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THE APPLICATION OF A MANAGEMENT PROCEDURE TO REGULATE THE DIRECTED AND BYCATCH FISHERY OF SOUTH AFRICAN SARDINE *SARDINOPS SAGAX*

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The South African sardine *Sardinops sagax* resource is subjected to both directed fishing that targets adult fish, and bycatch of both juvenile and adult fish taken in the directed fisheries for anchovy *Engraulis capensis* and round herring *Etrumeus whiteheadi*. Two separate *TAC*s (Total Allowable Catch) for sardine are calculated in the management procedures considered. The first is a directed *TAC* linked to sardine abundance, and the second is a bycatch *TAC* with an "anchovy" component coupled to the anchovy population dynamics as a proportion of the anchovy *TAC*, plus a "round herring" component reflecting a fixed tonnage independent of round herring abundance. Requirements from the pelagic industry, such as a minimum economically viable annual directed catch and a maximum percentage decrease in the directed *TAC* that could be tolerated from year to year are also incorporated. The selection of a single management procedure for implementation is based on the comparison of performance statistics such as risk of severe depletion and average annual catch, which incorporate the consequences of random error in survey estimates of abundance and random fluctuations in recruitment from year to year. Sensitivity tests are carried out to ensure robustness over a range of alternative assumptions concerning resource dynamics. A description is given of the development of the management procedure for sardine that was implemented in 1994, and the rationale for its selection. A wide range of variants to this procedure, including those that consider alternative approaches for handling bycatch, are investigated. Performance of the management procedures considered demonstrates extreme sensitivity to the choice of the proportion of the anchovy *TAC* used in the sardine bycatch *TAC* calculation. A lack of robustness of the selected management procedure to possible bias in estimates of spawner biomass from hydroacoustic surveys, and poor precision of recruit survey estimates are argued as justification for adopting a conservative approach for managing sardine.

Although South African sardine (or pilchard, *Sardinops sagax*) were first canned in 1935, commercial purse-seine fishing for the species was initiated only in 1943 to satisfy the war-time demand for canned fish, and major development of the South African pelagic fishery took place only after the war (Crawford 1979, Butterworth 1983). Fishing was initially confined to the St Helena Bay area, where both sardine and horse mackerel *Trachurus trachurus capensis* were target species, but activities soon expanded beyond this area as catches declined and the pelagic fishery grew (Armstrong *et al*. 1985, Crawford *et al*. 1987). Fishing is currently concentrated in an area from south of Doring Bay on the West Coast to west of Cape Agulhas on the South Coast, and around Port Elizabeth on the South-East Coast (Fig. 1). The annual "sardine run" off the coast of KwaZulu-Natal around June also constitutes a small fishery for sardine in the form of beach-seine fishing regulated by limited entry (Baird 1971, Armstrong *et al*. 1991). The relative contributions of catches from different regions to the total catch are shown in Figure 1.

Annual landing of sardine peaked between 1957 and 1964, when catches ranged from 250 to 410 thousand tons and sardine formed the basis of the Western Cape purse-seine fishery (Fig. 2). Thereafter, a steady decline set in, followed by catches an order of magnitude lower for the next 25 years. The impact of this decline in sardine catches on the industry was offset in the mid to late 1960s by the introduction of nets with smaller mesh size, which permitted the capture of anchovy *Engraulis capensis* and juveniles of other pelagic fish. The introduction of the smaller mesh size led to several changes in the pelagic fishery:

(i) it brought about a pronounced change in the age composition of the sardine catch, the incidence of 0-year-old fish increasing to average some 60% of the annual total catch by number (Armstrong *et al*. 1983);
(ii) anchovy catches dominated pelagic landings from 1966 to 1994;
(iii) as anchovy and sardine frequently shoal together during their first few months of life (Crawford

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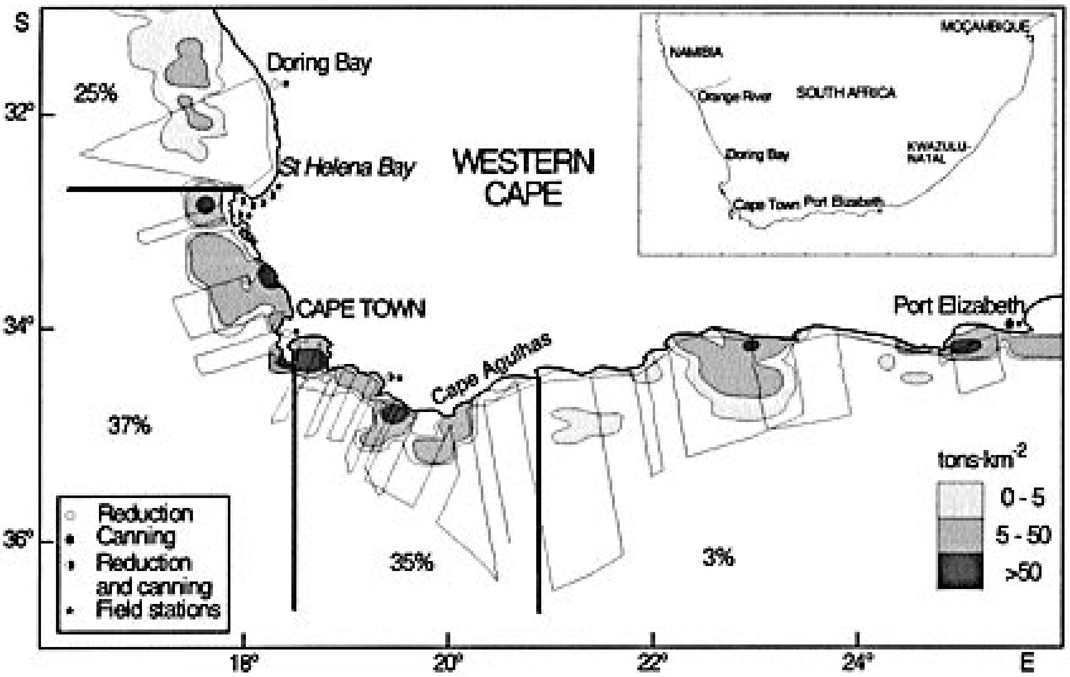

Fig. 1: Map of Southern Africa with the surface distribution of sardine density in November/December 1994, as interpolated by kriging, with survey tracks superimposed and shown by a thin solid line running perpendicular to the coast (reproduced with modification from Barange and Hampton 1997). The percentages given for each of four regions (separated by thick solid lines) indicate the average proportion of the total catch taken in the region from 1990 to 1994. Reduction, canning and combined reduction and canning factories for pelagic fish, and field stations, where scientific samples are taken to determine length and species composition of the landings, maturity and condition factors of the fish, and to collect otoliths for ageing, are also indicated

1981), directed fishing for anchovy was inevitably accompanied by a bycatch of juvenile sardine.

These consequences all have important implications for the development of a management procedure for sardine, as is explained later.

Various forms of restrictions have been applied to the pelagic fishery since 1950, including limitations on processing and vessel capacity, closed seasons, mesh size restrictions and a combined sardine and horse mackerel *TAC* (Total Allowable Catch), applied with varying degrees of strictness between 1953 and 1959 (Butterworth 1983). A global *TAC* encompassing the main contributors to the pelagic fishery, namely sardine, anchovy, horse mackerel, chub mackerel *Scomber japonicus*, round herring *Etrumeus whiteheadi* and lanternfish *Lampanyctodes hectoris* was applied from 1971 onwards. The basis for that *TAC* was intuitive rather than scientific, and was motivated by a belief that a global *TAC* would provide some insurance against fluctuations in the stock of a particular species in the context of a pelagic fishery which exploited many species (Butterworth 1983). The global *TAC* was reduced to a combined sardine and anchovy *TAC* in 1983, with no restrictions on the other pelagic species (to encourage diversification of the fishery, given its heavy dependence on anchovy), and to species-specific *TAC*s for sardine and anchovy from 1984 onwards to achieve more control over fishing on the reduced sardine resource and to prevent overexploitation of anchovy (Armstrong 1984).

In 1984, the Fisheries Advisory Council (FAC, the statutory body then providing advice to the minister responsible for fisheries management) adopted a conservative approach for harvesting sardine in order to encourage rebuilding of the resource (Anon. 1986, 1989). Sardine *TAC*s were kept relatively low between 1984 and 1989, and scientific advice to the FAC was always accompanied by a strong recommendation to avoid catching juvenile fish. Over this period, sardine

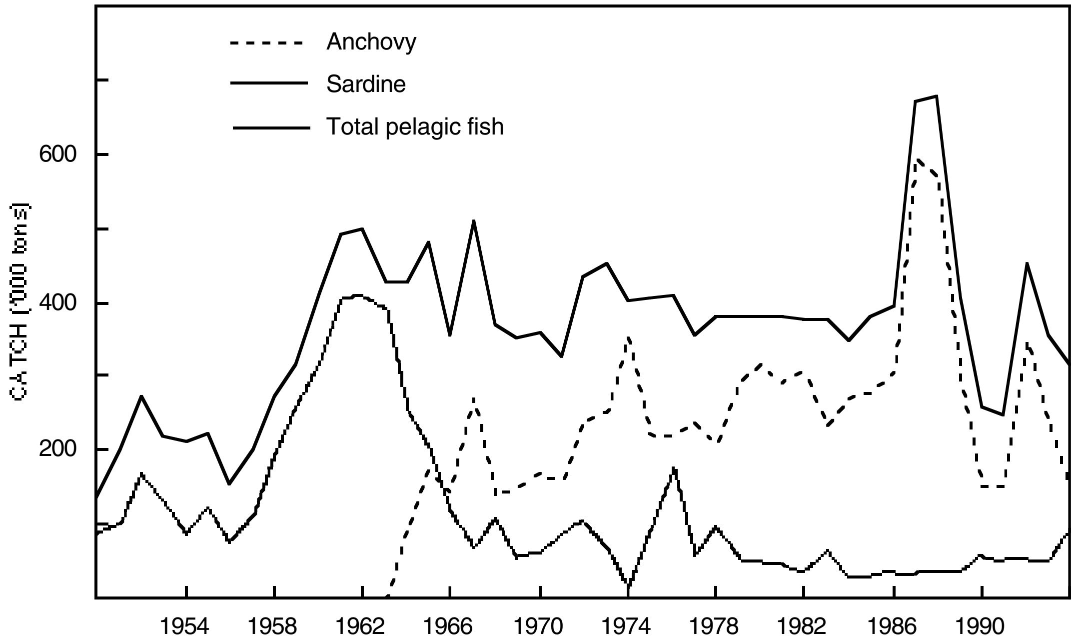

Fig. 2: Annual landings of all pelagic fish (i.e. sardine, anchovy and other species) combined, and separately of sardine and of anchovy, in South Africa from 1950 to 1994

*TAC*s remained between 30 and 40 thousand tons and were derived on the basis of biomass trends from VPA analyses of commercial catch-at-age data. Although annual hydroacoustic estimates of stock biomass (both sardine and anchovy are covered by these surveys) were available from November 1984, they were not used for setting *TAC*s until 1987, because the earlier results were considered too imprecise because of the low abundance and patchy nature of the sardine resource (Anon. 1988, Hampton 1992). A constant proportion strategy was used to recommend *TAC*s from 1987 to 1989, with the *TAC* calculated as 15% of the November hydroacoustic survey estimate plus 30% of the historic mean recruitment biomass (Punt 1989).

A maximum likelihood VPA assessment approach (MLVPA) for sardine similar to ADAPT (Gavaris 1988) and based on maximum likelihood estimation was developed during 1989 (Punt 1989), and population parameters and variables estimated by this method form the basis of the management procedure discussed in this paper. The MLVPA can take into account all available information on independent indices of abundance and their associated standard errors, in addition to commercial catch-at-age data (Appendix 1). It treats the fishing mortalities at age for the last year for which data are available as estimable parameters, so as to provide trends in biomass and recruitment that match the trends inferred from the independent indices as closely as possible (Anon. 1989, Punt 1989). This approach constituted a notable advance over the earlier VPAs, which had not taken appropriate account of the variances and possible bias associated with the biomass estimates from surveys (Anon. 1989).

Over the period 1990–1993, the MLVPA was used to calculate *TAC*s directly by using an $F_{status\text{-}quo}$ strategy, which sets the fishing mortalities in the year for which the *TAC* is being calculated to a constant multiple of those in the most recent year, or to the average over a pre-defined period (Punt 1989, Cochrane *et al*. 1998). The reasons for the change were that Punt (1989) found that the constant proportion strategy could lead to large interannual variations in *TAC*, whereas the $F_{status\text{-}quo}$ strategy yielded *TAC*s which were more precisely estimated and varied considerably less. Furthermore, the constant proportion strategy was based on assumed reliability of the hydroacoustic estimates of biomass in absolute terms. In contrast, the $F_{status\text{-}quo}$ strategy sought to keep fishing mortality at the same level (even though the magnitude of that level was not well determined because, for example, of uncertainties about the value of natural mortality) as the average over the period 1987–1989. The sardine resource had increased over the period 1987–1989, so that a strategy of continuing to apply the corresponding average level of fishing mortality was considered a reasonably safe approach.

However, as time progressed, concerns grew that this somewhat *ad hoc* choice of a target level of fishing mortality might not be making the best use of the resource. Furthermore, problems with sardine bycatch were being encountered that undermined the effectiveness of the recommendations based on the $F_{status\text{-}quo}$ approach, and there was an increasing need for separate sardine directed and bycatch *TAC*s. Therefore, an entirely new approach for setting sardine *TAC*s was used from 1994 onwards, when a "management procedure" was used as a basis for managing sardine for the first time. A brief description of the management procedure then applied is presented in Cochrane *et al*. (1998), in the context of an overview of the application of management procedures in the South African pelagic fishery. The aim of this paper is to give a detailed description of the methodology applied in developing this sardine management procedure, as well as to investigate various alternative options to manage sardine bycatch.

DEVELOPMENT OF A MANAGEMENT PROCEDURE FOR SARDINE

The concept of management procedures as applied to some of South Africa's major fisheries has its roots in research undertaken by the Scientific Committee of the International Whaling Commission towards developing the Revised Management Procedure for application to commercial whaling (Kirkwood 1992, Butterworth *et al*. 1997, Cochrane *et al*. 1998). Management procedures are described by Butterworth *et al*. (1997) as pre-agreed sets of possibly quite simple rules (called management decision rules) for translating data from the fishery into a *TAC* (or other regulatory measure) each year. The words "pre-agreed" define the underlying philosophy of management procedures, namely that all parties (scientists, industry and managers) should agree upon the decision rules *before* they are implemented. These rules specify exactly how the regulatory level is calculated, and what data are to be used for this purpose, and might typically be implemented for a period of 3–5 years, after which they would be reviewed in terms of new information and possibly modified in consequence.

The management procedure approach differs somewhat from the conventional fisheries management approach where the process of setting the regulatory measure is reviewed each year. This annual review typically includes a re-analysis of the data and methodology for setting the regulatory measure, and aims to achieve the best possible assessment of the resource each year. In contrast, once a management procedure is selected, it is left to operate "automatically" for the 3–5 year implementation period. Only after this period is a review of the data and methodology carried out; where necessary, these are modified in the light of any changes in understanding of the resource or fishery that may have occurred in the interim (Butterworth *et al*. 1997, Cochrane *et al*. 1998).

The selection of a management procedure from an array of candidate procedures is achieved by testing each candidate procedure for a range of possible future scenarios for the resource. These scenarios incorporate two levels of uncertainties. First, there is stochastic uncertainty that deals with observation (i.e. sampling) error in the data, the consequent imprecision of estimates of the values of model parameters, and future random fluctuations in recruitment. Second, there is the uncertainty about the assumptions made in the model, such as the nature of the stock-recruit relationship. The basis for selection from candidate procedures is the consideration of outputs of direct interest to industry and managers. These relate to anticipated performance of the fishery and resources in the medium term (10–20 years), and give attention to the uncertainties (mentioned above) associated with the status and productivity of the resource, and the important assumptions in the underlying model.

In their paper on the application of management procedures in the South African context, Butterworth *et al*. (1997) question whether the benefits of conventional methods of managing fisheries based on annual "best assessments" (such as the $F_{status\text{-}quo}$ strategy used for the fishery over the years 1990–1993) are justified in terms of their costs. They argue that these methods often require analyses of a large quantity of data each year involving many scientists, and hence are costly and tend to focus too much time on the short term instead of on more important problems that can be addressed properly only over a longer period. They add that substantive changes in the scientific understanding of developed fisheries occur on a time-scale closer to 5 years than 12 months, so that annual assessments, which often include only one new data point, generate little new information within one year. They suggest that the management procedure approach may be a more cost-effective way of managing fisheries. In addition, they suggest that a valuable spin-off is the automatic refocusing of research on the longer term, essentially towards

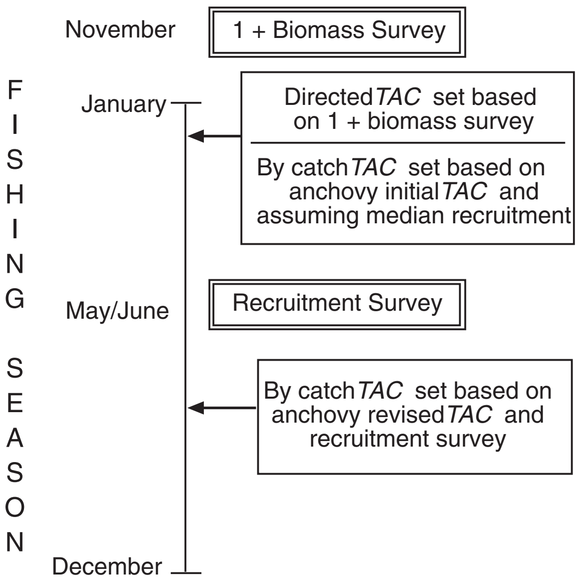

Fig. 3: Simplified representation of the process of setting *TAC*s for the South African sardine fishery

those model assumptions about which there is uncertainty to which simulation tests show the anticipated performance of the management procedure to be very sensitive.

Management decision rules

Development of a management procedure for sardine coincided with the update of a similar procedure for anchovy (Butterworth *et al.* 1993, De Oliveira 1995). Both these procedures were used for the first time at the start of 1994 to set *TAC*s, and the suggestion made by Butterworth *et al.* (1993) with respect to anchovy that the management procedure "should be kept extremely simple, so that this step in the overall management process involved minimal delay" was also followed for sardine.

Figure 3 reflects the typical annual cycle in the management of the sardine fishery. The diagram shows the importance of the pelagic spawner biomass and recruit surveys for setting *TAC*s. Essentially, the management procedure for sardine provides three *TAC*s each year based on these surveys. The first *TAC*, a directed catch *TAC*, is set in January/February, and is calculated as a proportion (z) of the 1+ biomass estimate from the preceding November spawner biomass survey:

$$TAC_{dir}(y) = zB^{sur}_{y-1,1+} \quad , \qquad (1)$$

where $B^{sur}_{y-1,1+}$ is the 1+ biomass estimate from the November spawner biomass survey in year y–1.

The other two *TAC*s apply to sardine bycatch, and are designed to accommodate the bycatch of sardine which occurs with directed fishing for other species of pelagic fish. Each bycatch *TAC* (initial and revised) consists of two bycatch components – adult and juvenile. The adult component is a constant quantum (the same for both the initial and revised bycatch *TAC*s) and is intended to accommodate the adult sardine taken as a bycatch in, primarily, the directed fishery for round herring (some adults are also taken in the directed anchovy fishery). The size of the juvenile component of the *TAC* is related to that of the anchovy *TAC*, and (for the revised bycatch *TAC* only) also to the estimate of sardine recruitment from the midyear recruitment survey. This component is intended to accommodate the juvenile sardine unavoidably taken as a bycatch in the directed juvenile anchovy fishery because of the mixed-species nature of the shoals.

The initial sardine bycatch *TAC* is calculated in January/February and depends upon the initial anchovy *TAC*:

$$TAC^{init}_{byc}(y) = TAC^{ad}_{byc} + x^{init}\, TAC^{init}_{anch}(y) \quad , \qquad (2)$$

where TAC^{ad}_{byc} is the adult bycatch component taken primarily in fishing for round herring, and

$TAC^{init}_{anch}(y)$ is the initial anchovy *TAC*.

The revised sardine bycatch *TAC* is calculated following the midyear recruitment survey and depends both upon the revised anchovy *TAC* and the estimate of sardine recruitment from that survey:

$$TAC^{rev}_{byc}(y) = TAC^{ad}_{byc} + x^{rev}\, TAC^{rev}_{anch}(y) \quad , \qquad (3)$$

$$x^{rev} = \begin{cases} x^{init} & R(y) < R_{med} \\ x^{init} + 0.06\left(\dfrac{R(y) - R_{med}}{2R_{med}}\right) & R_{med} \le R(y) < 3R_{med} \\ x^{init} + 0.06 & R(y) \ge 3R_{med} \end{cases} \quad , \qquad (4)$$

where $TAC^{rev}_{anch}(y)$ is the revised anchovy TAC,

R_{med} is the past (1987–1991) median recruitment level, calculated by the MLVPA (Appendix 1), and

$R(y)$ is the recruitment level at the beginning of the year, back-calculated from the recruit survey estimate (see Appendix 2).

Table I: Sardine bycatch over the period 1987–1993 (Sea Fisheries, unpublished data). The figures in parenthesis are the ratios of juvenile bycatch to anchovy catch, expressed as percentages

Year	Bycatch (thousand tons)	
	Juvenile	Adult
1987	7 (1.2%)	4
1988	8 (1.3%)	2
1989	13 (4.5%)	2
1990	9 (6.1%)	6
1991	6 (4.1%)	7
1992	16 (4.6%)	5
1993	11 (4.8%)	11

An important feature of Decision Rules (2) and (3) is that they were developed with input from representatives of the pelagic fishing industry. For example, an earlier version of the management procedure for sardine consisted of Rules (1) and (2) only, where Rule (2) did not contain the TAC^{ad}_{byc} term, and the remaining term was assumed to represent all the sardine bycatch. However, the industry claimed that a marked portion of the bycatch (originally thought to consist mainly of juveniles) consisted of adult sardine. This claim was subsequently verified through closer analysis of unpublished commercial catch data and, as a result, the TAC^{ad}_{byc} term was added.

Another concern expressed by industry with respect to this earlier version was that the sardine bycatch allocation (then proposed to be x^{init} = 6% of the anchovy *TAC* on the basis of the maximum ratio of juvenile bycatch to anchovy catch over the 1987–1993 period – Table I) was hopelessly inadequate. The problem was exacerbated earlier by the bycatch allocation being made only once at the beginning of the season (i.e. no adjustment was made to the 6% during the season). With no information on the forthcoming sardine recruitment available at the start of the year, making it impossible to predict the level of sardine recruitment midyear, the bycatch allocation at the beginning of the season was necessarily conservative.

Table II: Summary performance statistics for the selected management procedure MP_{sel} and variants thereof for the South African sardine resource. The performance statistics are defined as follows: $\bar{C}_{byc}$, $\bar{C}_{dir}$ and $\bar{C}_{tot}$ are the projected average annual bycatch, directed catch and total catch respectively of sardine over the next 20 years; *risk* is taken to be the probability that the 1+ biomass falls below 20% of *K* (the average 1+ biomass in the absence of exploitation) at least once during the 20-year projection period; *V* is the mean annual change in directed catch *TAC* as a proportion of $\bar{C}_{dir}$; $grow_A$ and $grow_B$ are the average 1+ biomass at the end of the projection period as a proportion of the 1+ biomass at the start of the projection period, assuming a stock-recruit relationship in Fig. 4 of Type A or B respectively. The *TAC* constraints are defined as follows: *mindir* is the lower bound on the annual directed catch *TAC*; *maxdec* reflects the maximum proportion by which the directed catch *TAC* can be reduced from one year to the next; TAC^{ad}_{byc} is as defined in the main text (the figure of 7 500 tons for MP_{sel} is based on the average for 1991–1993 – see Table I). The control parameter *z* was chosen to give, where possible, a *risk* of 2.6%. All quantities related to catches/*TAC*s are given in thousand tons

Management procedure variants	Control parameters		*TAC* constraints			Summary performance statistics						
	z	x^{init}	TAC^{ad}_{by}	*mindir*	*maxdec*	$\bar{C}_{byc}$	$\bar{C}_{dir}$	$\bar{C}_{tot}$	*risk*	*V*	$grow_A$	$grow_B$
MP_{sel}	0.100	0.06	7.5	25	0.25	29	39	68	2.6%	24%	0.69	1.31
Varying x^{init}												
Variant 1	0.320	0.03	7.5	25	0.25	20	115	135	2.6%	28%	0.63	0.95
Variant 2	0	0.09	7.5	25	0.25	36	24	60	31.4%	1%	0.52	1.21
Variant 3	0	0.09	7.5	0	No limit	38	0	38	15.4%	0%	0.56	1.39
Varying TAC^{ad}_{byc}												
Variant 4	0.120	0.06	5.0	25	0.25	27	46	72	2.6%	26%	0.68	1.25
Variant 5	0	0.06	10.0	25	0.25	32	25	57	2.8%	0%	0.72	1.59
Varying mindir												
Variant 6	0.115	0.06	7.5	0	0.25	29	43	72	2.6%	27%	0.68	1.25
Variant 7	0	0.06	7.5	50	0.25	29	50	79	6.4%	0%	0.66	1.44
Varying maxdec												
Variant 8	0.073	0.06	7.5	25	0.1	29	34	63	2.6%	12%	0.70	1.36
Variant 9	0.110	0.06	7.5	25	No limit	29	39	68	2.6%	34%	0.69	1.31

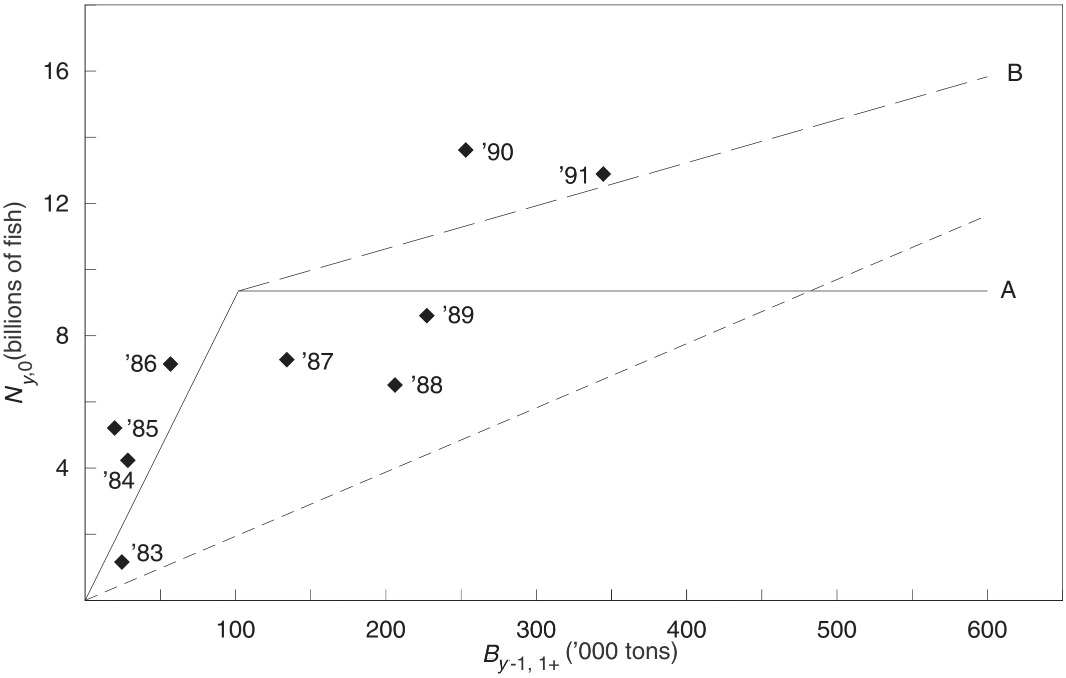

Fig. 4: Estimates of recruitment ($N_{y,0}$) and 1+ biomass ($B_{y-1,1+}$) from the base-case (M = 0.8·year^{-1}, k_1 = 1.0) application of MLVPA (Appendix 1) shown in the form of a stock-recruit plot. Note that the point plotted for year y refers to recruitment in year y and 1+ biomass at the end of year y-1. Curve A shows the deterministic component of the stock-recruit relationship (described by Equation (A2.3)), and Curve B shows the deterministic component of the optimistic stock-recruit variant (described by Equation (A2.5)). The replacement line used to calculate K (given in Equation (A2.4)) is shown as the dotted line. Summary statistics $grow_A$ and $grow_B$ correspond to Curves A and B respectively

However, particularly large sardine recruitment could lead to unforeseen bycatch problems midyear, especially when anchovy abundance was low and as a result the ratio of juvenile sardine to anchovy in the sea was high. The two-stage bycatch *TAC* strategy, i.e. Rules (2) – (4), alleviated this problem to some extent (although it remains an industry concern) by allowing bigger sardine bycatches in years of better recruitment. Difficulties nevertheless are the poor precision of the survey estimates of recruitment (see Appendix 2) and the fact that the bycatch *TAC* can only be revised upwards (when there is good recruitment and hence high bycatch) after the actual recruitment has been estimated following the midyear survey. The recruit surveys are conducted no earlier than May or June because they were originally aimed specifically at anchovy and had to ensure that as many as possible of the recruits were acoustically detectable (Hampton 1987). The same has been assumed to apply to sardine recruits which seem to undertake a migration similar to that of anchovy recruits along the West Coast (Armstrong *et al*. 1987). However, unlike anchovy, sardine spawn throughout the year with the possibility of at least two peak periods of spawning activity: one around August and the other in January (Shelton 1986, Armstrong *et al*. 1989). This fact, coupled with factors such as the more aggregated, yet widespread distribution of sardine, and sardine's preference for inshore and warmer waters as opposed to the situation for anchovy, highlights the possible inappropriateness of the present timing of hydroacoustic surveys for sardine (Barange and Hampton 1997).

The control parameters in Rules (1) – (3) are essentially the two proportions z and x^{init} (x^{rev} being a function of x^{init} and the back-calculated recruit survey result $R(y)$ used in Rule (4)). These control parameters are readily understood by a lay audience and can be adjusted so that a management procedure yields the most desirable performance in terms of selected summary statistics (defined later). In determining this, a sensible point of departure is to consider only those management procedures that yield *TAC*s that best meet the objectives of both industry and the managers. In order to establish these objectives, a questionnaire was drawn up and completed by industry, and the results were discussed with them. As a result, the following key insights of industry preferences were obtained.

1. The minimum annual directed *TAC* for sardine that can be accommodated, without excessive disruption, by the industry who use this fish for canning is 25 000 tons (see *mindir*, Table II).
2. The industry can tolerate a decrease in directed sardine *TAC* of up to 25% from one year to the next (see *maxdec*, Table II).
3. The bycatch allowance should
   (i) not unduly limit anchovy fishing, and
   (ii) be as large as possible at the beginning of the year in relation to any possible midyear increase, to facilitate operational planning of the fishery.

The concern expressed in 3(i) is partially addressed by the second term in Rules (2) and (3), where the magnitude of the juvenile sardine bycatch depends on the anchovy *TAC*. However, 3(ii) is more difficult to achieve because of the uncertainty at the beginning of the year regarding recruitment at midyear. Nevertheless, an appropriate combination of values for the control parameters will achieve 3(ii) to some extent. Therefore, Rules (1) – (4) and industry preferences 1 and 2 (the two preferences together with TAC_{byc}^{ad} are referred to below as *TAC* constraints) form the basis from which a management procedure for sardine was developed.

Testing a candidate management procedure

Candidate management procedures differ from one another according to the decision rules and *TAC* constraints used (see Table II). Tests of these candidate procedures are based on forward projections of the population over a 20 year period, subject to the management decision rules which, in the case of sardine, determine the *TAC* levels. These projections are based on an "operating model", which describes the assumed underlying population dynamics of the sardine stock. Details of the operating models considered (each reflecting different model assumptions) are given in Appendix 2.

The key features of all the various operating models are a population with six age-classes (fish 0–5 years old), subject to a constant (year- and age-invariant) natural mortality, and to pulse fishing of 0-year-olds and continuous fishing of older ages throughout the year. The expected level of recruitment is independent of spawner biomass above a given threshold, below which recruitment declines proportional to spawner biomass (Curve A, Fig. 4). Point estimates of key population parameters and variables, which form the basis of the operating models, were provided by a MLVPA assessment (Punt 1989, Appendix 1; the fit of the MLVPA 1+ biomass estimates to the survey 1+ biomass estimates are shown in Fig. 5). For the purpose of comparing alternative management procedures, these point estimates are treated in a Myopic Bayes manner in the projections (i.e. they are taken to be fixed, so that any improvements in precision as a result of the availability of more information in the future are not taken into account in this particular analysis).

The testing of alternative candidate procedures is carried out on a Monte Carlo basis, whereby 20-year projections are repeated a number of times (typically 500 for each operating model). For each 20-year trajectory, numbers-at-age are projected forward and reduced by the effects of natural mortality and future catches, where values for the latter are provided by the decision rules of the management procedure being tested. Each trajectory reflects a different resource scenario according to the set of random numbers used to generate the series of "future" recruitments and the observation errors associated with the survey estimates (Appendix 2). This testing process implicitly assumes that exactly these *TAC*s indicated by the management procedure will be awarded by the Minister, and will be neither under- nor over-caught. (To assume otherwise would require that the analysis be extended to incorporate models of the behaviour of both the Minister and the industry in these respects!) This is not too unrealistic an assumption in the South African environment, where there has been fairly vigorous following of the scientific recommendations for directed sardine fishing over recent years. However, it must be added that, on occasion, sardine bycatch allowances have been raised mid-season contrary to scientific advice, and dumping of some catches with a high juvenile sardine bycatch component is suspected.

The selection between candidate procedures is made by inspecting summary performance statistics of results from the testing procedure described above. The summary statistics (averages over the 500 20-year trajectories) reflect average annual catch $\overline{C}_{tot}$, *risk*, interannual catch variability *V*, and growth under both a conservative ($grow_A$) and an optimistic ($grow_B$) stock-recruit relationship (Fig. 4). These statistics are described in the caption to Table II and are similar to those used by Butterworth *et al.*

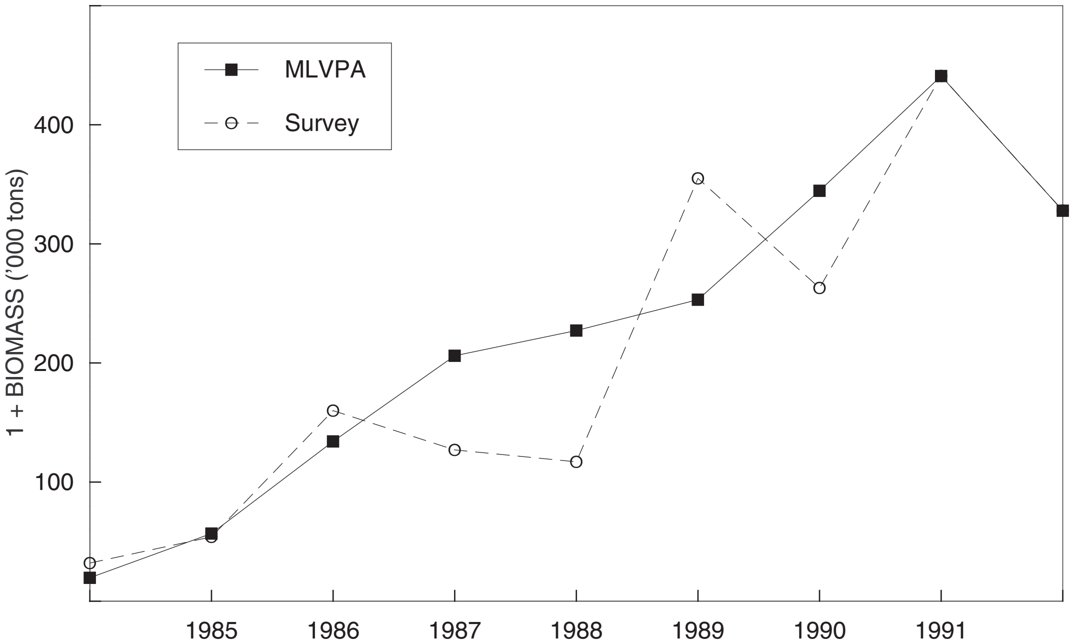

Fig. 5: Base-case MLVPA (Table App.1.2) and November hydroacoustic survey estimates (Table App.1.1) of the 1+ biomass time-series

(1993). It was decided to consider $grow_B$ in addition to $grow_A$ because the latter provides no scope for future increases in recruitment as the 1+ biomass increases (Fig. 4); i.e. Curve A interprets recent increases in the sardine biomass as simply recruitment fluctuations above a lower mean, whereas Curve B allows the alternative interpretation of a steady increase in recruitment with spawner biomass as the stock recovers to higher levels.

THE SELECTED MANAGEMENT PROCEDURE AND VARIANTS THEREOF

The selection of a management procedure is a long process, and in practice follows roughly the following schedule.

1. The model that is considered to reflect the "best" assessment of the resource is selected as the base-case operating model.
2. A wide range of management procedures is tested in terms of the base-case operating model.
3. The list of candidate management procedures is narrowed down, with the help of managers and industry members, to those candidate procedures which best achieve an appropriate trade-off between $\overline{C}_{tot}$ and V (an industry objective is to maximize the former and minimize the latter) on the one hand and *risk* and $grow_B$ (important for conservation and long-term growth of the resource) on the other.
4. An appropriate set of equally plausible alternative operating models is selected by isolating those assumptions in the base-case operating model for which there are key uncertainties, and developing alternative models that incorporate changes to these assumptions which fall within the plausible range of uncertainties.
5. The candidate management procedures are tested for robustness to the alternative operating models of 4.
6. The candidate management procedure that displays adequate robustness across all the operating models, while simultaneously meeting the "industry" and "conservation/growth" objectives of 3 as best possible, is selected.

For the sake of ease of presentation, the above scheme is not followed here. Instead the selected

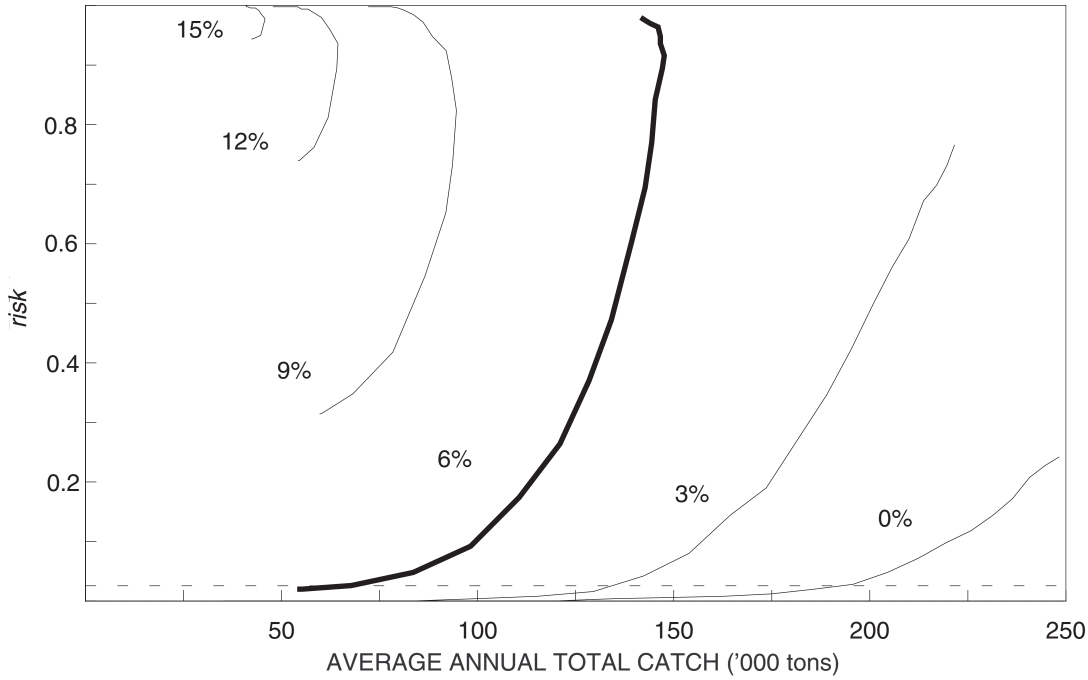

Fig. 6: Plots of *risk* against average annual total catch C_{tot} (see Table II caption for definitions). Each curve is associated with a different value for x^{init}, indicated as a percentage next to each curve (see Decision Rules (2)–(4)), under restrictions of a lower bound in the directed catch *TAC* (*mindir*) of 25 000 tons, a maximum reduction in the directed catch *TAC* (*maxdec*) of 25% from one year to the next, and an adult bycatch level (TAC^{ad}_{byc}) of 7 500 tons. The points within each curve are obtained by varying z (Decision Rule (1)). The horizontal dotted line is drawn at a *risk* level of 2.6%, and intersects the thick curve (x^{init} =0.06) at the point which corresponds to MP_{sel} shown in Table II

management procedure (MP_{sel}) and the rationale for its selection is first presented, followed by variants of MP_{sel}, chosen to reflect the sensitivity of management procedure performance to changes in the control parameters and *TAC* constraints (the base-case operating model is used for all these variants). Finally, the robustness of MP_{sel} to alternative operating models is investigated.

Selecting MP_{sel}

The anticipated performances of alternative management procedures defined by Rules (1)–(4) in terms of the base-case operating model (Appendix 1) are illustrated in Figure 6 in the plot of *risk* against $\bar{C}_{tot}$ for various values of the control parameters z and x^{init}. Individual curves in Figure 6 are associated with different values of x^{init}, whereas the points within each curve are obtained by varying z. The further to the right a curve lies on this plot (i.e. the larger the $\bar{C}_{tot}$ for a particular *risk*), the better a management procedure, with the associated value of x^{init}, will perform in terms of these two attributes. Values for the constraints *mindir* (the minimum directed *TAC* in any one year) and *maxdec* (the maximum decrease in directed *TAC* from one year to the next) were fixed at 25 000 tons and 25% respectively, to coincide with the industry preferences listed above.

Figure 6 shows a very rapid deterioration in the performance of management procedures with increasing x^{init} values, so that ideally x^{init} should be kept as low as possible. However, Table I shows that, over the period 1987–1993, juvenile sardine bycatch as a percentage of the anchovy catch was as high as 6%, so that, given the increasing pressure from industry for higher bycatch allocations, an essential requirement for a management procedure to be acceptable was that x^{init} should be at least 6%. Furthermore, the performance of the procedure in Table II for which $z = 0.1$ and $x^{init} = 0.06$ shows that there is some scope for growth ($grow_B = 1.31$) under an optimistic

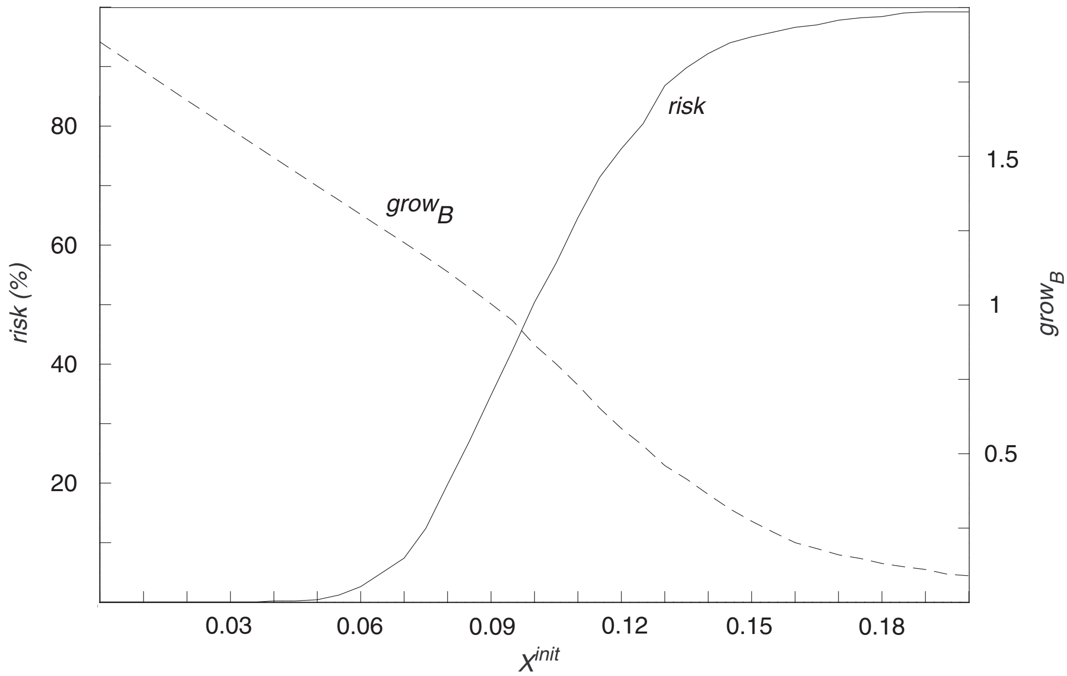

Fig. 7: The plot of *risk* v. x^{init} corresponding to the left *y*-axis, and $grow_B$ v. x^{init} corresponding to the right *y*-axis, reflecting essentially the same results as Table III (i.e. $z = 0.1$) but for a wider range of x^{init} values

stock-recruit relationship. This option was therefore used as the selected management procedure, MP_{sel}, for sardine, i.e.: $z = 0.1$; $x^{init} = 0.06$; TAC^{ad}_{byc} 7 500 tons; $mindir$ = 25 000 tons; $maxdec$ = 25%.

Variants of MP_{sel}

Results for MP_{sel} and variants thereof are listed in Table II. In each case, the control parameter z has been adjusted to give, where possible, the same *risk* value as the MP_{sel}, namely 2.6%. Alternative management procedures can therefore be compared on the basis that they will have the same impact on the resource in terms of *risk* as defined here, but may differ with respect to other attributes such as $\overline{C}_{tot}$, V, $grow_A$ and $grow_B$.

VARYING x^{init}

Variants 1–3, where the juvenile bycatch proportion x^{init} is varied, illustrates the extreme sensitivity of the management procedure performance to changes in x^{init}. A decrease in x^{init} from 0.06 to 0.03 means that z can be increased from 0.100 to 0.320 without increasing *risk*. On the other hand, an increase of x^{init} to 0.09 means that, with z set to 0, *risk* increases more than 10 times (Variant 2). It was impossible to achieve 2.6% *risk*, even with z set to 0 and the constraints *mindir* and *maxdec* removed, if x^{init} was kept at 0.09 (Variant 3). In Table III, z is kept at 0.1 so that the effect on *risk* and $grow_B$ of increasing x^{init} is illustrated further. In that instance, a plot of *risk* v. x^{init} resembles a sigmoid curve, with $x^{init} = 0.06$ occurring just before the curve becomes steep (Fig. 7).

Table III: Performance statistics for a management procedure with identical *TAC* constraints to MP_{sel} (Table II), but with control parameter z kept at 0.1 (i.e. no attempt is made to adjust management procedures to reflect the same *risk*). Control parameter x^{init} is varied to show sensitivity of management procedure performance to changes in this parameter. Notation is as for Table II

x^{init}	$\overline{C}_{byc}$	$\overline{C}_{dir}$	$\overline{C}_{tot}$	*risk*	V	$grow_A$	$grow_B$
0.03	20	44	64	0%	26%	0.82	1.59
0.06	29	39	68	2.6%	24%	0.69	1.31
0.09	36	33	68	34.8%	21%	0.49	1
0.12	34	24	58	76.2%	24%	0.24	0.59

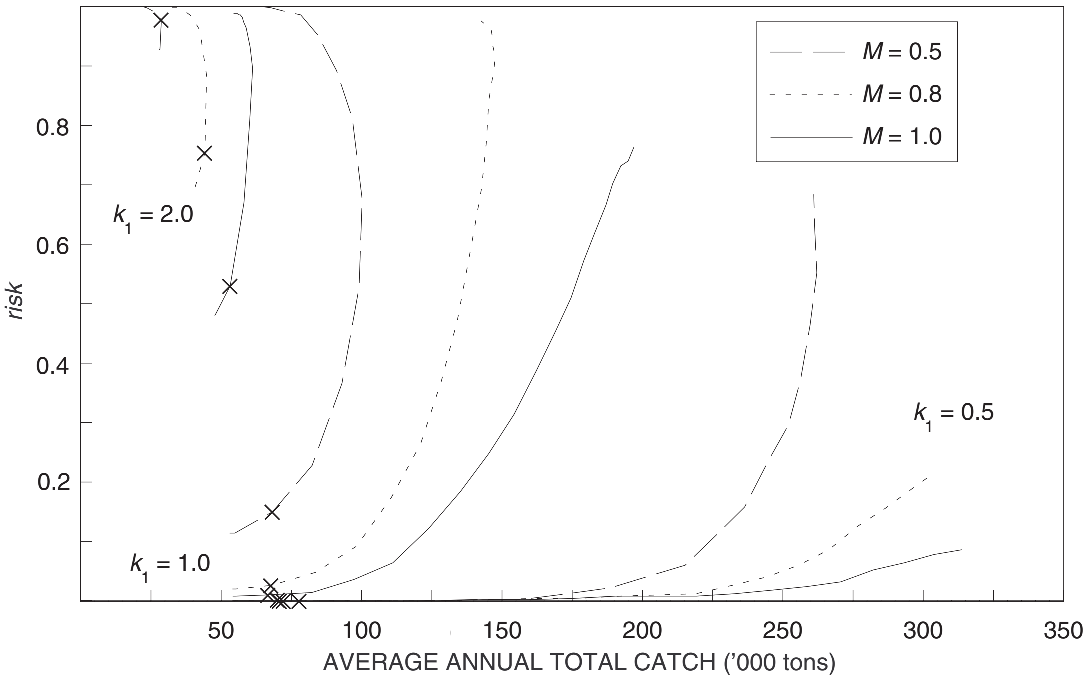

Fig. 8: Sensitivity of the bold curve in Fig. 6 to changes in values assumed for the 1+ biomass survey bias (k_1) and natural mortality (M) in the operating model. From the bottom right hand corner of the plot, each group of three curves is associated with a single k_1 value (0.5, 1.0 and 2.0 for each group respectively). The results for MP_{sel} are highlighted with stars

Values of x^{init} beyond this point are accompanied by a rapid increase in *risk* with little or no positive growth under the optimistic stock-recruit relationship (Fig. 7).

VARYING *mindir* AND TAC^{ad}_{byc}

A reduction in TAC^{ad}_{byc} (Variant 4) leads to an improvement in z, and hence $\bar{C}_{tot}$, but with the loss of some growth compared to MP_{sel}, whereas an increase in TAC^{ad}_{byc} (Variant 5) means that even a z = 0 is unable to achieve a *risk* of 2.6%, and the total catch at a *risk* of 2.8% is lower than that at 2.6% for MP_{sel}. The results for varying *mindir* follow the same pattern, but varying *mindir* does not have the same effect as varying TAC^{ad}_{byc}. The reason for this is that, although TAC^{ad}_{byc} and *mindir* both refer to adult sardine only and imply a "guaranteed" quantity of fish per year, constraint *mindir* will not always come into play because, when $z > 0$, the directed *TAC* (Rule (1)) will frequently be above *mindir* and the latter will therefore not be invoked. However, any changes to TAC^{ad}_{byc} will affect Rules (2) and (3) whenever they are applied, increasing the "guaranteed" adult catch by the amount specified by TAC^{aa}_{byc}. For example, Variants 4 and 6 reflect almost identical performance in terms of $\bar{C}_{tot}$, *risk*, *V*, $grow_A$ and $grow_B$, but this is achieved by sacrificing different quantities of "guaranteed" adult catch when compared to MP_{sel}: 2 500 tons for Variant 4 and 25 000 tons for Variant 6.

Variants 5 and 7 no longer depend on the November 1+ biomass survey estimates (z = 0), and in each case, $\bar{C}_{dir}$ is the same fixed amount each year (provided the resource is not extirpated). These variants are therefore unable to capitalize on high survey estimates of 1+ biomass, leading to higher $grow_B$ values than that for MP_{sel}, and get into trouble with low survey estimates of 1+ biomass because the "guaranteed" catch is set too high, leading to higher *risk* values than MP_{sel}.

VARYING *maxdec*

A decrease in *maxdec* has the effect of stabilizing catch fluctuations (V = 12% for Variant 8 compared to 24% for MP_{sel}), but at the expense of $\bar{C}_{tot}$. Dropping the *maxdec* constraint altogether (Variant 9) allows

Table IV: Performance statistics for alternative bycatch procedures. In each case, the directed catch component of the management procedure and the *TAC* constraints are as for the MP_{sel} (Table II); control parameter *z* is as for MP_{sel}. The other control parameters are associated with the bycatch component of the management procedures (see Appendix 3) and are adjusted to reflect the same *risk* as MP_{sel}. Bycatch Procedure 1 is independent of anchovy *TAC*; Bycatch Procedure 2 is a constant bycatch procedure; Bycatch Procedure 3 is a combination of the bycatch component of MP_{sel} and Bycatch Procedure 2. Notation is as for Table II

Alternative bycatch procedures	Control parameters	$\bar{C}_{byc}$	$\bar{C}_{dir}$	$\bar{C}_{tot}$	*risk*	*V*	$grow_A$	$grow_B$
MP_{sel}	$x^{init} = 0.060$	29	39	68	2.6%	24%	0.69	1.31
Bycatch Procedure 1	$\alpha = 24.6$; $\beta = 0.6$	39	33	73	2.6%	21%	0.55	0.82
Bycatch Procedure 2	$\alpha = 23.5$	31	38	69	2.6%	24%	0.64	1.36
Bycatch Procedure 3	$\alpha = 15$; $x^{init} = 0.037$	32	37	69	2.6%	23%	0.65	1.20

an increase in *z*, but it does not result in any change to the other performance statistics except *V*, which deteriorates. The overriding factor here seems to be *mindir*, which limits the effectiveness of removing the *maxdec* constraint as a means of obtaining a better trade-off between *risk* and $\bar{C}_{tot}$ (compare Variant 9 to the base-case and Variant 6).

Robustness of MP_{sel} to alternative operating models

Sensitivity of a selected management procedure to alternative operating models, reflecting changes in model assumptions, is an important aspect to consider to ensure that the management procedure is robust to key model uncertainties. Two key uncertainties were investigated, namely the value for natural mortality (*M*) and bias in the November 1+ biomass survey. Results are shown in the *risk* v. $\bar{C}_{tot}$ plots of Figure 8, where each group of three curves is associated with a certain multiplicative bias (0.5, 1, 2) and the individual curves within a group are associated with different values of *M* (0.5, 0.8, 1.0·year^{-1}). Clearly, the performances of the management procedures shown are more sensitive to changes in bias than to changes in *M*. MP_{sel} (highlighted with a star) is particularly sensitive to positive bias (i.e. the 1+ biomass survey overestimate the true 1+ biomass). This result demonstrates the need to adopt a conservative approach when selecting a management procedure for sardine until there is more confidence in the reliability of the November hydroacoustic survey estimates viewed as estimates of abundance in absolute terms.

ALTERNATIVE BYCATCH PROCEDURES

The original motivation for investigating alternative bycatch procedures came after MP_{sel} was actually implemented in 1994. Cochrane *et al*. (1998) discuss the experiences of applying management procedures in the South African pelagic fishery, and describe the relative failure of MP_{sel} to provide adequate bycatch management. Although the industry accepted this procedure, they were never really happy with the x^{init} value of 6%, stating that it was unrealistically low. Part of the problem was the "switching" of anchovy and sardine relative abundance (from 1994 onwards, November estimates of 1+ biomass were larger for sardine than anchovy, whereas prior to 1994, the opposite applied), with the consequent high ratio of sardine to anchovy in the sea, leading to a sharp rise in sardine bycatch.

In an attempt at developing alternative management procedures that offered higher average bycatch ($\bar{C}_{byc}$) levels than MP_{sel} without increasing *risk* levels, three alternative bycatch procedures were investigated (Appendix 3). These procedures differed from MP_{sel} by varying Rules (2)–(4), while keeping Rule (1), with a *z* of 0.1, unchanged. Table IV lists the results of each of these bycatch procedures after they were tuned to reflect the same *risk* as MP_{sel}.

Bycatch Procedures 1 and 2 set bycatch levels independently of the anchovy *TAC*. The first of these uses an approach similar to that used for anchovy (Butterworth *et al*. 1993), where the initial and revised bycatch *TAC*s are essentially a weighted combination of the 1+ biomass and recruit survey estimates. Although a substantial increase in $\bar{C}_{byc}$ is achieved (Table IV), $grow_A$ and $grow_B$ are both reduced substantially, reflecting the failure of this procedure to make allowance for the possibility of recovery of the resource to higher levels.

Bycatch Procedure 2 reflects a constant bycatch approach. In this case, a moderate increase in $\bar{C}_{byc}$ is offset by a moderate decline in $grow_A$ compared to MP_{sel}. However, $grow_B$ is slightly larger, implying that the constant bycatch approach may perform marginally more favourably than MP_{sel} under conditions of an optimistic stock-recruit relationship. This is because the procedure protects the juveniles against increases in exploitation levels when there is growth, so allowing a compounding effect in growth. Bycatch Procedure 3 is a hybrid of the bycatch component of MP_{sel} and the constant bycatch procedure. It offers a guaranteed minimum bycatch even if the anchovy *TAC* is low, so that more bycatch is offered in circumstances where the ratio of sardine to anchovy in the sea is likely to be higher. It performs marginally better than Procedure 2 in terms of $\bar{C}_{byc}$ and $grow_A$, but not in terms of $grow_B$ because of the higher $\bar{C}_{byc}$ levels under optimistic growth.

DISCUSSION

Management procedures have proven a very useful basis to facilitate interaction of scientists with managers and industry members. In this case, by considering the effects of the various decision rules and *TAC* constraints on the anticipated performance of alternative candidate management procedures, industry members had a ready means of considering the consequences of their choices on performance statistics to which they could relate and in which they were interested (such as $\bar{C}_{tot}$, V and $grow_B$), without having to understand the "complicated" models underlying the management procedure. However, results are not always intuitive, as was evident from the differences in changing TAC^{ad}_{byc} and *mindir* (see discussion earlier). This highlights the need for careful consideration of the effects of different combinations of constraints on the summary performance statistics.

A key feature in this example of management procedure performance, and the one which generated the greatest problems for management, is the extreme sensitivity to changes in x^{init}. This can be explained by considering the multispecies nature of the management procedures considered. In terms of the models used, the abundance of anchovy and sardine fluctuate independently (assessments conducted over the period since the surveys started are not suggestive of either positive or negative correlation between sardine and anchovy recruitment each year). Therefore, instances where the anchovy abundance is high but sardine recruitment weak are possible. In these instances, Rules (2) and (3) will yield bycatch *TAC*s that will result in a high proportion of the number of sardine recruits available being taken. Therefore, x^{init} need be increased only marginally to have a large impact on *risk*, where too many recruits are being taken more often at the "wrong" time, driving the population more frequently below the selected threshold of 20% of K, which was used to define *risk*. Under the circumstances of low abundance of anchovy and high abundance of juvenile sardine that prevailed subsequent to the implementation of MP_{sel} at the start of 1994 (Cochrane *et al*. 1998), Bycatch Procedure 3 would perhaps have been a more appropriate choice for the industry, where juvenile bycatch is still linked to the anchovy *TAC*, but not as strongly as in MP_{sel} (Rules (2) and (3), Appendix 3).

The choice of 2.6% as an appropriate level of *risk* to which the management procedures were tuned (Table II) was based on a number of factors. In the selection of MP_{sel} for sardine, an x^{init} of 6% seemed to offer the best compromise between a value that was the maximum experienced in the recent past, but one that was still low enough to achieve a reasonable trade-off between $\bar{C}_{tot}$ and *risk* (Fig. 6). Furthermore, a z value of 0.1 allowed the "scope for growth" criterion to be achieved under favourable recruitment. However, the choice of 2.6% *risk* for sardine remains somewhat arbitrary; for example, the common criterion could instead have been chosen as $grow_B = 1.2$ instead of 1.31 when $risk = 2.6\%$ (Table II), thereby allowing a higher value of *risk*. In their discussion on *risk*, Cochrane *et al*. (1998) discuss the difference between the *risk* levels for anchovy and sardine (30% for the former according to De Oliveira [1995], and 2.6% for the latter corresponding to MP_{sel}), and conclude that the choice of *risk* will retain an arbitrary component as long as there is limited or imprecise knowledge on stock-recruit relationships and other factors that regulate recruitment. Nevertheless, even though a value of 2.6% for sardine seems low compared to anchovy, it satisfies the need for a more conservative approach which could be justified on the basis of the sensitivity to survey bias of MP_{sel} (Fig. 8) and the uncertainty surrounding the recruit survey estimates (Appendix 2).

Another arbitrary component of the choice of *risk* is demonstrated by considering the relative merits of *risk* and "scope for growth" as performance criteria. The choice of MP_{sel} was driven more by the "scope for growth" ($grow_B$) results than by the *risk* results, partly because the "growth" criterion is something tangible and easily understood, whereas *risk* and its absolute value are more abstract concepts. However, the importance ascribed to "growth" is also a result of the perception that the resource is likely to continue to grow. Under those circumstances, sacrifices made now will be more than equally rewarded in the future as growth is realized. The question therefore is how important would the "growth" criterion have been had the perception instead been that recruitment would remain constant over the next 20 years? It is possible that, under such conditions, a greater *risk* value would have been accepted at the expense of growth when selecting a management procedure.

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APPENDIX 1

In the MLVPA (Punt 1989, Borchers 1990), the stock dynamics are assumed to be:

$$N_{y+1,a+1} = N_{y,a} e^{-(F_{y,a}+M)} \qquad a = 0,1,...,4 \quad , \quad \text{(A1.1)}$$

$$B_{y,1+} = \sum_{a=1}^{5} N_{y+1,a} w_a \qquad , \qquad \text{(A1.2)}$$

where $N_{y,a}$ is the number of fish of age a at the start of year y,
$F_{y,a}$ is the instantaneous rate of fishing mortality on fish of age a in year y,
M is the instantaneous rate of natural mortality, assumed to be age- and year-invariant,
$B_{y,1+}$ is the 1+ biomass at the end of year y (i.e. start of year y+1), and
w_a is the mean mass-at-age of fish at the start of the year, assumed to be year-invariant.

The relationship between the numbers of fish and catch (in numbers) is then:

$$C^n_{y,a} = \frac{F_{y,a}}{F_{y,a} + M} N_{y,a}[1-e^{-(F_{y,a}+M)}] \qquad a = 0,1,...,5 \quad , \quad \text{(A1.3)}$$

where $C^n_{y,a}$ is the catch in numbers of fish of age a in year y.

Fishing mortalities for fish aged 3 years or more are assumed to be the same for the most recent year (i.e. the last year for which data are available), and to relate to the fishing mortality of 2-year-olds in that year, as follows:

$$F_{y\max,a} = \alpha F_{y\max,2} \qquad a = 3,4,5 \quad , \quad \text{(A1.4)}$$

where α is an age-invariant parameter, and
$y$max is the most recent year.

Given values for $F_{y\max,0}$, $F_{y\max,1}$, $F_{y\max,2}$ and α, the numbers-at-age matrix can be reconstructed backwards in time by applying the following algorithm.

1. Compute the fishing mortality in year $y$max on fish aged 3 and older by using Equation (A1.4).
2. Compute the numbers at the start of the most recent year ($N_{y\max,a}$, a = 0,...,5) by solving Equation (A1.3).
3. Set $y = y$max.
4. Compute the fishing mortalities and numbers in the previous year ($F_{y-1,a}$ and $N_{y-1,a}$, a = 0,...,4) by solving Equations (A1.1) and (A1.3).
5. Set $F_{y-1,5} = F_{y-1,4}$.
6. Compute $N_{y-1,5}$ from Equation (A1.3).
7. If y is greater than the first year for which data are available, then set $y = y-1$ and go to Step 4.
8. Stop.

The survey data available to fit the model are shown in Table App.1.1. These consist of:

(i) hydroacoustic estimates of 1+ biomass $B^{sur}_{y,1+}$ from the November surveys with associated CVs $\sigma^{sur}_{y,1+}$ and constant of proportionality k_1 (fixed on input), which are available for years y = 1984,...,1992 (these years are denoted as I below);
(ii) hydroacoustic estimates of recruitment numbers $N^{sur}_{y,0}$ from the midyear recruitment survey with associated CVs $\sigma^{sur}_{y,0}$, which are taken to be a relative index of recruitment numbers with an estimable constant of proportionality k_2, and are available for years y = 1985,...,1992, excluding 1988 (these years are denoted as J below); and
(iii) estimates of mean egg density D^{egg}_y from the November surveys with associated CVs σ^{egg}_y which are taken to be a relative index of 1+ biomass with an estimable constant of proportionality k_3, and are available for years y = 1983,...,1992 (these years are denoted as K below). [Note, a different method of collecting eggs was used from 1988 to 1991; although this is actually taken into account in computations by estimating different k_3 values for these two periods, this is not shown specifically later in the interests of simplicity.]

Table App.1.1: Survey estimates of 1+ biomass, recruitment and mean egg density used in fitting the population model. *CV*s are given in parenthesis. Note that sampling *CV*s for $N_{y,0}^{sur}$ were first reported in 1991, because that was the first recruit survey aimed specifically at sardine as well as anchovy (Hampton 1992). *CV*s prior to that were assumed to be 0.5

Year (y)	$B_{y,1+}^{sur}$ (thousand tons)	$N_{y,0}^{sur}$ (billions)	D_y^{egg} (Numbers per m^2)
1983	–	–	12.69 (0.66)
1984	32 (0.87)	–	15.55 (0.36)
1985	54 (0.39)	2.616 (0.50)	20.79 (0.48)
1986	160 (0.41)	3.287 (0.50)	36.17 (0.38)
1987	127 (0.39)	5.563 (0.50)	47.54 (0.23)
1988	117 (0.56)	–	96.48 (0.48)
1989	355 (0.20)	3.383 (0.50)	84.80 (0.19)
1990	263 (0.27)	1.751 (0.50)	50.10 (0.27)
1991	441 (0.26)	1.921 (0.38)	64.70 (0.29)
1992	328 (0.36)	8.326 (0.39)	34.75 (0.37)

In order to estimate the parameters $F_{y\max,0}$, $F_{y\max,1}$, $F_{y\max,2}$ and α from these data, a maximum likelihood approach is used. The log-likelihood function to be maximized assumes log-normality of the distribution of survey estimates and approximates the standard errors of these log-distributions by the *CV*s of the untransformed distributions. Accordingly, it has the form:

$$\ell nL = -\tfrac{1}{2}W_1\sum_I\left\{\frac{[\ell nB_{y,1+}^{sur} - \ell n(k_1B_{y,1+})]^2}{[\sigma_{y,1+}^{sur}]^2} + \ell n[2\pi(\sigma_{y,1+}^{sur})^2]\right\}$$

$$-\tfrac{1}{2}W_2\sum_J\left\{\frac{[\ell nN_{y,0}^{sur} - \ell n(k_2N_{y,0})]^2}{[\sigma_{y,0}^{sur}]^2} + \ell n[2\pi(\sigma_{y,0}^{sur})^2]\right\} \quad ,$$

$$-\tfrac{1}{2}W_3\sum_K\left\{\frac{[\ell nD_y^{egg} - \ell n(k_3B_{y,1+})]^2}{[\sigma_y^{egg}]^2} + \ell n[2\pi(\sigma_y^{egg})^2]\right\} \qquad \text{(A1.5)}$$

where W_1, W_2 and W_3 are weighting factors associated with the 1+ biomass, recruitment and mean egg-density terms of the log-likelihood equation respectively, and are assigned a value of either 1 or 0, the latter indicating that the associated data are ignored in the fitting procedure. For the base-case operating model, parameter k_1 is assumed to be 1 (i.e. the November hydroacoustic surveys are taken to provide unbiased estimates of biomass in absolute terms), except when MP_{sel} is tested for robustness to survey bias (Fig. 8, Table App.1.2). Closed form solutions for k_2 and k_3 are obtained through partial differentiation of ℓnL, and M is fixed externally. The remaining estimable parameters in the log-likelihood are therefore $F_{y\max,0}$, $F_{y\max,1}$, $F_{y\max,2}$ and α.

Attempts to fit all the available data provided evidence of substantial model mis-specification, i.e. in terms of the model assumptions made, the data are in conflict. The 1+ biomass estimates from the November hydroacoustic surveys were regarded as the most reliable, because the recruitment estimates were subject to large sampling and other unquantified errors (Table App.1.2, Appendix 2), and the estimates of mean egg density do not provide a reliable index of abundance for batch spawners such as sardine, the spawning fraction and fecundity of which may vary from year to year (Armstrong 1988). Therefore, only the 1+ biomass estimates were fitted and the other indices ignored (i.e. $W_1 = 1$; $W_2 = W_3 = 0$). Recruitment variability σ_R was obtained from:

$$\sigma_R^2 = \tfrac{1}{4}\sum_{y=1987}^{1991}[\ell nN_{y,0} - \ell nR_{med}]^2 \quad , \qquad \text{(A1.6)}$$

where

$$R_{med} = \left[\prod_{y=1987}^{1991} N_{y,0}\right]^{\frac{1}{5}} \quad . \qquad \text{(A1.7)}$$

Equation (A1.7) corresponds to the assumption that recruitment is log-normally distributed. Years prior to 1987 and after 1991 were omitted because of the paucity of precise data with which to estimate these values, and because the 1987–1991 period was regarded as representative of the likely range of current and future recruitment levels. Selectivity of 1-year-old fish (see Appendix 2) was estimated from

$$S_1 = \tfrac{1}{5}\sum_{y=1987}^{1991}\frac{F_{y,1}}{F_{y,2}} \quad . \qquad \text{(A1.8)}$$

The resultant point estimates for parameters and variables for different operating models used in testing alternative management procedures are given in Table App.1.2. Estimates for the parameter α show strong positive correlation with the value of M input, so that M cannot be estimated from fits to these data, but must be fixed externally. The value of M = 0.8·year^{-1} for the base-case (for which k_1 = 1.0) was chosen to give a value of α close to 1, i.e. to reflect similar fishing mortalities on fish of age 2 and those of older ages in the most recent year. The model was also fitted for two other choices for M (0.5 and 1.0·year^{-1}), to reflect the uncertainty in this regard. Similarly, to reflect uncertainty in the hydroacoustic estimates as measures of biomass in absolute terms, all these calculations were repeated for k_1 = 0.5 and 2.0, i.e. assuming that the estimates provided were (on average) either half or double the true values.

Table App.1.2: Point estimates of parameters and variables provided by the MLVPA for different operating models used in testing alternative management procedures (Appendix 2). The results in this Table were used to obtain Fig. 8; however, only the middle column (k_1=1.0, M=0.8·year^{-1}), reflecting input values for the base-case operating model, was used to obtain the results given in Table II. The Ns and R_{med} are in billions of fish. The log-likelihood ℓnL reflects the value given by Equation (A1.5) for the various operating models, and shows that none can be rejected at the 5% significance level

Parameter/ variable	Operating model								
	k_1=0.5 M=0.5	k_1=0.5 M=0.8	k_1=0.5 M=1.0	k_1=1.0 M=0.5	k_1=1.0 M=0.8	k_1=1.0 M=1.0	k_1=2.0 M=0.5	k_1=2.0 M=0.8	k_1=2.0 M=1.0
$N_{1993,2}$	4.510	4.217	4.221	2.331	2.376	2.226	1.303	1.386	1.357
$N_{1993,3}$	2.756	1.988	1.517	1.312	0.893	0.660	0.551	0.317	0.183
$N_{1993,4}$	0.909	0.451	0.265	0.391	0.174	0.091	0.126	0.035	0.007
$N_{1993,5}$	0.399	0.139	0.064	0.164	0.050	0.020	0.048	0.008	0.001
R_{med}	10.164	16.766	23.170	5.804	9.353	12.571	3.613	5.551	7.286
σ_R	0.313	0.341	0.368	0.293	0.333	0.344	0.265	0.300	0.302
α	0.672	0.967	1.239	0.748	1.115	1.502	0.964	1.682	2.976
S_1	0.482	0.374	0.318	0.456	0.355	0.302	0.408	0.318	0.270
$\ell n\ L$	–4.450	–4.346	–4.349	–3.652	–3.662	–3.766	–2.995	–3.168	–3.306

APPENDIX 2

The process used to test alternative management procedures consists of four components, namely the MLVPA variable and parameter estimates, the operating model which reflects the actual underlying dynamics of the resource and is based upon these estimates, the decision rules of the management procedure being tested (these rules have no exact knowledge of the actual underlying dynamics, and have to be applied to data of the type and subject to the errors to be expected in practice), and the summary performance statistics. The decision rules and summary statistics are discussed in the main text, and the MLVPA estimates considered are shown in Table App.1.2. These estimates remain unchanged for each particular test of the management procedure, forming the basis for projections into the future. The operating model is used to project numbers-at-age forward, given the values for future catches provided by the procedure being tested, as follows:

$$N_{y+1,1} = \left(N_{y,0}\mathrm{e}^{-M/2} - \frac{C_{y,0}}{\overline{w}_{0c}}\right)\mathrm{e}^{-M/2}$$

$$N_{y+1,a+1} = N_{y,a}\mathrm{e}^{-(S_aF_y+M)} \qquad a = 1,...,4 \quad , \qquad \text{(A2.1)}$$

$$B_{y,1+} = \sum_{a=1}^{5} N_{y+1,a}w_a$$

where $\overline{w}_{ac}$ is the mean mass of fish aged a in the catch (averaged over 1987–1991), w_a is as defined in Appendix 1, M is set equal to 0.8·year^{-1} for the base-case operating model, and selectivities of fish aged 2 years and more are calculated as follows:

$$\begin{aligned} S_2 &= 1 \\ S_a &= \alpha S_2 \qquad a = 3,4,5 \end{aligned} \quad . \qquad \text{(A2.2)}$$

Future recruitment is assumed to be log-normally distributed about a stock-recruit relationship (Curve A in Fig. 4):

$$N_{y,0} = \begin{cases} R_{med}\mathrm{e}^{\varepsilon_y} & B_{y-1,1+} \geq 0.2K \\ R_{med}\left[\dfrac{B_{y-1,1+}}{0.2K}\right]\mathrm{e}^{\varepsilon_y} & B_{y-1,1+} < 0.2K \end{cases} , \text{(A2.3)}$$

where ε_y is drawn from $N[0;(\sigma_R)^2]$, and K (the average 1+ biomass in the absence of exploitation) is calculated from

$$K = R_{med}\mathrm{e}^{\sigma_R^2/2} \sum_{a=1}^{5} w_a\mathrm{e}^{-aM} \qquad . \qquad \text{(A2.4)}$$

Note that, for this paper, serial correlation in recruitment was not taken into account.

K is essentially given by the intersection between the replacement line $R = \left(\sum_{a=1}^{5} w_a\mathrm{e}^{-aM}\right)^{-1}B_{1+}$, which defines (in a deterministic sense) the level of recruitment required to maintain the 1+ biomass at its current level, and $R = R_{med}\mathrm{e}^{\sigma_R^2/2}$. When a "favourable" recruitment scenario is considered which admits the possibility of considerable further growth in the resource, an "optimistic" stock-recruit relationship is used (Curve B in Fig. 4) which intersects the replacement line at 3K, and is defined by:

$$N_{y,0} = \begin{cases} \left[\dfrac{3K\left(\sum_{a=1}^{5} w_a\mathrm{e}^{-aM}\right)^{-1} - R_{med}}{3K - 0.2K}(B_{y-1,1+} - 0.2K) + R_{med}\right]\mathrm{e}^{\varepsilon_y} & B_{y-1,1+} \geq 0.2K \\ R_{med}\left[\dfrac{B_{y-1,1+}}{0.2K}\right]\mathrm{e}^{\varepsilon_y} & B_{y-1,1+} < 0.2K \end{cases} . \text{(A2.5)}$$

The TACs given by management procedure Decision Rules (1)–(3) – see main text – are split between the age-groups thus:

$$C_{y,0} = x^{rev}TAC^{rev}_{anch}(y) \qquad \text{(A2.6)}$$

[When alternative bycatch procedures are used, the right-hand side is replaced by the corresponding terms given by the equations in Appendix 3, i.e. the TAC^{ad}_{byc} term is omitted in Equations (A3.2), (A3.3) and (A3.5).],

$$C_{y,1+} = TAC_{dir}(y) + TAC^{ad}_{byc} \qquad . \qquad \text{(A2.7)}$$

$C_{y,1+}$ can then be substituted into the following equation to solve for the F_y to be used in Equations (A2.1):

$$C_{y,1+} = \sum_{a=1}^{5} N_{y,a}\frac{S_aF_y}{S_aF_y + M}[1 - \mathrm{e}^{-(S_aF_y+M)}]\,\overline{w}_{ac} \qquad . \qquad \text{(A2.8)}$$

The survey biomass estimates generated by the operating model are given by:

$$B^{sur}_{y,1+} = k_1 B_{y,1+}\, e^{\varepsilon_{y,1+}} \quad \varepsilon_{y,1+} \text{ from N}[0;(\sigma^{sur}_{1+})^2]$$
$$N^{sur}_{y,0} = R_{y,0}\, e^{\varepsilon_{y,0}} \quad \varepsilon_{y,0} \text{ from N}[0;(\sigma^{sur}_{0})^2] \quad , \text{(A2.9)}$$

where k_1 is assumed to be 1 (except in the robustness tests for bias in the survey estimates) and

$$R_{y,0} = \left[N_{y,0} e^{-M/4} - \frac{x^{init} TAC^{init}_{anch}(y)}{\bar{w}_{0c}} \right] e^{-M/4} . \text{ (A2.10)}$$

However, Decision Rule (4) of the management procedure (see main text) requires that $N^{sur}_{y,0}$ be back-calculated to the start of the year, assuming a fixed value of 0.8·year^{-1} for M (regardless of the operating model used), as follows:

$$R(y) = \left[N^{sur}_{y,0} e^{0.8/4} + \frac{x^{init} TAC^{init}_{anch}(y)}{\bar{w}_{0c}} \right] e^{0.8/4} . \text{ (A2.11)}$$

Equation (A2.11) is as applies in the simulations, but in practice, the $x^{init} TAC^{init}_{anch}(y)$ term is replaced by the actual 0-year catch taken between the beginning of the year and the start of the recruit survey, $\bar{w}_{0c}$ is replaced by the corresponding mean mass, and the $N^{sur}_{y,0}$ term is the actual recruit survey estimate.

The approximate *CV*s for future surveys are assumed to equal the averages attained historically, namely $\sigma^{sur}_{1+} = 0.35$ and $\sigma^{sur}_{0} = 0.4$. However, σ^{sur}_{0} only reflects the sampling variance associated with the recruit survey. A subsequent analysis (assuming log-normality and using data up to 1993) of MLVPA estimates of recruitment and the recruitment estimates provided by the recruit surveys revealed that the true precision of the index provided by the recruit survey is poor – the overall *CV* is some 65%. Nevertheless, the recruit survey estimates are the only usable indices of recruitment available *before* the fishing season is over, and even though they aren't used in the fitting criterion for the MLVPA adopted in practice [$W_2 = 0$ in Equation (A1.5)], they constitute an important management tool for setting bycatch levels and are consequently used in the management procedures considered. In the testing of management procedures, only the sampling component (inter-survey-transect variability) of the overall variance is used.

The summary performance statistics for each test are calculated from quantities of interest derived from 500 simulations of 20-year projections, with the 20-year trajectories differing from one another because of the error components in Equations (A2.3), (A2.5) and (A2.9). However, when alternative management procedures are compared, the same series of 20×500 error "realizations" are used to reduce the effect of Monte Carlo variation on the differences between performance statistics, and the operating model is left unchanged. For the robustness tests of Fig. 8, changes are made to the operating model, while the management procedure (given by Decision Rules (1)–(4), the *TAC* constraints in the main text and Equation (A2.11)) are left unchanged. These changes mean that alternative assessments of the resource need to be carried out, and each assessment, reflecting changes in k_1 and M, is represented by a column in Table App.1.2.

APPENDIX 3

In addition to the bycatch component of MP_{sel} described in Decision Rules (2)–(4) in the main text (with x^{init} = 0.06), three alternative bycatch procedures were considered. In each case, the operating model used is the base-case operating model (Table App.1.2), a value of $TAC_{byc}^{ad} = 7.5$ is used, and Decision Rule (1) in the main text is kept unchanged, with $z = 0.1$ (as for MP_{sel}).

Bycatch Procedure 1

This procedure is essentially independent of the *TAC* for anchovy, and is similar in form to the management procedure for anchovy described by Butterworth *et al*. (1993):

$$TAC_{byc}^{init}(y) = TAC_{byc}^{ad} + 0.7\alpha\left[\beta + (1-\beta)\frac{B_{y-1,1+}^{sur}}{\bar{B}_{1+}^{sur}}\right] , \quad \text{(A3.1)}$$

$$TAC_{byc}^{rev}(y) = TAC_{byc}^{ad} + \alpha\left[\beta\frac{R(y)}{\bar{R}(y)} + (1-\beta)\frac{B_{y-1,1+}^{sur}}{\bar{B}_{1+}^{sur}}\right] , \quad \text{(A3.2)}$$

where $$\bar{R}(y) = \frac{1}{y-1987-1}\left[\sum_{i=1989}^{y-1} R(i) + R(1987)\right]$$

(note that there was no recruit survey in 1988 – see Table App.1.1), and

$$\bar{B}_{1+}^{sur} = \frac{1}{8}\sum_{y=1984}^{1991} B_{y,1+}^{sur} \quad .$$

In the above, $R(y)$ is taken from Equation (A2.11), and α and β are the control parameters.

Bycatch Procedure 2

This procedure is a constant bycatch procedure, with α as the control parameter:

$$TAC_{byc}^{init}(y) = TAC_{byc}^{rev}(y) = TAC_{byc}^{ad} + \alpha \quad . \quad \text{(A3.3)}$$

Bycatch Procedure 3

This procedure is a combination of the bycatch component of MP_{sel} (Decision Rules (2)–(4)) and Bycatch Procedure 2:

$$TAC_{byc}^{init}(y) = TAC_{byc}^{ad} + \alpha + x^{init}TAC_{anch}^{init}(y) \quad , \quad \text{(A3.4)}$$

$$TAC_{byc}^{rev}(y) = TAC_{byc}^{ad} + \alpha + x^{rev}TAC_{anch}^{rev}(y) \quad , \quad \text{(A3.5)}$$

where the control parameters are α and x^{init} (x^{rev} being a function of x^{init} in an identical manner to Decision Rule (4)).