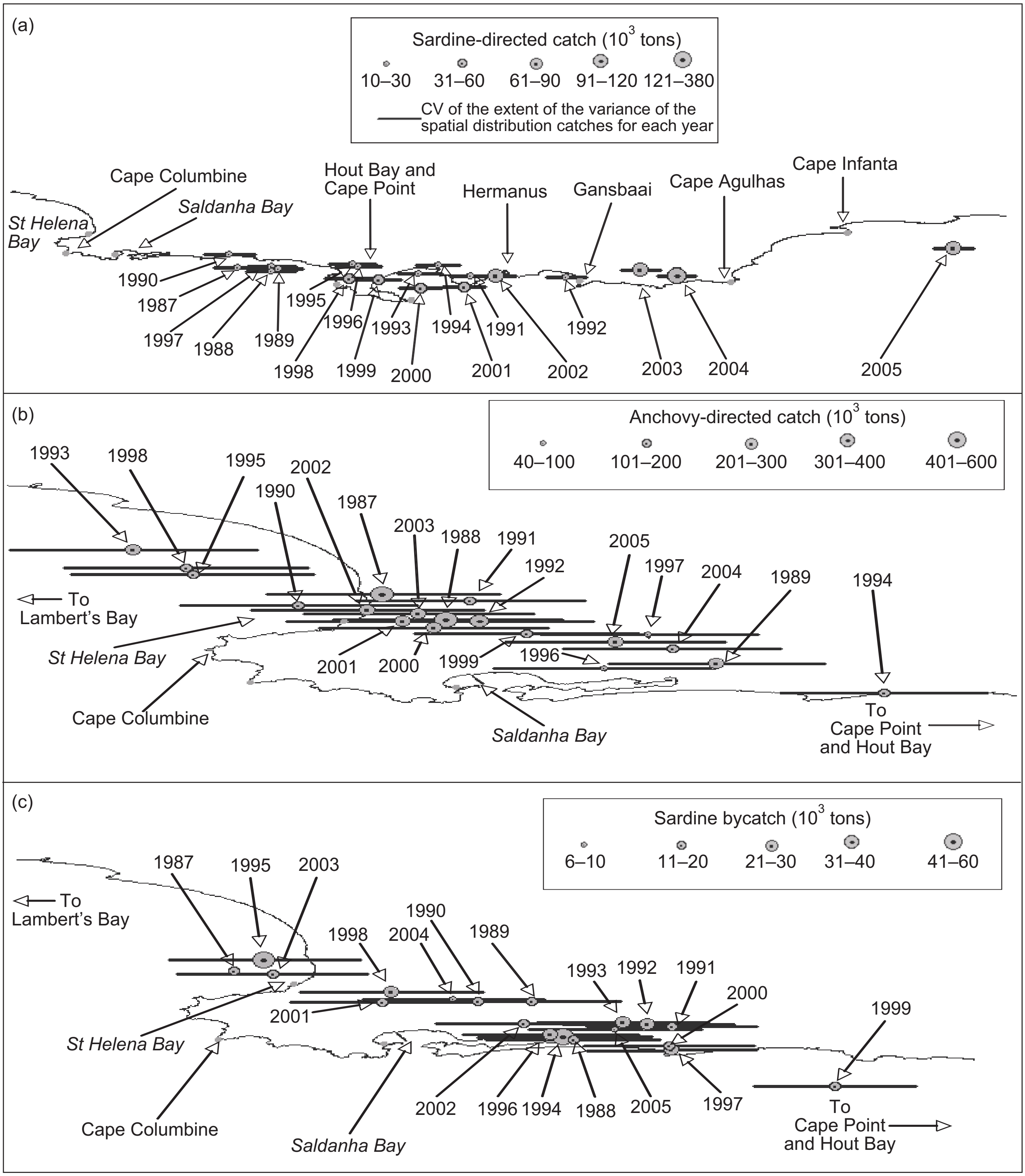

Figure 7: Annual catch centroids for (a) sardine-directed catch, (b) anchovy-directed catch and (c) sardine bycatch depicted on a linearised South African coastline. Each point represents an annual centroid and point size is proportional to total catch for that year

Lambert's Bay and Hout Bay since 1987. This is a far smaller distribution range compared to sardine catches and there is no evidence of an eastward shift. However, with the exception of five years (1987, 1989, 1994, 2003 and 2004), the annual anchovy CoGs are positioned west of their corresponding sardine bycatch CoGs.

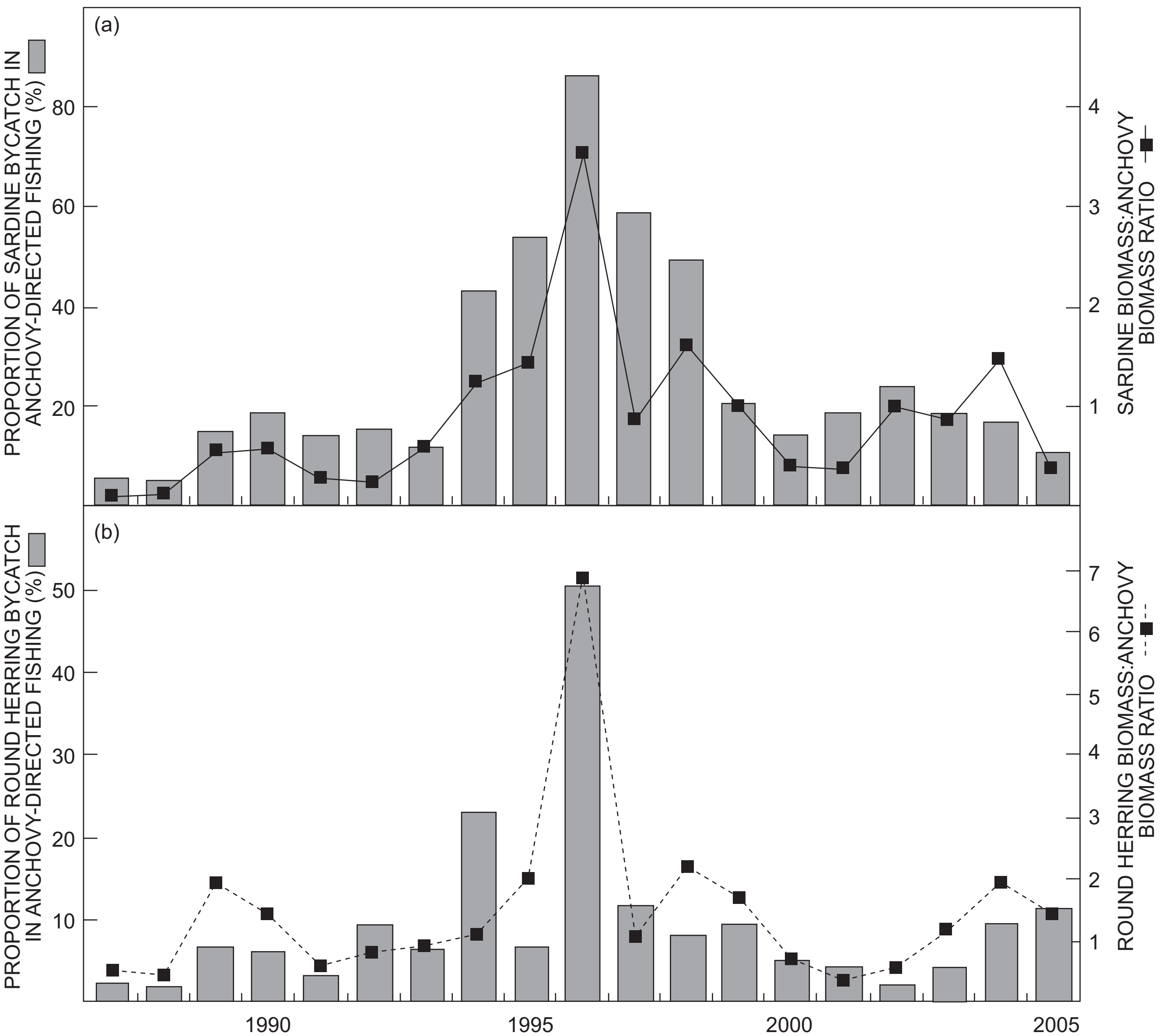

Figure 8: (a) Annual proportion of sardine bycatch in anchovy-directed fishing and sardine biomass to anchovy biomass ratio from 1987 to 2005; (b) annual proportion of round herring bycatch in anchovy-directed fishing and round herring biomass to anchovy biomass ratio from 1987 to 2005

Ratio of bycatch

All possible combinations of R_xB_i were investigated. Only R_SB_A and R_RB_A had an apparent correlation to ratio of their respective spawner biomass estimates (Figure 8), which was confirmed by linear regression (Figure 9) analysis. Although the data for 1996 appear to be an outlier (Figure 9a; $r^2 = 0.73$, $p < 0.001$), when the data for 1996 are omitted less variability is explained ($r^2 = 0.52$) but the relationship remains highly significant. Similarly, for Figure 9b ($r^2 = 0.78$, $p < 0.001$) a regression removing the outliers of 1994 and 1996 explains less variation, but the relationship nevertheless remains significant ($r^2 = 0.36$, $p < 0.05$).

Management of sardine bycatch is vital to ensuring that the recruitment of sardine is not negatively affected by anchovy-directed fishing. As such, the TAB is allocated in order to monitor and control the juvenile sardine bycatch (R_SB_A). An estimate of the proportion of sardine bycatch that is considered as adults may provide a useful management indicator for monitoring compliance to bycatch limits.

Using annual L_{50}^{S} as the definition of an adult fish, it could be concluded that anchovy-directed fishing has landed relatively little adult sardine since 1999, although this was not the case in 2005 (Figure 10a). However, if the cut-off points chosen in the categorisation flowcharts (Figure 3) are used, it appears that a far large proportion of R_SB_A has in fact been adult sardine (Figure 10a). Similarly, using the flowchart, it could be concluded that >95% of sardine-directed catch has been adult fish (Figure 10b). This could have several implications for the management and assessment of the stock.

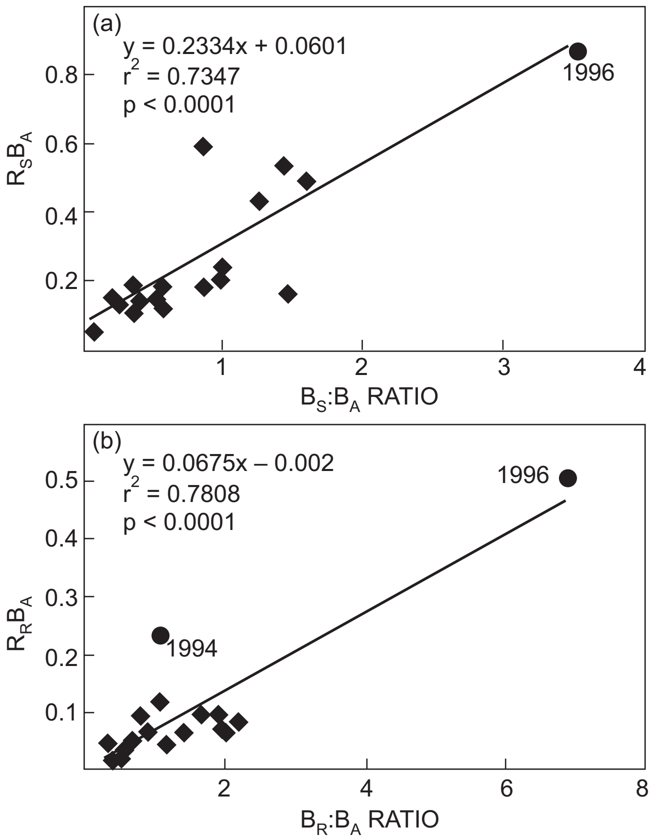

Figure 9: (a) Regression between the proportion of sardine bycatch in anchovy-directed fishing (R_SB_A) and sardine biomass (B_S) to anchovy biomass (B_A) ratio from 1987–2005; (b) regression between the proportion of round herring bycatch in anchovy-directed fishing (R_RB_A) and round herring biomass (B_R) to anchovy biomass (B_A) ratio from 1987–2005. Exclusion of the outliers 1994 and 1996 did not change the significance of the relationships

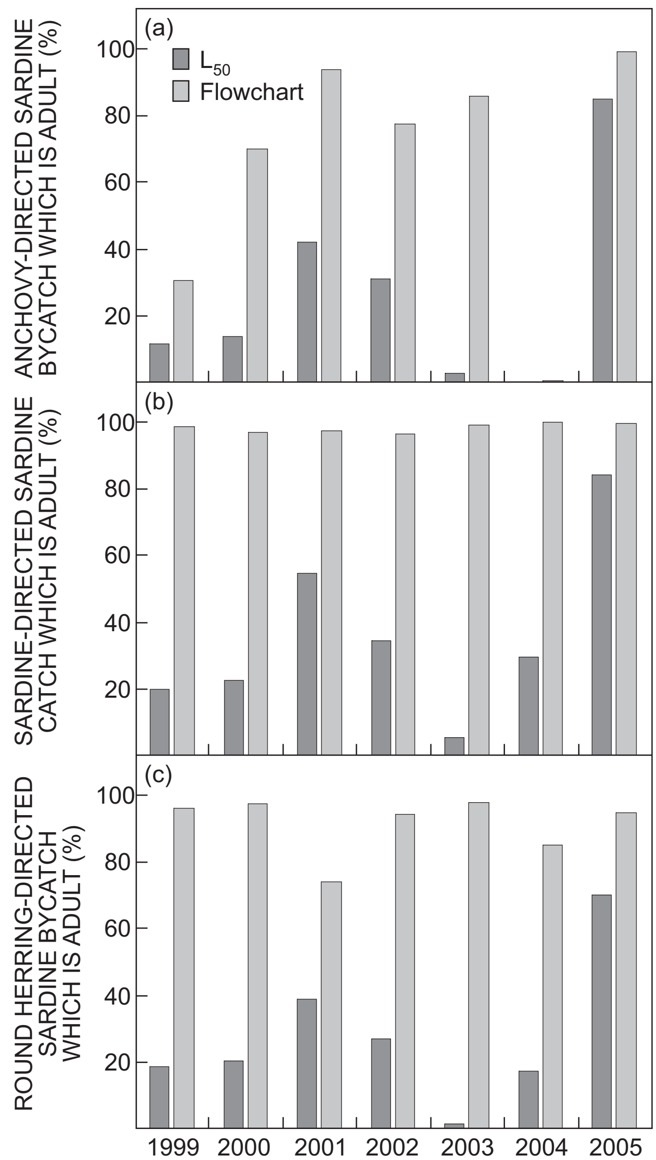

Figure 10: Proportion of adults in (a) anchovy-directed sardine bycatch, (b) sardine-directed catch and (c) round herring-directed sardine bycatch given two scenarios: annual sardine length-at-50% maturity is true or the annual cut-off stipulated in the catch categorisation (flowcharts) applied is true

Management has further allocated a proportion of the sardine TAC for adult sardine bycatch in the round herring-directed fishery (R_SB_R). Using the flowchart cut-off points indicates that the vast majority of R_SB_R has been adult (Figure 10c). However, if L_{50}^S estimates are applied, it can be concluded that 40–99% of R_SB_R has in fact been juvenile since 1999.

Discussion

Mean length of catch

The variability in sardine monthly and annual mean length was attributed to both the large size range of sardine and their adaptable life-history strategy (Shelton and Armstrong 1983). The general trend of catches of larger fish at the extremes of the calendar year is consistent with the fishing industry's ability to take advantage of the life-history strategy of sardine and to target larger adults when they form schools that are independent of anchovy. Nevertheless, annual raised length frequencies of catches are consistently bimodal (data not shown), reflecting the targeted adult catch as well as the juvenile bycatch component. Small sardine are caught in both sardine- and anchovy-directed fishing.

Size-based indicators have been widely proposed as population/ecosystem indicators (Daan *et al.* 2005), and it is well established that increasing fishing pressure will generally result in a population dominated by smaller individuals (Shin *et al.* 2005), although these studies generally rely on survey data or model outputs. Trenkel and Rochet (2003) found that the mean length of the catch was a 'precise' indicator with good statistical power, and thus they considered it an accurate indicator of change in population structure. Although the change might be due to environmental effects (Patterson 1992), it would nevertheless provide insight into the population structure.

Trenkel and Rochet (2003) suggest $\overline{L} > L_{50}$ as a target reference point in order to give at least half the individuals of a cohort a chance to reproduce. However, annual L_{50} varies significantly in sardine (Figure 5) and, given the high numbers of small sardine caught in both sardine-directed fishing and particularly as bycatch in anchovy-directed fishing, it is unsurprising that sardine $\overline{L}_S << L^S_{50}$.

Caddy and Mahon (1995) also suggest $\overline{L} > L_{50}$, but add the caveat of relating it to a target percentage spawning stock biomass which would depend on natural mortality. Jennings and Dulvy (2005) suggest reference points that could be adjusted annually, because they summarise how fluctuations in the environment will influence the size composition of an exploited population. Although there is a significant positive relationship between annual sardine spawner biomass and $\overline{L}_S$, a longer time-series that includes a downward trend in spawner biomass is required before a target reference point could be estimated with any level of confidence.

Whereas $\overline{L}$ cannot be used as a target reference point for sardine or anchovy, it is nevertheless important to monitor it in order to place other indicators in context, or to evaluate the data used to derive other indicators. Investigation of the temporal shifts in $\overline{L}_S$ indicates that the majority of large sardine are caught from October to December; L^S_{50} is based on samples collected between January and March, because, until recently, fishing had all but stopped in the last quarter of the year. If L^S_{50} is to be used as an indicator, it would be worthwhile to monitor $\overline{L}_S$ in order to ensure large/adult fish are sufficiently sampled during the spawning season. This would limit any bias in the calculation of L^S_{50}, although the trade-off is that $\overline{L}_S$ will not be a powerful indicator but it is much too costly to collect fishery-independent samples throughout the year or even during the spawning season.

Length-at-50% maturity

Excluding sardine <12cm SL is considered unlikely to have biased the analysis, because each annual ogive starts at zero maturity or close to it (data not shown). It is unlikely that there is a bimodal peak of reproductively active fish at 6–8cm and then mainly immature fish from 12cm onwards. Additionally, we have assumed here that shifts in the seasonal pattern of spawning do not cause sampling bias. Armstrong *et al.* (1989) concluded that distance offshore has no influence on standardised gonad mass (SGM) of sardine, but that longshore position contributes significantly to variations in SGM. Similarly, Kreiner *et al.* (2001) reported that sardine collected from the South Coast, east of 21°E, had different condition factors and gonadosomatic index characteristics than those collected elsewhere in the southern Benguela. Analysis of longshore and seasonal effects on sardine maturity patterns are discussed by van der Lingen *et al.* (2006a).

SBS samples are collected in November, the middle of the spawning period, as opposed to January and March, which is the end of the spawning period when the FS biological samples are collected. Kreiner *et al.* (2001) showed that gonadosomatic index (GSI) values decrease for both sexes of sardine from January to March. Therefore, the fish sampled in the FS data probably had smaller gonads than if they had been sampled in November. This has the effect of decreasing the number of mature fish per length-group and thus increasing L_{50}, which is why the SBS L_{50} values are consistently lower than the FS L_{50} values for the same year.

L_{50} is documented as declining following the heavy exploitation and collapse of the sardine resource (Armstrong *et al.* 1989) and increasing during a period of sardine stock recovery (van der Lingen *et al.* 2006a). Armstrong *et al.* (1989 p 100) suggested this change could be caused by a 'combination of density-dependence, enhanced natural selection and the consequences of changing age-structure within length-classes with extensive overlap of length-at-age distributions', and the case for density dependence has been further argued by van der Lingen *et al.* (2006a).

Several studies suggest that faster growth, earlier maturity and increased fecundity are responses to increased fishing mortality (Ware 1985, Rijnsdorp 1994, Trippel 1995, Rochet 1998, Rochet 2000). It could be debated whether these are density-dependent responses or not, and if so, was the population influenced by fishing or environmental conditions? Several studies attribute changes in population dynamics to environmental factors independent of or in conjunction with fishing pressure (Alheit 1989, Evseenko *et al.* 1990, Lluch-Belda *et al.* 1991, Prager and MacCall 1993, Wada and Jacobson 1998). Regardless of the cause of the population decline, the crucial point is that the population dynamics of the target resource have changed, which impacts sustainable fishing effort. Population viability (i.e. the ability to reproduce) is thus a key parameter and is easily quantified by using length-at-50% maturity. In the case of sardine, L_{50} appears to be positively correlated with population size, and if L_{50} is decreasing, it can be concluded that population size is decreasing and thus the population's viability may be negatively affected and fishing effort and catches may need to be reduced.

The 2004 stock assessment model for sardine assumes maturity at one year of age (at a size of 16.5cm TL (Cunningham and Butterworth 2005). The finding that L_{50} fluctuates with spawner stock biomass has significant implications for the current assessment and management of the sardine fishery. The 2004 assessment model fit to the maturity ogive derived in this study was less satisfactory than that achieved for the initial assumption made that all sardine mature at Age 1 (Cunningham and Butterworth 2005). However, resource projections using the current OMP indicate that the risk to the resource is higher under the current assumption of maturity at one year of age than if the model used maturity ogives (Cunningham and Butterworth 2005). It is proposed that L^S_{50} be used as a descriptive indicator, because the indicator peaked in 2003, at the second highest value since 1953, and began a steady decline in 2004, providing a concurrent indication that biomass would continue to decline as it has.

There are additional factors that must be resolved. These include the conversion from length-at-maturity to age-at-maturity, which requires the use of age-length keys that are not available for all years. In addition, the discrepancy between the ogives from fishery-independent and fishery-dependent data must be investigated.

The much shorter time-series for anchovy limits reasonable assessment of possible population dynamics such as density-dependence. In order to improve the quality of data available for assessing anchovy L_{50}, there are two options: collect similar data to that collected for sardine from commercial catch samples (although this is only logistically possible if samples are collected on board the vessels immediately after catches are made) or extend sampling procedures on research surveys.

Total mortality

Although the values obtained using Baird's (1970) data are more similar to the values produced by Shannon *et al.* (2003), and its correlation to sardine spawner biomass was highly significant, the Kerstan (pers. comm. in Shin *et al*. 2004) Z values cannot be ignored. The von Bertalanffy parameters calculated by Baird (1970) were estimated at a time when sardine biomass was severely depleted, which likely affected the results of the age and growth study at that time. This is obvious when one compares the von Bertalanffy parameters (Table 6) with those presented by Kerstan (pers. comm. in Shin *et al*. 2004) from data collected in the 1990s; both K and t_0 are appreciably different to those presented by Baird (1970). In addition, Thomas (1985) considers Baird's estimates inaccurate because secondary rings may have been interpreted as annuli. Although neither set of parameters is ideal, they will have to suffice until von Bertalanffy parameters can be estimated on a more regular basis in the future.

Trenkel and Rochet (2003) found that Z, while being relatively imprecise, showed good agreement with $\overline{L}$. However, it was not possible to apply their model to estimate M for either sardine or anchovy. Z is necessary for the calculation of E and will hopefully be possible in the future using annual von Bertalanffy estimates.

Exploitation rate

Patterson (1992) recommends the target reference point E* = 0.4 for small pelagic stocks, a more conservative value than the E* = 0.5 target reference point for a selection of pelagic stocks identified by Mertz and Myers (1998) and supported by Trenkel and Rochet (2003). Mertz and Myers (1998) show that the pelagic stocks they investigated are currently at 0.5, but those authors did not discuss the sustainability of the fisheries from which their estimates were derived. Patterson's (1992) conclusions are considered more appropriate in terms of the precautionary approach recommended by the UN (FAO 1995).

Nevertheless, sardine spawner biomass has increased since 1984, implying that E_S is an effective performance indicator that reflects that the sardine fishery has been successfully managed, albeit from a conservative standpoint (given the number of years when E < 0.4). Yet, it is notable that E_S for both data-series has increased in 2004 and is beyond the reference point for 2005, which could be interpreted as confirming that the population abundance of sardine is starting to decline, a trend suggested by L_{50}^{S} and spawner biomass survey estimates (Figure 5).

Centre of gravity of catches

Cury *et al.* (2000) suggest that overfishing may alter relative abundances of typically co-occurring species and thus alter school dynamics. However, the sardine spawner biomass virtually doubled from 1997 to 1998 when the eastward shift started, and has maintained a high abundance until 2005. It therefore seems unlikely that the eastward shift has had a negative effect on the sardine population.

Expansion and contraction of the fishing range may correlate with that of the pelagic fish biomass, which is known to be localised in periods of low biomass (McCall 1990). As a descriptive indicator, CoG is a useful tool for assessing the distribution of fishing effort, because fishery managers and operators could use it to determine the relative cost (in terms of fuel, distance to factories, etc.) of harvesting the resource. The eastward shift of catches corroborates anecdotal reports by fishers that sardine have 'moved' to the South Coast (Fairweather *et al.* 2006). There are indications from other data sources including distribution patterns of sardine and the location of their major spawning habitat, as observed during acoustic surveys (van der Lingen *et al.* 2005). Eastward and westward shifts in the annual catches happened to a varying degree prior to 1997, so it is unlikely that the location of the CoG of catches can be predicted for future years.

The westerly position of anchovy CoGs relative to sardine bycatch CoGs is an expected scenario, because anchovy catches west of Cape Columbine are generally 'cleaner' as sardine recruits are generally found east of Cape Columbine (J Coetzee, MCM, pers. comm.). There is no obvious explanation for the five anomalous years; relative biomasses of the two species for these years vary widely as does monthly $\overline{L}$, indicating the anomaly is possibly attributable to changes in fishing strategy.

It is proposed that CoG is also used as a descriptive indicator, to monitor the impact on the fishery in terms of distance travelled and increased costs.

Ratio of bycatch

Management of sardine bycatch is important to ensure that the recruitment of sardine is not negatively affected by anchovy-directed fishing. As such, the TAB is allocated in order to monitor and control the juvenile sardine bycatch (R_SB_A). An estimate of the proportion of sardine bycatch that is considered as adults may provide a useful management indicator for monitoring compliance to bycatch limits.

Geromont *et al.* (1999) illustrated a possible relationship between the ratio of anchovy-directed sardine bycatch and the biomass of anchovy in South Africa. Cury *et al.* (2000) found that, at high abundance, anchovy tend to form pure schools, whereas at lower abundance they formed mixed schools with other species, and school composition tracked relative abundance of the species in three species of sardine in Cote d'Ivoire and Senegal, as well as South African sardine and anchovy.

However, annual TACs have been set for the pelagic fishery since 1987 (Table 1), and in 1994 a total allowable bycatch (TAB) for juvenile sardine was implemented to accommodate the anchovy fishery, because clean anchovy catches are not possible for the majority of the year. This may have affected the proportion of bycatch. A right-holder who reaches their apportioned sardine TAB has to stop fishing immediately or 'buy' bycatch from another right-holder. Therefore, bycatch in any one year is limited.

However, it is notable that since the juvenile sardine TAB was introduced in 1994, the limit was reached annually until 1997, after which the first catch categorisation flowcharts were introduced and the TAB is yet to be reached. Since then, the utilisation of the directed sardine and anchovy TAC has varied over the years, and it appears that the directed fishing TAC is a more likely limiting factor on juvenile sardine bycatch than the TAB. Therefore, it can be concluded that school composition is a reliable descriptive indicator of relative abundance in small pelagic species.

A point of concern is that the catch categorisation analysis is providing contradictory results, in particular the scenario that the vast majority of R_SB_A since 1999 should have been categorised as adult, using the flowchart cut-off points. This is unrealistic, possibly because the majority of sardine form shoals separate of anchovy once they are adult (Crawford 1981, De Oliveira 2002). However, this has major management implications, because it appears the flowcharts have not been applied historically because the incongruity would have been quickly noted by the industry. In resolving this issue, the limitations of capacity and funding on fishery management should not be underestimated. The majority of R_SB_A is caught in Area 1, whereas the majority of sardine-directed catch is caught in Areas 2 and 3. It is suggested that monitoring of catches for these scenarios could be highlighted to those areas.

Ratio of bycatch is proposed as a descriptive indicator, given its correlation to relative abundance, and in combination with L^S_{50} has highlighted that the definition of bycatch and its quantification is crucial to the management of the fishery.

Conclusions

Of the six biological and/or fishery indicators investigated, only L_{50} could be directly incorporated into the stock assessment of sardine. The five other indicators have highlighted issues or corroborated conclusions about various aspects of the fishery or stock status obtained from direct biomass estimations from surveys. For example, anecdotal reports of changing sardine distribution patterns have been corroborated by the CoG plots, changes in L_{50} appear to be relatively well-coupled with stock size, and exploitation rate provides an easily interpretable indicator for use by fishery managers and other stakeholders. The indicators provide useful additional information that could be either directly incorporated into assessment models, and/or used to aid management procedures. For example, consideration should be given to spatially restricted fishing mortality given the shifts in the population distribution. The comparison of indicators derived in this study with the acoustic biomass estimates has demonstrated the utility of some of those indicators in reflecting stock status, indicating that they could possibly be used elsewhere in fisheries that lack good data on stock status and distribution patterns.

The results of this study have raised several issues that require continued or further investigation in order to improve management of the South African pelagic fishery. The quantity and quality of historical data available to analyse the sardine fishery is substantial. The samples collected at field stations proved invaluable for the investigation of L_{50} and such collection must continue in the future, particularly to ensure that catches are sufficiently sampled between October and December, given that fishing currently extends for almost an entire year. Subsamples of the length-frequency analysis of each catch must include at least 50 fish with the range 12–20cm SL in order to develop a comprehensive biological database. Age-at-maturity is a vital component of the sardine stock assessment and it is essential that the reproductive biology of sardine is investigated at a histological level. It would also be beneficial to collect the otoliths of all fish sampled for reproductive data, which can then be used to determine age-at-maturity without using age-length keys.

The value of collecting long-term data-series of relatively simple parameters for management of the fishery cannot be underestimated. Some of the indicators derived in this study were already taken into account in the development of the OMP, in an advanced and rigorous manner. However, it is the independently derived nature of the indicators that is in itself useful in illuminating models that are perceived as opaque by many stakeholders. These indicators are in no way considered to be replacements for the current OMP and stock assessment models, but should be used on a complementary basis. In their current form, the indicators are intended to be informative in the sense of promoting understanding. Incorporation of indicators into the process of providing management advice is under consideration.

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