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CHANGES IN ABUNDANCE OF THE NORTHERN BENGUELA SARDINE STOCK DURING THE DECADE 1990–2000, WITH COMMENTS ON THE RELATIVE IMPORTANCE OF FISHING AND THE ENVIRONMMENT

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The northern Benguela stock of sardine *Sardinops sagax* used to be considered one of the major clupeoid stocks of the world; it supported an average annual catch of >700 000 tons throughout the 1960s. The stock has been in a depressed state for more than two decades, as demonstrated by annual catches that averaged around 50 000 tons between 1978 and 1989 and only slightly more in the 1990s. It has experienced fluctuations in abundance of several orders of magnitude during the most recent decade. Population size increased until 1992, when the acoustic estimate of biomass was about 750 000 tons. Catches increased accordingly, averaging 100 000 tons between 1992 and 1995, but from 1992 to 1996 the stock was in decline and the lowest annual catch in the history of the fishery was taken in 1996. Although there was a small increase during the last three years of the decade, the stock remains seriously depleted. Survey-based recruitment indices suggest that the changes in the 1990s were initiated by fluctuations in recruitment, but the decline was almost certainly exacerbated by continued fishing. Poor recruitment and decreasing catch rates between 1993 and 1996 in a number of other key resources suggest that system-wide environmental changes were an important factor in the decline of the sardine stock at that time. Anomalous oceanographic conditions, such as extensive hypoxic shelf waters in 1993/94 and a Benguela *Niño* in 1995, support this conclusion.

Key words: environmental effects, fishing effects, northern Benguela, recruitment, sardine

The southern African sardine *Sardinops sagax* (also known as pilchard, *Sardinops ocellatus* – Bianchi *et al*. 1999) is one of the major species of pelagic fish occupying the rich waters of the Benguela Current. Sardine are distributed from KwaZulu-Natal in South Africa to southern Angola (Beckley and van der Lingen 1999), but the strong perennial Lüderitz upwelling cell, that divides the Benguela Current into northern and southern sections, forms an ecological barrier separating the population into two discrete stocks (Boyd and Cruickshank 1983). The two stocks are managed separately by Namibia and South Africa.

The northern Benguela stock occurs from the northern edge of the Lüderitz upwelling cell (Crawford *et al*. 1987), at approximately 25°S, to the southern edge of the Angola/Benguela front in southern Angola, which varies between about 16 and 17°S (Fig. 1). The greatest part of the total sardine catch of the region has come from the northern stock, Namibian catches between 1950 and 1999 totalling 14.7 million tons in comparison with the 5.9 million tons of South Africa (Beckley and van der Lingen 1999). In addition, de Campos Rosado (1974) reports that a further 500 000 tons of "sardina" were landed at Angolan harbours between 1956 and 1972. Whether this fish was sardine or sardinella *Sardinella aurita* was not recorded, but most is believed to have been sardine (de Campos Rosado 1974). Those catches were made in International Commission for the Southeast Atlantic Fisheries Division 1.3 (15–20°S), which includes southern Angola and northern Namibia.

Catch rates of sardine in the northern Benguela in the late 1950s and early 1960s suggested that the stock was several million tons in size and was relatively stable (Cram 1981). VPA estimates indicated a stock size >10 million tons during the mid 1960s (Thomas 1986), but it is believed that the biomass was inflated above the long-term mean by a series of strong cohorts entering the stock during the early 1960s. Catches in excess of a million tons per year were made in 1968 and 1969 (Fig. 2), but this level of exploitation, combined with poor recruitment, led to a crash in biomass in the late 1960s, to <2 million tons by 1970. Then, in 1972, a strong year-class entered the fishery, leading to a partial increase in biomass in the mid 1970s. This gave industry and fisheries managers the impression that the decline of the previous years had been a temporary phenomenon (Cram 1981). Catches were allowed to increase to around 500 000 tons for much of the mid 1970s until 1977 when, with the realization

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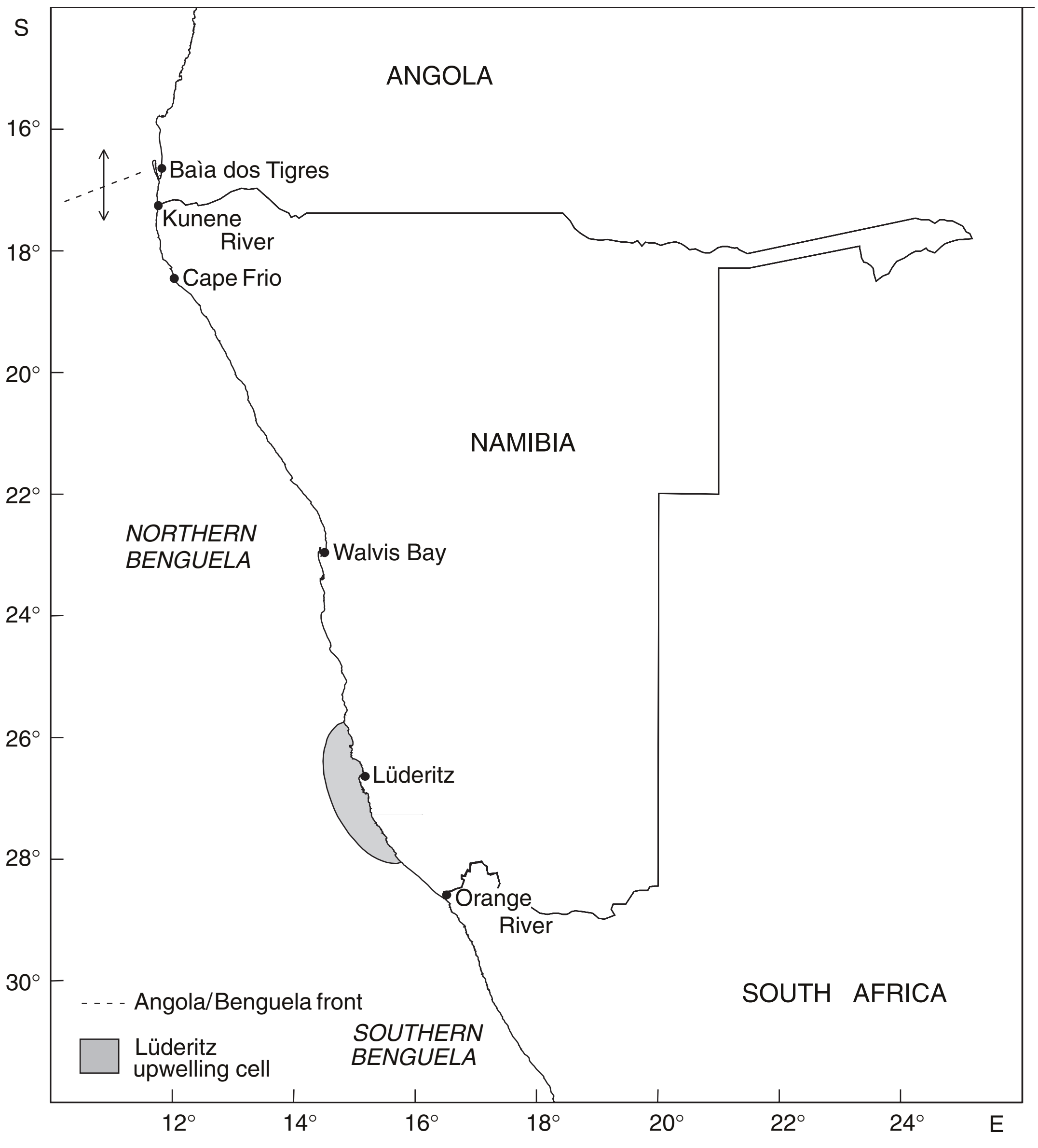

Fig. 1: Map of southwestern Africa showing places mentioned in the text

that the biomass really had been reduced considerably, the Total Allowable Catch (*TAC*) was reduced to 181 000 tons. Finally all sardine-directed catching was stopped in 1981 (Cram 1981). From 1982 to 1988 quotas ranged between 30 000 and 42 500 tons, but despite these comparatively low levels of harvesting, the stock remained depleted (Crawford *et al.* 1987).

Sardine has long been considered the most important pelagic fish species harvested in Namibia (Lees 1969), more important than Cape anchovy *Engraulis capensis* and juvenile Cape horse mackerel *Trachurus t. capensis*. Prior to 1977 sardine catches were larger

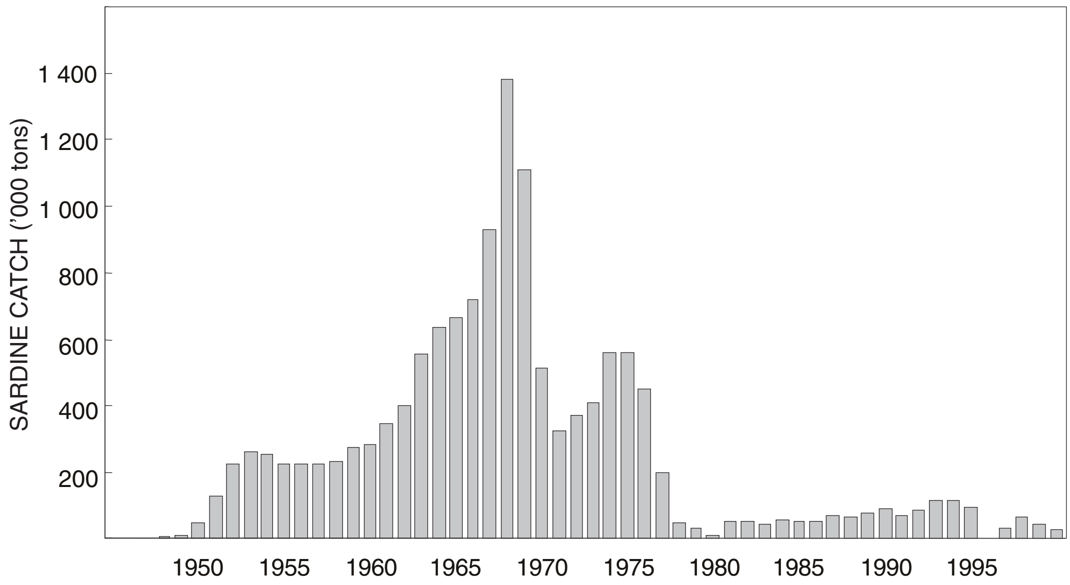

Fig. 2: Catches of sardine from the Namibian part of the northern Benguela since 1947

than those of any other pelagic species, and usually more than the other species combined. However, since 1978, sardine, anchovy and horse mackerel have on average provided roughly equal amounts to the pelagic harvest, although sardine remains the preferred species, in terms of both economic value and employment opportunities.

Sardine in the northern Benguela have previously been reported by Matthews (1964) and Le Clus (1979) to spawn in two peaks between June and April, in winter-spring (September–November) and late summer-autumn (February–April). Back-calculating the birthdate of young fish, using standard growth rates, indicates that this is still the case. The fish are given a nominal birthdate of 1 January. Young fish start schooling during the second half of the year and are first assessed acoustically in October/November, as "pre-recruits" (Fig. 3). The fishing season starts in March and this cohort is first targeted by the fleet at this stage, when they are nominally 15 months old and have a total length of around 19 cm. At this point the fish are termed "recruits". The total length at 50% maturity is about 20 cm, when the fish are some $1\frac{1}{2}$ years old, and most fish spawn for the first time during the following spawning season when they are approaching 2 years of age. Therefore, the recruits caught prior to this are mostly immature. Indeed, about 20% of all sardine landed in the 1990s had not had a chance to spawn.

In the absence of any analytical assessment of sardine stock dynamics and productivity during the first half of the past decade, the annual *TAC* was recommended to be a constant proportion of the total estimated stock size. This was set at a level approximately equivalent to an instantaneous fishing mortality of 0.2 year^{-1}, which equalled about 18% of stock size, calculated at the beginning of the fishing season. This level was based on an $F_{0.1}$ strategy, calculated by a yield per recruit analysis carried out by Thomas (1986). Since Namibian Independence in 1990, the stated aim of the Namibian authorities was that of "rebuilding depleted fishery stocks to their level of full potential. This will be accomplished through a programme of catch restrictions and other regulations over an expected time period of 5–10 years" (MFMR 1991, p. 42). In the case of the northern Benguela sardine stock, this strategy has obviously not been successfully implemented.

Changes in abundance of the sardine stock during the past decade are described in this paper. Further, two possible major causes of the continued depleted status of the stock are discussed and compared: environmental factors that affect stock dynamics primarily through recruitment, and activities of the fishing industry (see also Lasker and MacCall 1983, Crawford 1987).

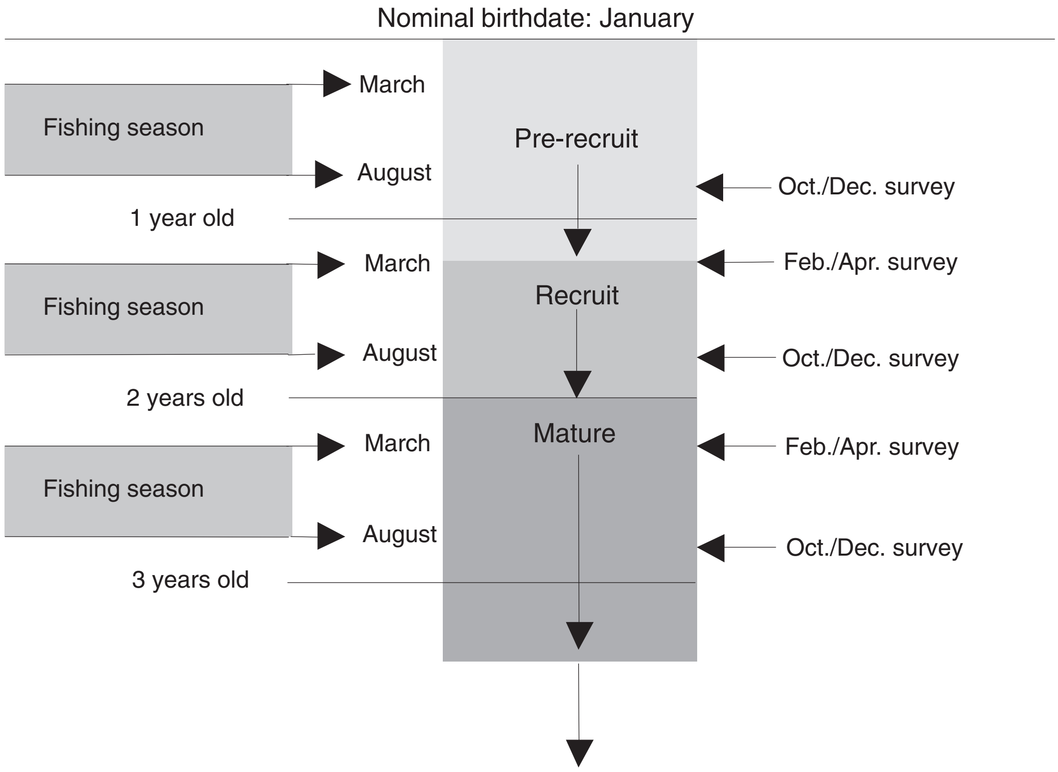

Fig. 3: Major annual events in the fishery and assessment surveys in relation to the life history of northern Benguela sardine

MATERIAL AND METHODS

Assessment of Namibian sardine in the 1990s relied almost entirely on acoustic survey data. The commercial fishing season for sardine is open from March to August each year, but catches tend to be made during only part of this period and are spatially clumped. Hence, production–type models are likely to be biased and catch per unit effort (*cpue*) is recognized to be a poor indicator of pelagic stock size (Beckley and van der Lingen 1999). An additional problem faced with applying such analyses to Namibian pelagic stocks is that the fishery is a multispecies one, so complicating interpretation of *cpue* data. Age determination of Namibian sardine is problematic owing to the lack of seasonality in the northern Benguela system; this results in the formation of varying numbers of hyaline rings each year (Thomas 1984, Agnalt 1995). Therefore, until a more reliable age determination methodology is developed, age-based assessment models cannot be used. In contrast, a series of 2–4 surveys per year provide a synoptic description of stock size and structure that cannot currently be gained from other sources.

Research survey data

Regular hydroacoustic surveys to determine the biomass of sardine and other pelagic species in the northern Benguela have been conducted since 1990. The methods are described in various cruise reports (e.g. Coetzee *et al.* 1993, Fossen *et al.* 1999).

In all, 31 surveys have been conducted during the past decade (Table I). The surveys aimed to assess the entire northern Benguela sardine stock, although during some surveys it was not possible to assess the southern Angolan region. This was a drawback because some surveys during the early years of the decade

Table I: Summary of some of the logistic details of sardine biomass surveys conducted between 1990 and 2000

Date	Research vessel(s)	Scientific acoustic equipment	Number of scouting vessels
March 1990	*Dr Fridtjof Nansen**	Simrad EK400	–
June 1990	*Dr Fridtjof Nansen**	Simrad EK400	3
March 1991	*Dr Fridtjof Nansen**	Simrad EK500	–
August 1991	*Benguela*	Simrad EK400	3
November 1991	*Dr Fridtjof Nansen*/Benguela*	Simrad EK500/EK400	1
June 1992	*Dr Fridtjof Nansen*/Benguela*	Simrad EK500/EK400	3
August 1992	*Benguela*	Simrad EK400	–
November 1992	*Dr Fridtjof Nansen*/Benguela*	Simrad EK500/EK400	3
March 1993	*Dr Fridtjof Nansen**	Simrad EK500	–
June 1993	*Dr Fridtjof Nansen**	Simrad EK500	–
August 1993	*Benguela*	Simrad EK400	2
November 1993	*Benguela*	Simrad EK400	1
February 1994	*Benguela / Dr Fridtjof Nansen***	Simrad EK400/EK500	–
June 1994	*Dr Fridtjof Nansen***	Simrad EK500	1
November 1994	*Dr Fridtjof Nansen***	Simrad EK500	1
March 1995	*Welwitchia*	Simrad EK500	–
June 1995	*Dr Fridtjof Nansen**/Welwitchia*	Simrad EK500	–
November 1995	*Welwitchia*	Simrad EK500	3
March 1996	*Welwitchia*	Simrad EK500	3
June 1996	*Dr Fridtjof Nansen***	Simrad EK500	–
November 1996	*Welwitchia*	Simrad EK500	–
March 1997	*Welwitchia*	Simrad EK500	5
June 1997	*Welwitchia*	Simrad EK500	3
October 1997	*Welwitchia*	Simrad EK500	4
April 1998	*Welwitchia*	Simrad EK500	–
May 1998	*Welwitchia*	Simrad EK500	4
November 1998	*Welwitchia*	Simrad EK500	4
April 1999	*Welwitchia*	Simrad EK500	4
November 1999	*Welwitchia*	Simrad EK500	3
March 2000	*Welwitchia*	Simrad EK500	2
June 2000	*Welwitchia*	Simrad EK500	–

* = former *Dr Fridtjof Nansen*
** = latest *Dr Fridtjof Nansen*)

indicated that the proportion of the sardine stock in Angolan waters varied from up to 50% during winter to less than 10% during summer. Surveys in autumn (February–April) and, in the early years of the decade, between May and August, determined the abundance and distribution of adults, whereas those in spring (October–December) assessed the adult stock and also provided an index of recruitment.

Several different research vessels were used. Each was fitted with a 38 kHz split-beam transducer, calibrated acoustically by the standard sphere method (Foote *et al.* 1987). Additionally, intercalibration exercises were conducted between the vessels and indicated that the echo intensities measured were broadly comparable (Boyer *et al.* in prep.). Simrad EK400 scientific echosounders were used on the earlier surveys and EK500s on the latter ones (Table I). Barange (1998), as cited by Barange *et al.* (1999), reports that echoes in excess of -29.9 dB tend to be underestimated by the EK400. This bias has not been corrected for in the results reported here. While this bias may be significant (J. C. Coetzee, Marine & Coastal Management [MCM], Cape Town, pers. comm.), it will merely serve to accentuate the decline recorded in stock size during the mid 1990s (see Discussion); survey results from the R.V. *Benguela* between 1991 and 1993 (Table I) will be negatively biased.

While the surveys focused primarily on sardine, prior to 1996 they were also designed to estimate abundance of anchovy, juvenile horse mackerel and Whitehead's round herring *Etrumeus whiteheadi*. Systematic zig-zag transects were used in the early 1990s, allowing all three stocks to be assessed simultaneously. In areas of abundance of sardine, transect spacing was reduced in order to increase the sampling intensity. Subsequent analysis of the spatial processes underlying the distribution of pelagic fish off South Africa (Barange and Hampton 1997) and Namibia (Coetzee *et al.* 2001) have emphasized the patchy nature of sardine aggregations, so justifying

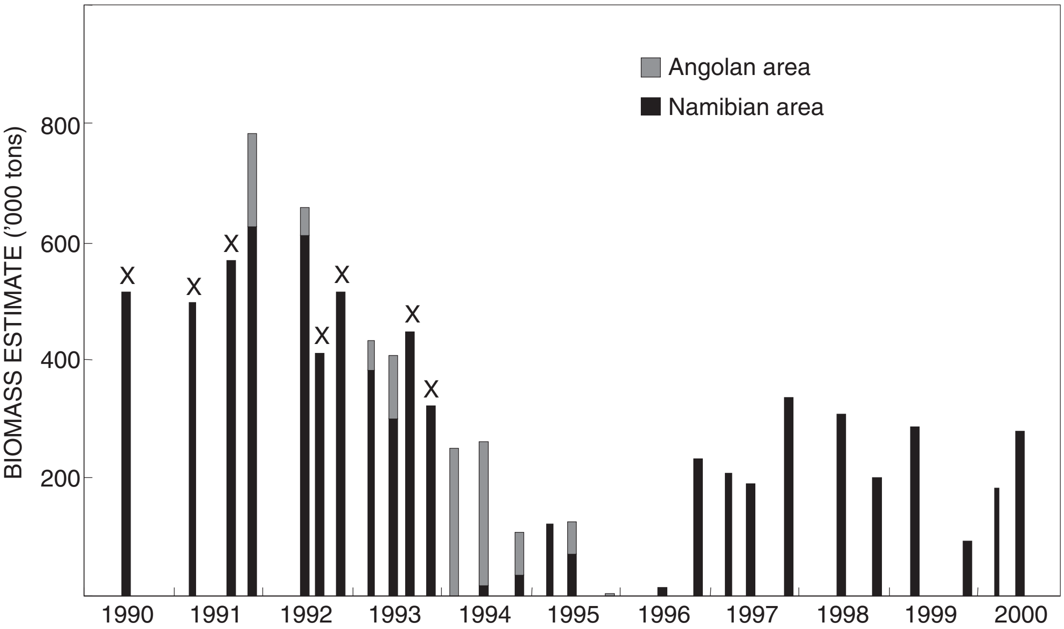

Fig. 4: Biomass estimates of the sardine stock from acoustic surveys from 1990 to 2000. Bars with an X indicate that the Angolan area was not surveyed although sardine was probably present

this strategy. Those studies also indicate that the distribution of anchovy and horse mackerel develops over larger areas with gradual transitions between areas of low and high density. A survey designed to estimate the biomass of sardine would therefore be efficient in assessing the biomass and capturing the spatial structure of other pelagic fish species. During many surveys, fishing vessels were deployed inshore and offshore of the survey grid to ensure that schools were not missed. As the sardine stock declined and became concentrated in smaller areas, and as individual school-groups contributed an increasing proportion of the biomass, repeated coverages of areas of high biomass or areas where the estimate was uncertain were conducted with increased frequency. Another important strategy that developed with the declining stock and increased difficulty of finding such concentrations, was a reliance on fishing vessels to scout for schools of fish in addition to checking the perimeter areas. In 1997 a formal two-stage adaptive strategy was adopted (Boyer *et al.* in prep.). Fishing vessels were used to find school-groups and to outline the area of distribution of such groups, then the research vessel assessed the abundance of each school-group using closely spaced parallel transects. Repeated coverages were made according to predefined criteria in areas of high abundance or high variance. This survey design was aimed at solving the problems associated with surveying a scarce, highly clustered, mobile population.

Acoustic back-scattering data were raised to fish density using standard methods (e.g. Hampton 1987). All echoes exceeding a threshold of -65 dB were allocated to plankton or various fish species; primarily sardine, anchovy, juvenile horse mackerel, round herring or pelagic goby *Sufflogobius bibarbatus*. This allocation was based on the species composition of trawls targeting nearby schools and the characteristic appearance of the schools recognized on the echo recordings. The mean echo level of each species per transect was averaged to give a mean per stratum, after weighting for transect length. The numbers of each species were calculated using a length-based relationship for target strength based on Halldørsson and Reynisson's (1983) expression for North Sea herring *Clupea harengus*, because the target strength for southern African sardine has not yet been determined (though see Barange *et al.* 1996). Biomass was calculated by raising the numbers of fish according to the measured length-weight relationship.

Investigations into the target strength of sardine in the southern Benguela suggest that the target strength used may be 1.5 dB too low (Barange *et al.* 1996), so the biomass might be overestimated by about one-third. This biases the results in the opposite direction to the signal attenuation bias mentioned above. Therefore, at least during the early part of the time period of the surveys, the biases partially cancel each other out. The trends reported below will, however, remain the same.

Prior to 1997 the survey design did not permit calculation of confidence limits. Since then, sampling coefficients of variance (*CV*s) have ranged between 22 and 36%. As the earlier surveys used systematic rather than adaptive transect designs, it is assumed that the variances were greater. Several biases are likely to reduce the accuracy of the estimates. For example, target strength is unknown and consequently based on that of a similar species. Similarly, the effect of vessel- and net-avoidance may reduce precision. Further, the diel behaviour of sardine moving inshore during the day, and hence occasionally into waters too shallow for the research vessel, or close to the surface and above the transducer at night, may also reduce the precision of the estimates. Size- or species-selectivity during trawling could also result in a potentially significant bias, although comparisons of purse-seine and survey trawl catches made in the same area suggest that trawl catches are representative of the targeted schools. The importance of all these factors is currently being investigated.

Commercial catch data

All pelagic catches were landed at Walvis Bay during the period under review, so facilitating collection of reliable data. Landings were supervised by fisheries inspectors and all fish were weighed on electronic scales before passing into the processing factories. All vessels were sampled during offloading to determine species composition. In addition, random samples were collected for the measurement of length frequency and other biological parameters. The sampling rate varied during the early part of the 1990s, but in 1995 it was standardized to one random sample per 500 tons offloaded, with 50 fish selected randomly from this sample for biological analysis. Information on catches, including date, time and position of each set, estimated size of catch and species composition, was recorded on logsheets by the skippers.

As age-length keys are not available, the catch-at-length data were split into three size categories to compare the contribution of the different components of the population to the catches between years. Sardine of 16.5 cm total length and less were assumed to represent the 0-group, sardine of 16.6–22.4 cm the 1-group and sardine ≥22.5 cm the 2+ fish. These values are based on preliminary results of age determination (HJB unpublished data) and the theoretical ages calculated with length-based estimates of von Bertalanffy growth parameters. Thomas (1986) suggested a slightly faster growth rate, but Agnalt (1995) found that the first annulus was incorrectly identified, and her growth rates agree closely with the calculated rates for the first year. Examination of length frequency distributions suggests that these lengths give a reasonable separation between cohorts, but some overlap, especially for the larger fish, is inevitable.

RESULTS

Biomass and recruitment

The biomass estimates of the hydroacoustic surveys conducted from 1990 to 2000 are given in Figure 4. The survey estimates indicate a consistent trend from survey to survey, despite sampling *CV*s of at least 25–30%, suggesting that they were sufficiently precise to track trends in the population. Figure 5 shows the number of pre-recruits estimated during the November surveys each year. Overall, the average annual estimate was >5 000 million pre-recruits, but this value was highly variable.

As no survey was conducted towards the end of 1990, the size of the 1990 cohort at the pre-recruit stage is unknown. However, the number of fish present in November 1990 can be back-calculated using the March 1991 survey results and assuming a mortality rate of 0.8 year^{-1}. This gives an approximate value of 2 250 million recruits, suggesting that recruitment from the 1990 cohort was poor. The 1991 and 1992 cohorts were much stronger than those of later years.

In November 1994, some 1 300 million pre-recruits were estimated, well below the average for the decade, but the following year only 1.4 million were estimated. In 1996 recruitment was above average, approximately 8 000 million pre-recruits being the estimate for that November. Since then, recruitment levels have been close to or below the average of the decade.

Catches

The number of purse-seiners in the pelagic fishing fleet remained fairly stable over much of the decade. In 1990, 38 purse-seiners were fishing in Namibian waters and, by 1999, despite the fluctuating catches of the decade, this had only decreased to 32. However, at the beginning of the year 2000 fishing season, as a

Fig. 5: Estimates of the number of pre-recruits (approx. 9–12 months old) obtained directly from acoustic biomass surveys in the period October–December

direct result of the reduced catches of both sardine and juvenile horse mackerel, as well as spiralling fuel costs, only 20 purse-seiners remained in the fleet.

The sardine fishing season opened in March of most years, and it usually closed at the end of August. When *TAC*s were high, for example in 1993 and 1994, catches continued at a steady rate throughout the season (Fig. 6). In the latter part of the decade, when *TAC*s were lower, most of the catch was landed by May. During 1995, fishing in Angola permitted the fleet to operate throughout the year. The *TAC*s for the 1996, 1997 and 2000 seasons were announced later than usual (13th May, 14th April and 1st May respectively).

The start of the decade saw the highest sardine catch since 1977, with 89 000 tons landed in 1990. The *TAC* for that year was only 60 000 tons, but this did not include bycatch, and much of the excess catch was said to result from species misidentification, purse-seiners netting sardine while searching for anchovy or horse mackerel (Boyer *et al.* 1997). More than 90% of the catch consisted of 1-year-old fish from the exceptionally large cohort of the previous year (Fig. 7, and Hewitson and Gilles unpublished, cited in Boyer *et al.* 1997).

A *TAC* of 60 000 tons was allocated for the 1991 fishing season. Having learnt a lesson from the previous year, the regulations were changed such that bycatch was included in the global *TAC* and, with strict control, the catch was 8 000 tons in excess of the *TAC*. The catch was mainly fish >22.5 cm and was therefore again largely reliant on the 1989 cohort (Fig. 7).

Recruitment from the 1991 and 1992 cohorts was reasonable (Fig. 5) and, over the following three years, the *TAC* and consequently the catches increased. The 1991 and 1992 cohorts sustained the catches of the 1992 and 1993 fishing seasons respectively, and a large proportion of the catches of those years consisted of fish <22.5 cm. In 1994 a *TAC* of 125 000 tons was allocated. However, the results of the biomass surveys were raising concerns of serious stock decline, so in the middle of the 1994 fishing season, after the June 1994 acoustic survey, it was recommended that all fishing cease. Regrettably this recommendation was not implemented and fishing continued. However, the fleet failed to catch the *TAC* and, by the end of the season, 10 000 tons of the *TAC* was outstanding. The majority of the catch that year consisted of fish >22.5 cm total length, reflecting poor recruitment from the 1993 cohort and therefore a reliance on older fish.

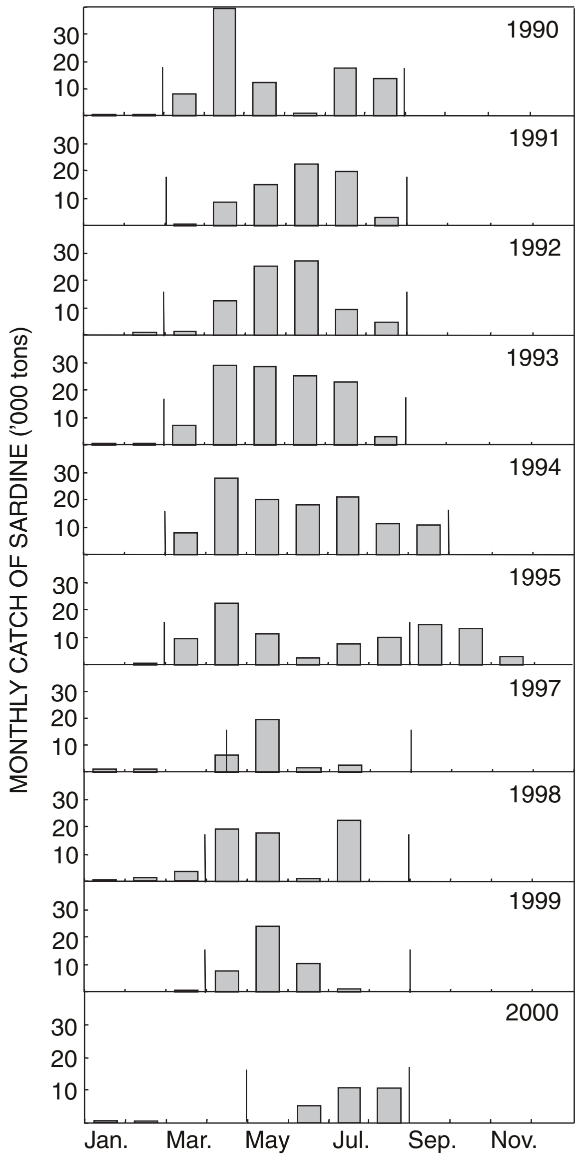

Fig. 6: Monthly sardine catches from 1990 to 2000. Lines indicate the beginning and end of the sardine fishing seasons. Note that the catches in 1996 were insignificant and are not shown. The fishing season was from mid May to end of August in that year

In 1995, despite a scientific recommendation for a moratorium on sardine fishing, a *TAC* of 45 000 tons was allocated. In addition, Angolan authorities gave Namibian purse-seiners licences to catch sardine in Angolan waters, and consequently a total of 92 000 tons was harvested from the northern Benguela that year. Catches were again based on older fish, reflecting the poor recruitment from the 1993 and 1994 cohorts.

From 1990 to 1992 most of the catches were made close to Walvis Bay. The quantity of sardine in Angolan waters had increased considerably in 1994, as a result of movement of sardine to the north. This was reflected in the catches, which in 1994 were made close to the Namibia/Angola border (Fig. 8). In 1995 the stock moved south in response to the Benguela *Niño*, and catches prior to April were made close to Walvis Bay. Following the Benguela *Niño* the stock moved back north and catches later in that season were made in Angola. By the end of the year catches made in southern Angolan waters were equal to those made in Namibia.

In 1996 the industry managed to convince the authorities that there was sufficient sardine to warrant a *TAC* of 20 000 tons, despite the alarming results of the biomass surveys. However only 2 000 tons were caught; 1 000 tons in Namibian waters as bycatch of the industrial fishery and 1 000 tons in Angolan waters. No sardine was canned.

Recruitment from the 1996 and 1997 cohorts was good, considering the size of the spawning stock (Fig. 9), and *TAC*s and catches increased over the following two years, with 65 000 tons of sardine being landed in 1998. In 1997 these catches consisted primarily of recruits from the 1996 cohort, fish of length 20–21 cm, whereas in 1998 and 1999 the fish were larger, 21–23.5 cm. The distribution of the catches shifted south and, similar to the situation in the early 1990s, catches were made close to Walvis Bay (Fig. 8).

Since then it has been argued that there should be a moratorium placed on sardine fishing, but it was recognized that the social and economic consequences would be severe. Hence, the authorities have allowed a low level of fishing to permit the continued survival of this sector of the fishing industry. However, the 1998 and 1999 recruitment indices were well below the average for the decade, and catches declined to 25 000 tons in 2000. The catch was almost entirely sardine <22.5 cm, indicating that the 1996 and 1997 cohorts had largely disappeared and that younger cohorts dominated the population.

DISCUSSION

At the beginning of the 1990s the surveys indicated that there was an increase in abundance of sardine, giving the impression that, after more than a decade

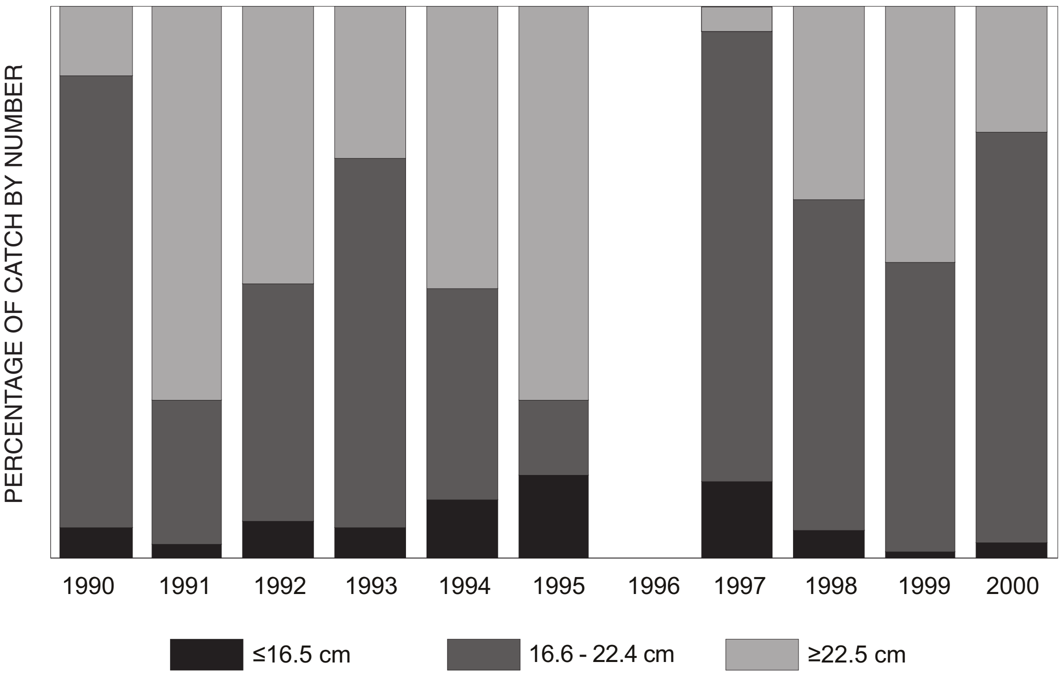

Fig. 7: Proportion of three length-classes (total length) of sardine in commercial catches for the period 1990–2000

of depletion, the stock was recovering. Given the uncertainties of certain key parameters, such as target strength, the survey estimates should be used as indices of abundance rather than absolute estimates. Therefore the absolute biomass at peak abundance in the early 1990s cannot be determined. However, the acoustic estimates are used for management purposes on the assumption that they are unbiased, so indicating a stock size of 600 000–800 000 tons of sardine between 1990 and 1992 (Fig. 4). The estimates discussed below are also presented in tons. Nevertheless, it must be remembered that they should be considered as relative estimates only. One data point generally accepted as accurate is that of the survey carried out at the end of 1995, which indicated that the stock had declined to a few thousand tons.

In addition to the possible negative bias of the early surveys as a result of signal saturation of the Simrad EK400 (see Methods), the changes in transect density, and in particular the increased searching strategy in recent years, are likely to have introduced a positive bias relative to earlier surveys. Work is being conducted to estimate the bias introduced by different searching strategies, but its level is currently uncertain. The practice of resurveying areas of high biomass will, in contrast, tend to introduce a negative bias. Overall it must be concluded that, as scientific equipment has improved and survey strategy has been refined, the accuracy of survey estimates has improved. The likely positive bias of surveys in the latter part of the decade relative to earlier surveys indicates that the declining trend reported here since 1992 will, if anything, have been underestimated.

The following discussion examines the relative importance of fishing and environmental impacts, particularly on recruitment, and why the beginnings of a recovery in the stock in the early 1990s were not sustained.

Effect of fishing

Official records of landings for the decade are a reasonably accurate reflection of total fishing mortality, in stark contrast to the 1960s and 1970s (see Cram 1981). Dumping of unwanted catch is not permitted and since 1991 has been controlled largely by the practice of placing fisheries observers on most fishing vessels. However, cutting nets loose and releasing fish when non-target species or juvenile fish are caught is a

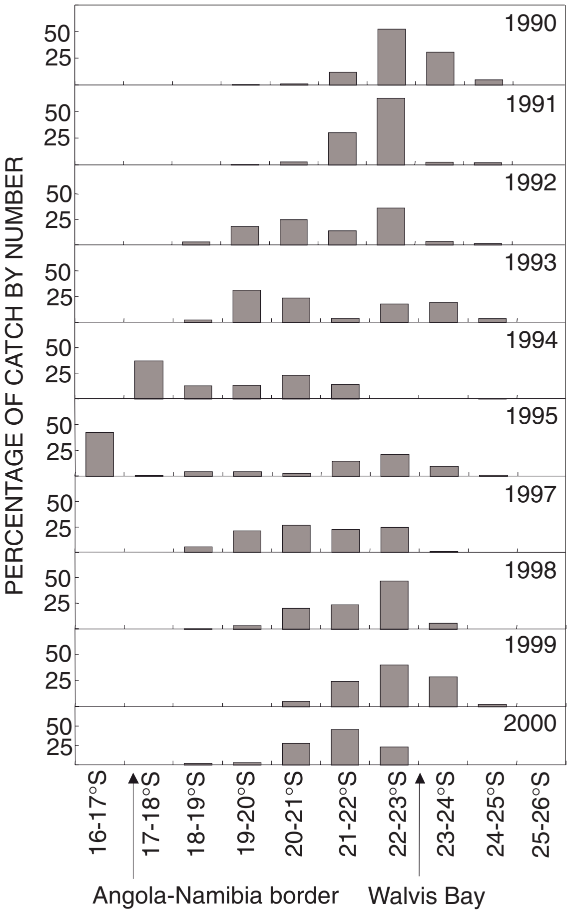

Fig. 8: Distribution of sardine catches by degree latitude during the period 1990–2000. Note that the catches in 1996 were insignificant and are therefore not shown

seemingly accepted practice, especially as punitive measures are often enforced to discourage landings of juveniles. The survival rate of sardine released in this way is not known, but it is likely to be low (James *et al.* 1988). Catching and subsequent release of adult sardine, while targeting other species, is probably not common, because schools of adult sardine are usually distinctive and can normally be identified by fishers before the net is set. However, if more sardine are caught in a set than can be accommodated in the hold of the vessel, or more than is required by the factory at that time, less scrupulous skippers may pump the required amount on board and discard the rest, rather than giving the excess fish, a practice locally termed "bolyn", to another vessel. The extent to which this

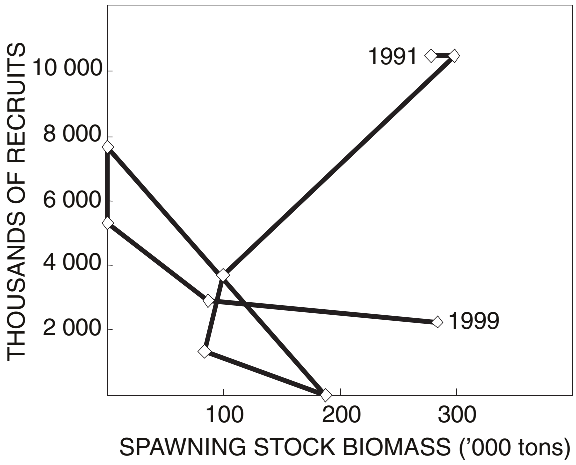

Fig. 9: Number of recruits estimated by the November survey plotted against spawning stock biomass in January of the same year

occurs is not known, but it is not believed to be significant.

During the first half of the decade, the Namibian *TAC* was set almost six months before the start of the fishing season. In 1990 recruitment was not measured, but in 1991, being the first "recruitment" survey, the results were not used for management purposes. For biomass-projection purposes, recruitment was assumed to be average in those years. However, 1991 appears to have been a year of good recruitment, so stock size increased at a faster rate than predicted, and the *TAC* for the subsequent year's fishing season was based on an underestimate of the fishable stock present by the time the season started. This subsequently resulted in fishing mortalities below the target level of 0.2 year^{-1}. It can therefore be concluded that fishing levels were moderate until 1992 or 1993 and probably played a relatively minor role in limiting the size of the sardine stock. Indeed, if conditions were favourable for recruitment and growth, it is entirely plausible that fishing mortality could have been higher than the target level without restricting the recovery of the stock (Jacobson and MacCall 1995).

The fishing pressure exerted during 1994 and 1995, given the size of the stock, was excessive. In 1994 the total biomass was estimated at just over 200 000 tons and the *TAC* was 125 000 tons, although only 115 000 tons were landed. This failure to catch the *TAC*, which had only previously occurred in 1976 and 1978, should have sent warning signals to all parties. However, despite a decline in the biomass to around 100 000 tons by 1995, a *TAC* of 45 000 tons was set. Given the

Table II: Summary of population trends in sardine, 1990–2000, their reasons, and the major environmental anomalies during the same periods

Period	Population trend	Reasons	Environmental anomalies
1990–1992	Increase	Good recruitment + moderate fishing levels	None
1993–1995	Severe decline	Poor recruitment + excessive fishing	Low oxygen, warm SST, Benguela *Niño*
1996	Large increase	Good recruitment + no fishing	None
1997–2000	Slight decrease	Poor recruitment + moderate fishing	None

small size of the stock, and its rapid decline since 1992, fishing at such a level was likely to be very risky.

In addition, for the first time in more than two decades, vessels were permitted to catch sardine in Angolan waters, starting in late 1994. No limits were placed on the catch, and this increased the harvest to 92 000 tons in 1995, from a stock estimated to be not much larger than this. Following the adverse environmental conditions of the Benguela *Niño* earlier in the year, this catch proved catastrophic. Apart from about 1 000 tons caught in 1996, and minor amounts harvested by artisanal fishers, no sardine have been caught in Angolan waters since 1995.

Despite the establishment of a *TAC* of 20 000 tons in 1996, industry was unable to catch sufficient sardine to open any canneries, supporting the survey results and so confirming that the stock had declined to levels rarely seen in any of the other major sardine stocks of the world (cf. Beverton 1990). Since then, the stock has increased slightly and *TAC*s have followed suit. Despite caution being advised by scientists, the final years of the decade saw *TAC*s once again based on a strategy of $F = 0.2$ year^{-1}. Finally, in 2000, despite intense lobbying from the fishing industry, the *TAC* was limited to 25 000 tons, approximately 10% of the total stock size.

Environmental effects

This paper does not attempt a detailed investigation into the effects of environmental factors on critical stock parameters (such as recruitment), but is rather a general synopsis of the major stock fluctuations during the past decade and the possible causes. For this purpose the environmental conditions in the 1990s have been divided into three broad periods (Table II).

1990–1992

There was a relatively cool period at the beginning of the decade until mid 1992 (Fig. 10), but this early part of the decade is not noted for any particularly adverse environmental features. Stock size was boosted by recruits from the 1989 cohort, and recruitment was above average in 1991 and 1992. During this period, the biomass reached its highest level since prior to the crash of the mid 1970s. Sardine recruitment is generally reported to improve during moderately warm periods (Jacobson and MacCall 1995, Cole and McGlade 1998). However, as outlined in Bakun's (1996) Triad hypothesis and the Optimal Environmental Window hypothesis of Cury and Roy (1989), the factors controlling successful recruitment are complex and, whereas sea surface temperature (SST) is a proxy for some of these, other factors may have assumed greater importance during those years.

1993–1995

Several major environmental anomalies were recorded during this second period. For much of 1993 and 1994, a body of poorly oxygenated water, estimated to be between 50 and 250 m in vertical extent, lay over the Namibian shelf, and levels as low as 0.25 mℓ ℓ^{-1} were measured between Cape Frio and Walvis Bay (Hamukuaya *et al.* 1998). Although poorly oxygenated bottom waters occur seasonally during periods of reduced upwelling as a result of the decay of organic matter, this event affected a much larger body of water and persisted for longer than usual. Events such as this are thought to be attributable to an influx of water from the Angola Dome (Bubnov 1972). Furthermore, much of the period was characterized by warm surface waters extending over the entire inshore region of the Namibian shelf (Fig. 10). This culminated in a Benguela *Niño* in February and March 1995, when a positive temperature anomaly of up to 8°C was recorded in the upper layers, with a deepening of the thermocline by about 20 m. This unusually warm water mass was found from Cabinda (5°S) to at least 24°S, although above-average temperatures were recorded as far south as Lüderitz (27°S). Benguela *Niños* are thought to be associated with large-scale changes in wind patterns resulting in the poleward movement of warm tropical waters. The southernmost penetration of surface waters was at the beginning of March 1995, after which it retreated with the onset of south-westerly

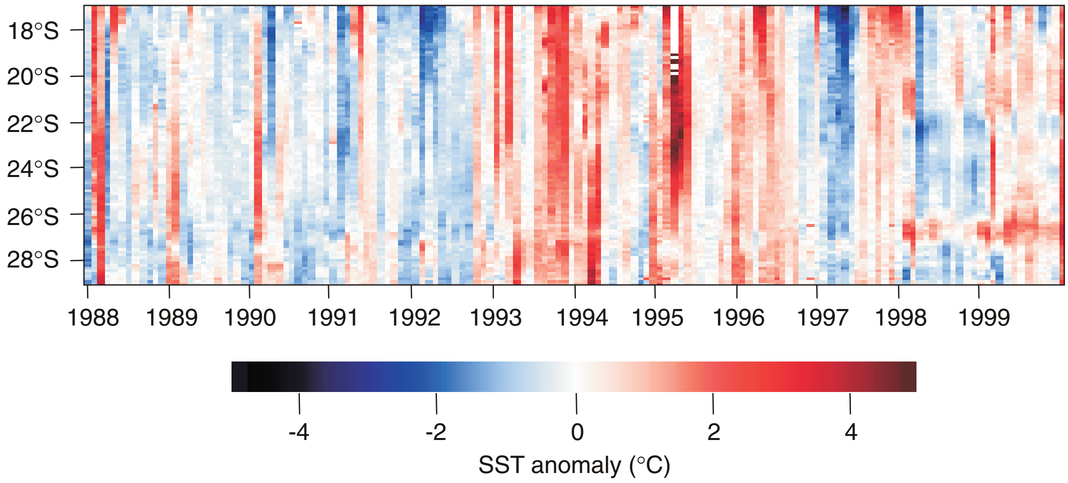

Fig. 10: Sea surface temperature along the Namibian coast (mean from the coast to 50 km offshore). Data supplied by EU project ENVIFISH, contract no. IC18.CT98-329

winds (Gammelsrød *et al.* 1998).

These anomalous environmental conditions are likely to have resulted in the poor recruitment of those years. De Decker (1970) reported a reduction in the number of sardine eggs following a low oxygen event off the west coast of South Africa in summer 1967/68. In 1963, a year in which a strong Benguela *Niño* was recorded in the northern Benguela, sardine eggs were virtually absent during the main spawning months (Stander and De Decker 1969). Boyd *et al.* (1985) reported an order of magnitude reduction in sardine egg production, but good survival of larvae, following the 1984 Benguela *Niño*. Therefore, it is perhaps not surprising that recruitment was poor during 1993 and 1995 and that the lowest recruitment index for the decade was estimated by the November 1995 survey. The composition of the 1993–1995 catches confirmed the poor recruitment indices, because they increasingly comprised larger fish.

Despite relatively high numbers of recruits entering the fishable stock in the early 1990s, these cohorts were reduced at rates seemingly greater than could be accounted for by fishing and expected rates of natural mortality (Fossen *et al.* 2001). Whether this apparently high rate of mortality was due to natural factors affecting the survival of sardine or was an artefact of survey bias is at present unclear.

Population declines and large-scale shifts in distribution were recorded in a number of other species during the period 1993–1995, suggesting an increased rate of natural mortality attributable to adverse environmental conditions. The Namibian hake stocks migrated farther offshore (Hamukuaya *et al.* 1998) and their fishable biomass declined by almost half. Monkfish catches fell by more than 25% (Maartens 1999), a significant decline in the horse mackerel stock was recorded and catches of both juvenile and adult components of that stock fell by about 50% (Boyer and Hampton 2001). The Namibian anchovy stock, which had been severely depleted for some years, almost disappeared, and since then catches have averaged around 1% of previous levels. This culminated in dramatic declines of several of the top predator populations, notably those of Cape fur seal *Arctocephalus pusillus pusillus*, which was reduced by about one-third in 1994 and 1995 owing to starvation (MFMR 1997, Roux 1998, Cury *et al.* 2000), and bank cormorant *Phalacrocorax neglectus*, which declined by an even greater amount (Crawford *et al.* 1999). Sardine mortalities were observed once, when a number of dead and dying sardine were found in Baìa dos Tigres during the 1995 Benguela *Niño*, where water temperatures were >27°C throughout the water column. However the numbers of sardine were small in relation to the total stock size. No large-scale die-offs, as reported in Australia at the same time by Schwartzlose *et al.* (1999), were observed.

1996–2000

No marked environmental anomalies were recorded during the latter half of the decade. Sea surface temperatures were close to the long-term average with the exception of early 1997, which was slightly cooler than average (see Fig. 10).

The 1996 and 1997 cohorts were relatively strong, and the sardine biomass increased from a few thousand tons in 1996 to around 300 000 tons a year later. The fact that this increase in biomass was a result of recruitment was supported by the fact that catches were composed of 96 and 65% fish <22.5 cm in 1997 and 1998 respectively.

The concept of a relationship between spawner biomass and recruitment may be simplistic, especially for a small pelagic species such as sardine, but a minimum threshold biomass has been used by management, suggesting that such an approach has been informative (see Ulltang 1996). It is worth noting that, during the 1990s, there has been a very poor spawner stock-recruitment relationship (Fig. 9). Whether this means that the relationship reported by Butterworth (1983), but see also Fossen *et al*. (2001), has broken down or, more likely, that other factors have superseded it, is not known.

The 1998 and 1999 recruitment indices were again below average for the decade, the biomass showed a downward trend, and the average size of the fish caught again increased as catches largely comprised older fish from the relatively strong cohorts of 1996 and 1997. It is interesting to note the change in distribution of the stock during 1997. Instead of the normal inshore distribution of sardine in a water depth of <100 m, most of the stock moved offshore to depths of 200–300 m, and remained there throughout 1997 and 1998. It is not known if recruitment was poor as a direct consequence of this change in distribution, or if it was attributable to the colder-than-normal conditions.

Long-term populations changes, regime shifts and ecosystem effects

In order to put the changes in sardine abundance recorded in the northern Benguela during the past decade into perspective, it is necessary to consider historical trends in the population, as well as the synchronous changes in small pelagic stocks in other upwelling systems (Schwartzlose *et al*. 1999) and the possibility of a linkage through global teleconnections to the northern Benguela sardine stock.

Indices of sardine abundance prior to commercial harvesting are limited, but core samples of anoxic sediments off Walvis Bay indicate that, during the past 500–600 years, sardine abundance fluctuated considerably in the absence of fishing, although it was the dominant clupeoid (Shackleton 1987). If correct, this is in contrast to other eastern boundary upwelling regions, where alternating periods of abundance of sardine and anchovy, known as regime shifts (Lluch-Belda *et al*. 1989, 1992), have been well established (Schwartzlose *et al*. 1999). Guano deposits also suggest substantial stock fluctuations during the early part of this century in the northern Benguela, prior to the onset of the commercial fishery (Crawford *et al*. 1983). Opinions differ as to the causes of these population fluctuations, but they include long-term environmental effects such as continuous modification of habitat, changes in food composition and temperature, as well as episodic environmental events that may trigger changes and result in a shift in species dominance (Beckley and van der Lingen 1999, Schwartzlose *et al.* 1999). Intense fishing on pelagic populations since the middle of the century has been an additional factor that further complicated the issue.

With the onset of commercial harvesting, and particularly following the decline of the sardine stock in the late 1960s and mid 1970s, pelagic goby, anchovy and horse mackerel stocks increased (Crawford *et al.* 1985, 1987). This suggests some form of replacement of sardine by other species. Yet during the 1990s, the stock levels of all small pelagics have been depressed. Anchovy catches declined from an average 170 000 tons per year in the 1970s and 1980s to 25 000 tons in the 1990s (Boyer and Hampton 2001), and a total of only 7 000 tons has been landed in the past five years. Annual catches of juvenile horse mackerel have been rather variable, averaging around 35 000 tons between 1971 and 1981 and then doubling to more than 75 000 tons until 1996. In the past four years they have declined to about 20 000 tons, and the fleet has been unable to land the *TAC* (Boyer and Hampton 2001). The starvation of thousands of seals in 1994 (MFMR 1997, Roux 1998, Cury *et al.* 2000) and again in 2000 (DCB, pers. obs.) provides evidence, albeit circumstantial, that the goby stock, a major prey item of seals during periods of reduced sardine and anchovy availability (David 1987), was also not abundant.

Following the collapse of the sardine industry in the late 1970s, a management strategy to reduce the anchovy population was implemented in the belief that it would enhance the chances of a recovery of the sardine stock (Butterworth 1983). While such a strategy is no longer followed, excessive fishing capacity in the local purse-seine fleet means that stocks of anchovy and juvenile horse mackerel are heavily fished whenever available. Cury *et al.* (2000) suggest that the removal of a dominant competitor (e.g. sardine in the northern Benguela) should favour the subordinate species provided the latter are lightly exploited. Hence, it seems quite possible that the anchovy stock, and perhaps also that of juvenile horse mackerel, has had little chance to occupy the vacant niche left by the reduced sardine stocks. Additionally, throughout the past century the seal population in the northern Benguela has been recovering from near extinction in the early 1900s (David 1989) to levels of around 1 million individuals by the mid 1990s (David 1997). As a major top predator of pelagic fish (Wickens *et al.* 1992), especially sardine, anchovy and horse mackerel, it seems reasonable to assume that seals have some impact on the population dynamics of the small pelagic resources.

In the late 1980s some of the major small pelagic stocks in eastern boundary upwelling systems, and in other regions, were showing signs of recovery, e.g. Californian sardine, anchovy *Engraulis ringens* in the Humboldt Current and sardine in the southern Benguela. In contrast, other populations were declining, most notably the Japanese sardine, sardine in the Humboldt Current and anchovy in the southern Benguela (Schwartzlose *et al.* 1999). Such synchronous changes in abundance led to the hypothesis of global teleconnections driving population changes (Lluch-Belda *et al.* 1989, Kawasaki 1991, Bakun 1996). The northern Benguela sardine stock seemed to show the beginnings of a similar increase in the late 1980s, but this reversed in the period 1992–1993. Schwartzlose *et al.* (1999) noted that fishing has the potential to decrease the extent and duration of periods of high abundance, as well as to depress and prolong periods of depletion, and suggested that fishing could even prevent the recovery of a species and so turn a potential period of high abundance into the continuation of a period of depletion. It is tempting to speculate that, in the absence of heavy fishing pressure in the middle of the decade, the northern Benguela sardine population may have weathered the adverse environmental conditions of the mid 1990s, and that by the end of the decade it could have been recovering along with many other small pelagic stocks around the world.

Sardine are considered an important component in the ecosystem as a controller of the abundance of both predator and prey species – the so-called wasp-waist hypothesis (Bakun 1996, Cury *et al.* 2000). The decline in sardine abundance off Namibia between 1991 and 1994 almost certainly contributed to the starvation of many tens of thousands of seals in 1994. In addition, sardine may also play a role in controlling primary productivity (Reid *et al.* 2000) and, during periods of low abundance, the result could be underutilization of phytoplankton and localized eutrophication of waters. Through this process, it seems likely that the fact that the sardine population has been reduced may actually be enhancing the build-up of poorly oxygenated water, possibly leading to enhanced production of toxic hydrogen sulphide. These processes could be further reducing the chances of a recovery in the stock, especially as the main recruitment area (off Walvis Bay) coincides with the region where the most severe anoxic conditions develop regularly.

Management considerations

It appears that the processes causing the decline of the sardine stock in the mid 1990s were similar to those of earlier declines; several years of poor recruitment led to reduction in biomass and narrowing of the age structure of the stock (see Fossen *et al.* 2001). Then continued fishing led to an ever-increasing fishing pressure until, in 1996, there were simply so few schools remaining that the fleet was unable to locate any sardine at all. Even the slight increase in 1997 and subsequent increase in fishing levels is remarkably similar to the recovery and increased *TAC*s in the early 1970s.

Similar stocks driven to such low levels have taken many years, and in some cases decades, to recover. The Japanese sardine reached low levels of abundance in the 1940s, and started to recover only in the early 1970s, whereas the Californian sardine crashed during the 1950s and only three decades later has a recovery become apparent. The sardine stock of the southern Benguela crashed in the 1960s and has also only shown a recovery in the past decade. While it is tempting to predict that the northern Benguela sardine stock may take many years to recover, even to the moderate levels of the early 1990s, the good recruitment from the 1996 year-class provides a clear reminder that, given favourable conditions, sardine stocks have the reproductive capacity to recover fairly quickly. Jacobson and MacCall (1995) suggest that target exploitation rates should be based not only on biomass levels, but also on recent sea surface temperature (SST) or other environmental variables (see also Fréon 1988). This is one of the few examples where an environmental index has actually been used in assessments to modify management action (Myers 1998). Additionally, the maximum sustainable yield for Pacific sardine was much lower when environmental factors were less favourable (in that system a colder-than-average SST) and much higher when environmental factors were more favourable, indicating substantial harvesting potential when conditions are favourable, but little or no harvesting potential when conditions are poor. Determining what conditions are favourable is complex and is a major preoccupation of many fisheries biologists, both in Namibia through collaborative and national research programmes, and elsewhere.

During much of the 1990s the stock was dominated by a single cohort and was clumped into a few small areas. The chances of benefiting from the combination of environmental conditions that result in good recruitment are likely to be considerably reduced under such circumstances. Le Clus (1989) noted that older fish have a more protracted spawning period and produce more and larger eggs. Also, of course, a population with several year-classes is more able to withstand years of poor recruitment. Therefore, in order to increase the likelihood of good recruitment, an increase in both the spatial distribution and the age structure is likely to be beneficial (Sharp 1995). Sharp and Csirke (1983) provide an overview of the variability in abundance of many of the world's major pelagic resources and, in particular, discuss management strategies that take account of large-scale changes in these systems.

Whether the Namibian sardine population will be able to rebuild to historical levels (prior to fishing) is less clear. Some changes in the system suggest that a regime shift may have occurred. Horse mackerel and anchovy, rarely seen in the 1960s, suddenly became abundant in the 1970s (although it must be noted that anchovy has since virtually disappeared again). Jellyfish *Chrysaora hysoscella* and *Aequorea aequorea* have increased to levels at which they affect surveys and disrupt fishing. Whether they also consume sufficient levels of ichthyoplankton to act as a control on the sardine stock is unknown, but the potential cannot be discounted (Möller 1984).

A weakness inherent in fisheries science is the uncertainty with which current stock sizes and productivity can be determined and the inability to project these into the future (Rose 1997). This has clearly been the case with the northern Benguela sardine stock, and this uncertainty has been exploited by industry to push for higher *TAC*s. Changes in assessment methodology have increased the accuracy of abundance estimates, but they have also meant that different estimates are not directly comparable. Further progress in improving the survey methodology to increase the precision and accuracy of the estimates is needed in order to provide managers with the quality of information needed to take politically unpopular decisions, particularly to defend reduced catches. Managing sardine on a single-species basis, and excluding cognisance of environmental forcing, also seems unlikely to succeed when exogenous factors are known to affect population abundance (see Fossen *et al.* 2001). The processes that lead to changes in abundance, distribution, recruitment, mortality rates and all the other factors that determine whether catches are good or poor need to be better understood and explained clearly to fisheries managers and industry. This will promote greater confidence in fisheries science and in the recommendations upon which management decisions are taken.

Almost three decades ago, Cram and Visser (1973, quoted in Cram 1981, p.149) noted: "industry had to decide what it wanted: restoration, or the stagnation of a reduced and fragile pilchard stock. It could not have increased quotas and [long-term] growth". This question still needs to be answered, although maybe it should be more appropriately addressed to policy makers rather than to industry. The current strategy of allowing a so-called socio-economic *TAC* to ensure survival of the industry, while simultaneously hoping that the stock will recover, has obviously not worked. If the northern Benguela sardine stock is to recover to anything like its former levels of abundance, managers must strive to promote a healthy spawning stock, composed of a number of age-classes widely spread throughout the region. Only then, and given favourable environmental conditions, are recruitment levels likely to be sufficient to support a strong sardine fishing sector again.

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