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Is the management procedure approach equipped to handle short-lived pelagic species with their boom and bust dynamics? The case of the South African fishery for sardine and anchovy

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Worldwide, small shoaling pelagic fish manifest rapid and substantial natural changes in abundance. Is the application of a management procedure (MP), evaluated using simulation tests [i.e. a MP approach otherwise known as management strategy evaluation (MSE)], to recommend total allowable catches (TACs) with constraints desired by industry on the extent of interannual changes viable for such resources, particularly given the customarily lengthy MP evaluation process? This question is examined by considering the rapid boom and then bust situation that arose for the South African fishery for sardine (*Sardinops sagax*) and anchovy (*Engraulis encrasicolus*) across the turn of the century. Novel adaptations to the MP in place at the time of the boom allowed enhanced resource use during the boom period without compromising the risk of unintended depletion of the populations. Importantly a two-tier threshold system allowed the normal constraints on the maximum extent of interannual TAC reduction to be modified when TACs rose above the specified thresholds. The general protocol underlying the application of MPs for South African fisheries proved sufficiently flexible for the approach to continue to be applied, despite the unanticipated rapid fish population boom and then bust experienced.

Keywords: anchovy, management procedure, MSE, risk, sardine, short-lived species, South Africa.

Introduction

Management strategy evaluation (MSE) (Smith *et al*., 1999; De Oliveira *et al*., 2008), alternatively termed the management procedure (MP) approach (e.g. Butterworth and Punt, 1999; Butterworth, 2007; see the Glossary in Rademeyer *et al*., 2007), involves simulation testing of a set of rules or formulae under consideration for use to provide resource management recommendations. The aim, in line with the precautionary principle (FAO, 1995), is to select a MP whose performance will be reasonably robust to uncertainties associated with the resource being managed, where those uncertainties are considered to be plausible rather than speculative. Here, performance relates to anticipated achievement in simulations of desired trade-offs among mutually conflicting objectives such as maximizing catch, minimizing interannual catch variability, and minimizing the risk of unintended depletion of the resource. [Note that fluctuations in recruitment and noise in resource monitoring indices can lead to population abundance dropping below the trajectory that would result under deterministic dynamics coupled to error-free information; this in turn could, for example, compromise future recruitment levels through stock–recruitment effects, attainment of recovery targets, or keeping catch per unit effort (cpue) above the level required for economic viability of the fishery.]

Although the application of the MP approach with consequent adoption of a MP is suggested to be best practice in fisheries management (FAO, 2008), and indeed the Marine Stewardship Council now seeks an agreed harvest control rule (HCR) as an important component of the attributes of a fishery for certification of sustainability to be warranted (Marine Stewardship Council, 2009), to date relatively few fisheries worldwide have been or are managed on this basis. Punt (2006), for example, lists only 16. One of the reasons for the slowness of this transition from the traditional best assessment approach to providing management recommendations may be the lengthier process and mathematically more-intensive analyses that the MP approach requires by comparison (Butterworth, 2007).

MPs were first developed in the International Whaling Commission (IWC; Punt and Donovan, 2007), where the whale populations under consideration are long-lived and generally considered to be unlikely to manifest high variability in annual recruitment—a situation in which one of the objectives of the MP approach of placing limits desired by industry on the extent of total allowable catch (TAC) changes from one year to the next might be expected to be readily achievable. In sharp contrast, populations of small shoaling pelagic species such as sardine and anchovy characteristically have short life expectancy and worldwide show large fluctuations in annual recruitment.

Consequently, their abundance can change rapidly and substantially (boom and bust) over time (Schwartzlose *et al.*, 1999; Barange *et al.*, 2009).

These characteristics of small pelagic species raise questions about the practicalities of successfully applying the MP approach for the associated fisheries:

(i) although restrictions on the extent of what might otherwise be large TAC changes from year to year (under, for example, an intended constant fishing mortality approach) become all the more desired by industry, is this possible without too large a risk of unintended resource depletion; and

(ii) is the relatively lengthy MP evaluation process (Butterworth, 2007) viable in circumstances where resource abundances can change so rapidly, with possible consequent needs for frequent re-evaluation of resource status and management measures, and hence perhaps of the MP itself?

The fact that just three of the examples of MP implementation listed in Punt (2006) involve short-lived species [the Australian northern prawn fishery (Dichmont *et al.*, 2006), the US–Mexico fishery on the northern subpopulation of Pacific sardine (Pacific Fishery Management Council, 1998), and the South African pelagic fishery for sardine and anchovy (De Oliveira *et al.*, 1998)] also hints that the approach may be poorly suited to such cases. Furthermore, the shoaling behaviour of small pelagic species renders cpue unreliable as an index of abundance, so that the effort-control basis used for the Australian northern prawn fishery could not be applied for these pelagic species.

This paper addresses these questions of practicality by considering the rapid boom then bust situation that arose across the turn of the century for the last of these fisheries, that for sardine (*Sardinops sagax*) and anchovy (*Engraulis encrasicolus*) off South Africa.

Sardine and anchovy form the backbone of the South African pelagic fishery, the country's second-most valuable fishery in monetary terms, which also takes smaller quantities of other species, usually dominated by round herring (*Etrumeus whiteheadi*). The fishery began during World War II, focusing first on sardine and horse mackerel (*Trachurus trachurus capensis*). The annual sardine catch peaked in the early 1960s at a little over 400 000 t, but dropped sharply thereafter, and remained low from the late 1960s until the mid-1990s (Figure 1; De Oliveira *et al.*, 1998). The anchovy-directed fishery began with the introduction of smaller-mesh nets following the fall in the sardine landings in the mid-1960s, and anchovy landings dominated the pelagic fishery from the late 1960s to the mid-1990s (Figure 1a; De Oliveira *et al.*, 1998).

These resources have been jointly managed using MPs since 1994 (De Oliveira and Butterworth, 2004). The reason for joint management under a single MP is that (for given risk levels for each species) landings of sardine and anchovy cannot be separately maximized. This is because the anchovy fishery primarily targets juveniles which shoal together with juvenile sardine for a large part of the time for which they are available to the fishery. Most anchovy landings are therefore associated with a juvenile sardine bycatch; the directed sardine fishery, which primarily targets adults for canning, is consequently negatively impacted in subsequent years. This trade-off of catches between the two species has resulted in a joint operational management procedure (OMP) being employed to propose a TAC for each species and an allowable bycatch for sardine (De Oliveira and Butterworth, 2004). (Note that the term "operational" is used in South Africa to make clear that the MP is not simply conceptual, but is fully specified so as to be immediately applicable in practice to provide management recommendations.)

The details of the MPs implemented have changed somewhat over time as further resource monitoring data have become available, and additional features of the fishery have been taken into account. In 2002, a new OMP, termed OMP-02, was implemented

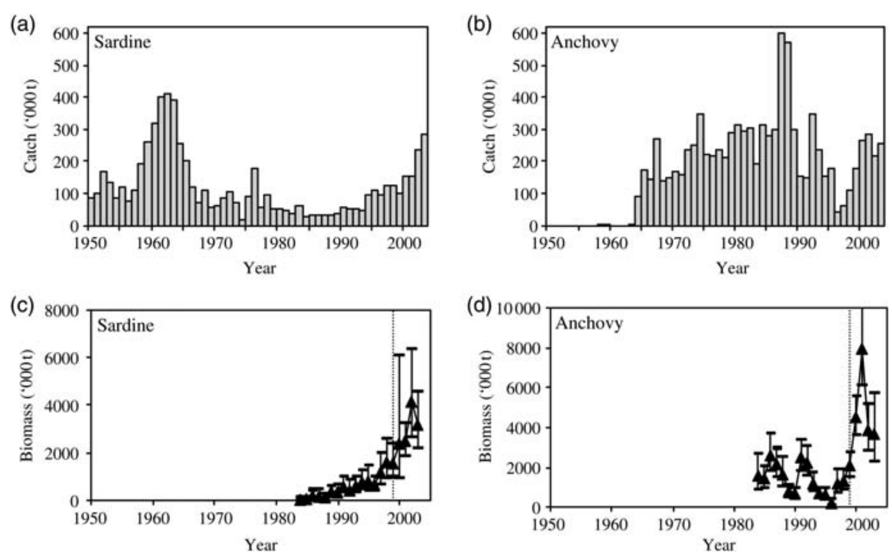

Figure 1. Annual catches of (a) sardine and (b) anchovy from 1950 to 2003. Data from 1980 are used in the assessments. The year y indicated for annual catches refers to the period from November of year $y - 1$ to October of year y. Hydroacoustic survey estimates of (c) sardine and (d) anchovy 1+ biomass from November 1984 to November 2003 are also shown. The data to the right of the vertical dotted line are the new data not used in the development of OMP-02.

for the fishery (De Oliveira and Butterworth, 2004). This OMP was developed using data available up to November 1999 for sardine and to May 2000 for anchovy (De Oliveira, 2003).

Across the turn of the century, however, there were substantial increases in the abundances of both sardine and anchovy. In 2001, the anchovy reached a record biomass, followed by sardine the next year (Figure 1). OMP-02 had been developed using the data available before these booms, and the associated simulation testing had not allowed for increases as large as occurred. Although MPs are typically reviewed only after periods of 4–5 years (Butterworth, 2007), a revision to OMP-02 was urgently needed to take these unanticipated events into account, and in particular to permit better use of the resources during a period of enhanced abundance whose duration was uncertain.

This paper discusses key novel features of the revised OMP, OMP-04, that was consequently developed, concentrating specifically on how the constraints on TAC changes from year to year were modified, and the application of the general protocol for OMPs for South African fisheries which cater for unanticipated events and can lead to the initiation of a review of an OMP ahead of the four-yearly schedule (see Appendix 2 of Rademeyer *et al*., 2008). It also explains why and how the definitions of risks to the resources had to be modified. This revised OMP was tested by simulation, using operating models provided by a Bayesian assessment of each resource based on data available up to November 2003 (de Moor and Butterworth, 2009). Crucially, the existing OMP-02 was modified to permit more effective use of the sardine and anchovy resources during a period of concurrent peak abundances, while still maintaining acceptable levels of risk to these resources. The benefits from OMP-04 are confirmed by showing how it performed, in terms of TACs set, compared with what would have transpired had OMP-02 not been revised.

Methods

Operating models

Key components in the development of a MP are the operating models of the underlying actual dynamics of the resources of interest (Rademeyer *et al*., 2007; De Oliveira *et al*., 2008), which provide the basis for the simulation testing. The models are used to project the resources forward under TACs specified by the MP and are linked to an observation model that generates the data (such as estimates of abundance from surveys) to be input into the MP. This framework is detailed in Supplementary Section A.

At the turn of the century, sardine biomass and recruitment were at peaks. Given the volatile nature of pelagic recruitment, it was impossible to predict for how long this above-average recruitment would continue. Historical catch trends in the South African sardine fishery had been compared with those elsewhere in the world. Results suggested that peaks in the South African fishery were atypical, being probably of a lesser duration than elsewhere, which compounded the prediction difficulties in that case (Cunningham and Butterworth, 2005). To follow a precautionary approach, the underlying operating models assumed that the stock–recruitment curve estimated in the assessment process pertained to only one further year after 2003; thereafter, the curve reverted to one for which maximum (expected) recruitment was lower (see details in Supplementary Section A). All results presented in this paper use the base-case operating models provided by the Bayesian assessments of each resource (de Moor and Butterworth, 2009).

Harvest control rules

Another key component of a MP is its HCRs, which determine TAC or total allowable effort recommendations based on resource monitoring information (ICES, 2006; Rademeyer *et al*., 2007; De Oliveira *et al*., 2008). The MP for the South African sardine and anchovy resources is empirical in that TACs are computed directly from these data (primarily abundance estimates from hydroacoustic surveys) without any intermediate assessment-like process to estimate resource status. For South African sardine and anchovy, HCRs are applied to set TACs and TABs (total allowable bycatches). These rules are described qualitatively below. The specific control parameters and constraints used in the HCRs for OMP-02 and the new OMP-04, together with the data required for input to OMP-04, are listed in Supplementary Section B, Tables B1 and B2.

Sardine and anchovy TACs and sardine TABs are set before the start of the pelagic fishery at the beginning of each year. The anchovy TAC and sardine TAB are revised midyear. This biannual process has been designed to follow the annual November 1+ biomass (biomass of fish of age 1 and above) and May recruitment surveys, from which key input data to the MP rules are obtained (Supplementary Section B, Table B2 and Figure B1). In addition, the anchovy TAC is split into two seasons, a normal season running from January to August and an additional season running from September to December. Separate anchovy TACs and sardine TABs are set for the normal and additional seasons, with the latter encompassing the period when anchovy and juvenile sardine commonly no longer shoal together in large quantities. This allows for better utilization of the anchovy resource later in the year, when only a small sardine TAB is required.

The sardine TAC computation basis is a constant fishing mortality (with modifications at high and at low levels of abundance) applied to the November survey abundance estimate. The initial anchovy TAC and sardine TAB are calculated assuming average forthcoming anchovy recruitment (which will contribute the bulk of the anchovy catch). A multiplicative scale-down factor ($\delta < 1$) is introduced to provide a buffer against possible poor recruitment (Table 1). Once the survey estimate of recruitment is available, the anchovy normal season TAC is revised and the δ reduction factor is no longer applied (Supplementary Section B, Table B3).

The sardine TAB includes a fixed tonnage to account for the mainly adult sardine bycatch with round herring and a second component, proportional to the anchovy TAC, to allow for the mainly juvenile sardine bycatch with anchovy (Supplementary Section B, Table B3). An estimate of the current abundance ratio of juvenile sardine to anchovy, based on very recent survey and catch data, is taken into account when revising the sardine TAB midyear. Naturally, any within-season adjustments to the anchovy TAC and sardine TAB are constrained to preclude any negative adjustments, as initial allocations could already have been caught by mid-season.

The directed sardine and anchovy TACs are subject to maximum and minimum constraints as well as constraints on the maximum interannual decrease and mid-season increase in the anchovy TAC (Supplementary Section B, Tables B1 and B3). These constraints provide for a smoother operation of the pelagic industry and take account of limitations in processing capacity. The maximum directed sardine TAC (c^{S}_{mxtac}) was

Table 1. Definitions and values of key MP parameters (all parameters are more fully defined in Supplementary Section B, Table B1), noting that the level at which the two-tier threshold is invoked is not exactly $c_{\mathrm{tier}}^{\mathrm{A/S}}$, but an adjustment of that value to take account of the normal extent of interannual TAC variation allowed, i.e. $(1-c_{\mathrm{mxdn}}^{\mathrm{A/S}})c_{\mathrm{tier}}^{\mathrm{A/S}}$.

Parameter	Definition	OMP-02	OMP-04
β	Directed sardine catch control parameter	0.18650	0.14657
α_{ns}	Directed anchovy catch control parameter for normal season	0.16655	0.73752
α_{ads}	Directed anchovy catch control parameter for additional season	0.99956	1.47504
δ	Scale-down factor applied to initial anchovy TAC	0.85	0.85
$c_{\mathrm{tier}}^{\mathrm{S}}$	Two-tier threshold for directed sardine TAC	N/A	240 000 t
$c_{\mathrm{tier}}^{\mathrm{A}}$	Two-tier threshold for directed anchovy TAC	N/A	330 000 t
$c_{\mathrm{mxdn}}^{\mathrm{S}}$	Maximum proportion by which directed sardine TAC can be reduced annually	0.20	0.15
$c_{\mathrm{mxdn}}^{\mathrm{A}}$	Maximum proportion by which normal season anchovy TAC can be reduced annually	0.30	0.25
$c_{\mathrm{mxtac}}^{\mathrm{S}}$	Maximum directed sardine TAC	250 000 t	500 000 t
$c_{\mathrm{mxinc}}^{\mathrm{ns,A}}$	Maximum increase in normal season anchovy TAC	150 000 t	200 000 t
$c_{\mathrm{mxinc}}^{\mathrm{ads,A}}$	Maximum additional season anchovy TAC	100 000 t	150 000 t
B^*	Threshold at which metarule invoked for sardine	N/A	800 000 t

N/A, not applicable

increased from the 250 000 t in OMP-02 to 500 000 t in OMP-04 in response to the rapid increase in the sardine abundance as well as an increase in the industry's processing capacity (Table 1). This ensured that the additional sardine suddenly available was not wasted [such wastage would have been contrary to clause 2 of South Africa's Marine Living Resources Act (Anon., 1998) which specifies an objective of achieving optimum utilization], because it could be turned into fishmeal if canning capacity or demand was exceeded. In addition, industry requested increases in the maximum mid-season increment in the anchovy TAC ($c_{\mathrm{mxinc}}^{\mathrm{ns,A}}$), the maximum additional season anchovy TAC ($c_{\mathrm{mxinc}}^{\mathrm{ads,A}}$) and the initial sardine bycatch during years of high sardine abundance (Table 1, and elaborated in Supplementary Section B). The constraints included minimum TACs to preserve the industry over a range of medium to low biomasses. These safeguard against potential false negatives in the survey estimates of abundance (i.e. estimates that are low not because the abundance is low but because of negative residuals arising from sampling error), which could result in the closure of smaller companies should the TAC drop below the minimum level for only a single year. The maximum interannual decrease provides some year-to-year stability for the industry. Under OMP-02, the anchovy normal season TAC could decrease by a maximum of 30% between years, and the directed sardine TAC by a maximum of 20% from one year to the next (Table 1).

A two-tier system for constraints on TAC decreases

Although limits on the extent of decreases in TACs are advantageous for the reason given above, the MP must still be able to decrease TACs sufficiently, and sufficiently rapidly, if there is a substantial decrease in abundance, so that risk criteria remain satisfied. The MP control parameters consequently have to be chosen so that a TAC cannot climb too high; otherwise, a series of TAC reductions that would see risk criteria met could not be achieved in sufficient time, given standard restrictions on downward adjustments. That would in turn result in unnecessary wastage of a resource during periods such as across the turn of the century when there is an abundance peak.

For OMP-04, a two-tier system was consequently designed to harvest the resources more effectively during such boom years, without unduly increasing risk if abundances dropped rapidly from such peaks. A two-tier threshold ($c_{\mathrm{tier}}^{\mathrm{A/S}}$; Table 1) was defined for each species below which constraints governing the maximum proportion by which directed sardine and anchovy TACs could be decreased interannually continue to hold (as for OMP-02). However, above those thresholds, a TAC could be decreased right down to a threshold level in the following year. This has the desired effect of allowing for greater TACs at high levels of resource abundance without compromising risk. Therefore, a greater proportional decrease from one year to the next is allowed in situations when high TACs have been awarded.

Exceptional circumstances

The stability afforded to the industry through the minimum TAC constraints clearly cannot be unconditional. These constraints apply as long as survey-estimated 1+ biomass remains above a specified threshold (Supplementary Section B, Table B1), below which exceptional circumstance provisions apply. Such low abundances relate to an increased risk of reduced recruitment, and more-stringent conservation measures have to be enacted should such a situation arise. These seek to be sufficiently corrective that the resource is able to rebound above the threshold as soon as possible, while balancing this against the socio-economic disruption of near-closure of the industry.

Exceptional circumstances are declared for sardine or anchovy at the end of the year if the recent November 1+ biomass is below such a species-specific threshold and at midyear for anchovy if the projected November 1+ biomass, taking the most recent survey estimate of anchovy recruitment and natural and anticipated fishing mortality into account, is below this threshold.

The updated rules chosen to apply if exceptional circumstances are declared are listed in Supplementary Section B, Table B4. For November, for example, the directed sardine TAC or initial anchovy TAC recommended by the OMP are adjusted downwards when a survey estimate of the November sardine or anchovy 1+ biomass drops below the exceptional circumstances threshold, and in a manner that depends quadratically on the survey estimate. In addition, the rules allow for the anchovy TAC to be set to zero if the survey estimate falls below one-quarter of the threshold.

Risk

The perception of the status and productivity of the sardine and anchovy resources changed when they were re-assessed taking

Table 2. The standard deviation of the log recruitment residuals ($\sigma_r^{S/A}$) and the average pristine biomass ($K^{S/A}$, '000 t) at the joint posterior mode and the medians of the marginal posterior distributions (95% probability intervals given in parenthesis) for the sardine and anchovy assessments based on data to November 2003 (de Moor and Butterworth, 2009).

	Sardine				Anchovy		
	Previous assessment	Updated assessment			Previous assessment	Updated assessment	
	MLE	Posterior mode	Posterior median		MLE	Posterior mode	Posterior median
σ_r^S	0.499	0.416	0.491 (0.405–0.691)	σ_r^A	0.685	0.740	0.883 (0.659–1.276)
K^S	1 552	5 926	6 754 (3 323–26 541)	K^A	1 802	2 307	2 492 (1 676–4 451)

A comparison is made with the maximum likelihood estimates (MLE) of these parameters from the previous assessment, used to develop OMP-02, which considered sardine data to November 1999 and anchovy data to May 2000 (De Oliveira, 2003).

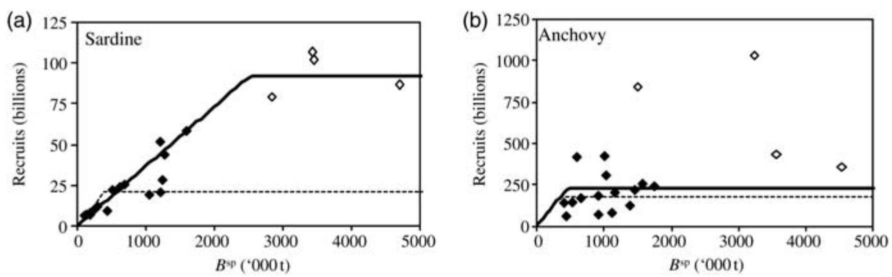

Figure 2. Model predicted November recruitment plotted against spawner biomass from 1984 to 2002 for (a) sardine and (b) anchovy (black diamonds). The four most recent recruitments which for sardine reached record levels are shown by open diamonds. The stock–recruitment relationships estimated using the assessment results are shown as heavy lines. The relationship from the previous assessment using data up to 1998 for sardine and 1999 for anchovy (De Oliveira, 2003) is also given for comparison as dashed lines.

both revisions of past data as well as data becoming available after the turn of the century into account (de Moor and Butterworth, 2009). In particular, estimates of the stock–recruitment relationships and the extent of variation about them changed appreciably from earlier values that had been based on sardine data up to 1999 and anchovy data up to May 2000 (De Oliveira, 2003; Table 2; Figure 2). These two sets of stock–recruitment relationship can be compared directly because the same values of natural mortality were used for both sets of base-case assessment. The estimates of the parameters of these relationships have important implications for risk when developing MPs. The higher the (log) recruitment residual standard deviation, $\sigma_r^{A/S}$, the more likely it would be that the resource is resilient to fluctuations to low levels (as these occur more frequently naturally), so the greater the probability of dropping below a specified fraction of the average pristine level (carrying capacity), $K^{A/S}$, that can be tolerated. OMP-02 was developed using the assessments from De Oliveira (2003). Table 2 shows that the estimate for σ_r^A increased for the updated assessment whereas that for σ_r^S decreased. Given also the updated perception of the values of average pristine levels, $K^{A/S}$, for these resources as a result of their recent peak abundances, a change in the definitions of risk for these resources also had to be considered.

OMP-02 was tuned to the risk levels $\mathrm{risk}_S^{OMP\text{-}02} \leq 0.1$ and $\mathrm{risk}_A^{OMP\text{-}02} \leq 0.3$ (De Oliveira and Butterworth, 2004), where risks were defined as

$\mathrm{risk}_S^{OMP\text{-}02}$—the probability that adult sardine biomass falls below 20% of K^S at least once during a 20-year projection period, and

$\mathrm{risk}_A^{OMP\text{-}02}$—the probability the adult anchovy biomass falls below 15% of K^A at least once during a 20-year projection period.

Ideally risk should be defined in a manner that is relatively robust to updates in the perception of the resource, given an updated assessment. However, as Table 2 shows, the updated assessment led to a substantial increase in the estimate of K^S. In addition, because $K^{A/S}$ depends on the stock–recruitment model assumed, the values estimated vary with different underlying stock–recruitment model assumptions (Supplementary Section C, Tables C2 and C3). These uncertainties concerning $K^{A/S}$ made it an undesirable parameter upon which to base a risk definition, so alternatives were sought.

Results

Risk

Given the problems described above with continuing to use proportions of K^S and K^A to define risk, these definitions were amended to

$\mathrm{risk}_S^{OMP\text{-}04}$—the probability that adult sardine biomass falls below the average adult sardine biomass between November 1991 and November 1994 at least once during a 20-year projection period, and

$\mathrm{risk}_A^{OMP\text{-}04}$—the probability that adult anchovy biomass falls below 10% of the average adult anchovy biomass between November 1984 and November 1999 at least once during a 20-year projection period.

The choice of the level of sardine abundance used in the above definition arose from the observation that the biomass in the early 1990s had proved sufficient to allow a rebound of the resource, extending even to record abundance levels at the turn of the century (de Moor and Butterworth, 2009). This period also represented a level of spawner biomass below which the resource should not fall if one wished to avoid a reoccurrence of the low abundances of the 1980s. The level chosen for anchovy (10% of the estimated average November 1+ biomass from 1984 to 1999) was 117 000 t for the base-case assessment, which is less than the $0.15K^{A}$ estimate of some 270 000 t that had been used previously. Some reduction was considered justified given the increase in the estimate of σ_r^{A}, with the specific management choice made by the Marine and Coastal Management's (MCM) Pelagic Scientific Working Group (PSWG). This is a group of scientists from within and outside MCM, appointed by the Chief Director, Research, at MCM to advise on scientific management measures, such as TACs, for the small pelagic resources, with industry members and other stakeholders having observer status at meetings.

Acceptable levels for these risks then had to be chosen and were maintained as $\mathrm{risk}_S^{\mathrm{OMP-04}} \le 0.1$ and $\mathrm{risk}_A^{\mathrm{OMP-04}} \le 0.3$, as used in developing OMP-02, in the interests of keeping a degree of continuity. The specific choice of the biomass level used in the anchovy risk definition was made to maintain the previous maximum average annual level of anchovy catch to be anticipated at its OMP-02 value of some 300 000 t, which was considered defensible given the previous history of catches typically averaging about this level from this resource over a 30-year period. The choices made for sardine reflect a similar relative shift to the left in the distribution of biomass as a proportion of average pristine biomass from the no-catch scenario that had been the case for the OMP-02 analyses (Figure 3a and c). However for anchovy, the extent of this shift was increased (Figure 3b and d).

Trade-off curves

A curve depicting the trade-off predicted between average directed sardine catch and average anchovy catch (with its associated juvenile sardine bycatch) subject to certain risk criteria being satisfied was used in the development of earlier OMPs for the South African pelagic fishery (De Oliveira, 2003; De Oliveira and Butterworth, 2004). Any point on that curve is given by a different set of values for the control parameters (β, α_{ns}, and α_{ads}; Table 1) and denotes a greater preference towards either directed sardine (larger β, smaller α_{ns}) or anchovy (smaller β, larger α_{ns}) catches. For OMP-02, the curve was determined by limiting $\mathrm{risk}_S^{\mathrm{OMP-02}} \le 0.1$ and $\mathrm{risk}_A^{\mathrm{OMP-02}} \le 0.3$ (Figure 4a). The near-horizontal portion of the curve was determined primarily by the specified acceptable sardine risk level, and the vertical line on the right side of the curve follows from the acceptable anchovy risk level.

The trade-off point on the curve chosen for OMP-02 was determined by an overall preferred sardine:anchovy ratio calculated once all rights-holders in the pelagic fishery had specified their individual preferred ratio (De Oliveira, 2003; De Oliveira and Butterworth, 2004). At the start of 2002, rights were allocated as proportional shares in the sardine/anchovy fishery as a whole, with each rights-holder given the opportunity to specify the ratio (their preferred ratio) of sardine to anchovy catches which they would wish to be awarded on average over time. This information was used to calculate the fractions of the annual directed sardine TAC and the annual anchovy TAC that they would

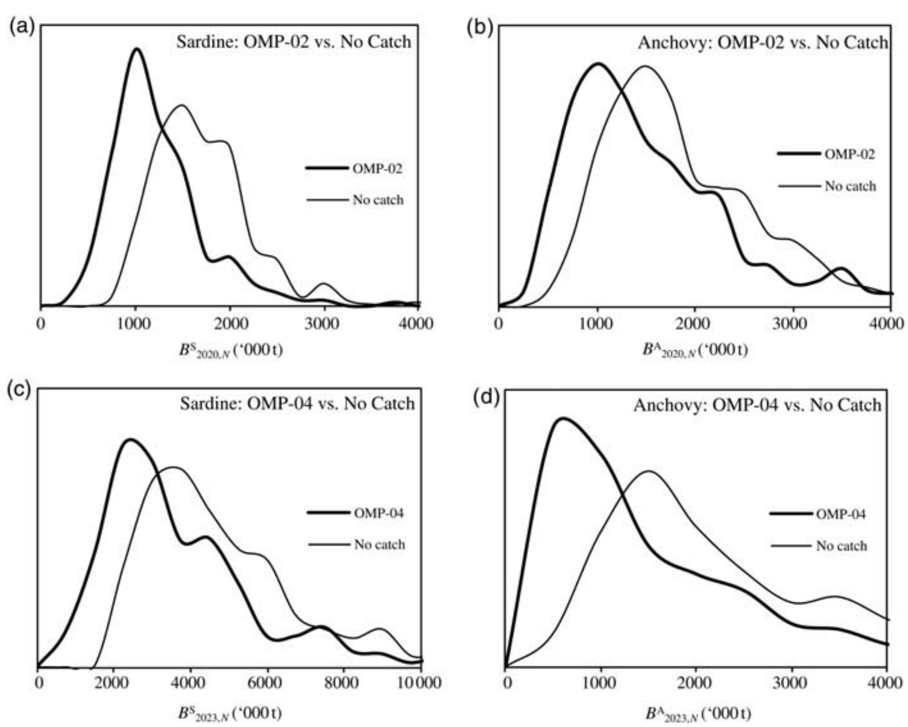

Figure 3. Distribution of 1+ biomass at the end of the 20-year projection period under OMP-02 for (a) sardine and (b) anchovy and under OMP-04 for (c) sardine and (d) anchovy, compared with a zero catch scenario (note that the operating model used to develop such projections under OMP-02 was updated using further resource monitoring data that had subsequently become available for the OMP-04 results shown). Note that the horizontal axis scale for sardine differs between (a) and (c).

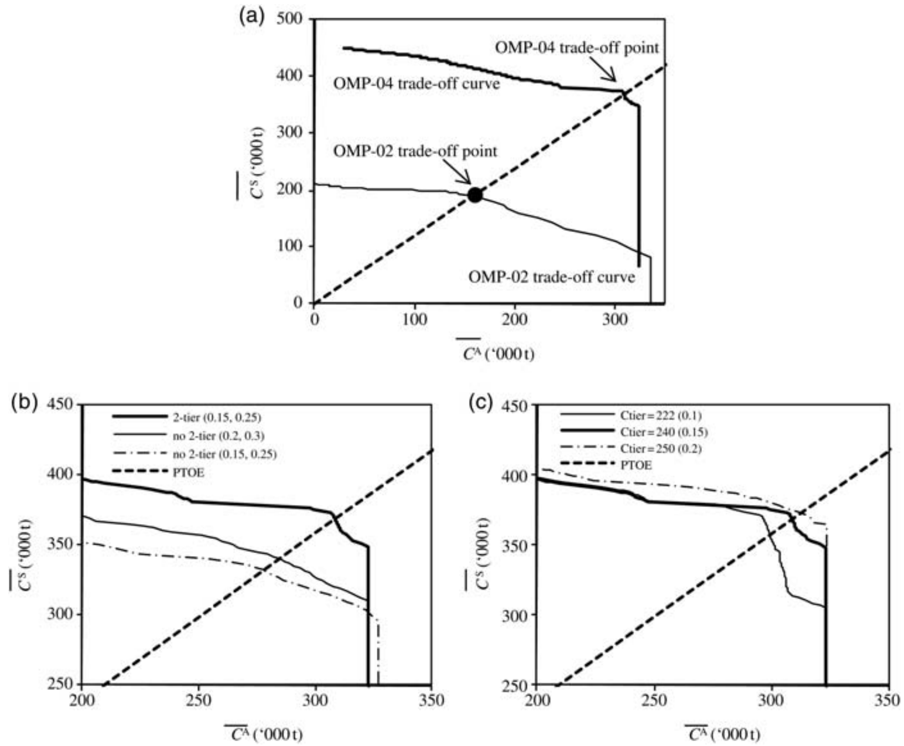

Figure 4. Trade-off curves between average annual directed sardine catch and average annual anchovy catch which satisfy the risk criteria $\text{risk}_S \leq 0.1$ and $\text{risk}_A \leq 0.3$ for (a) OMP-02 and OMP-04, and then for alternative two-tier options: (b) OMP-04 vs. no two-tier where the values in parenthesis are (c^S_{mxdn}, c^A_{mxdn}), and (c) alternative sardine two-tier thresholds to the 240 000 t chosen where the values in parenthesis are (c^S_{mxdn}). The PTOE line, obtained using the control parameter values for OMP-02, was used to determine the new trade-off selection for OMP-04. Note that in (b) and (c), the axes cover a smaller range than (a), to aid comparison.

receive each year (De Oliveira, 2003). The effective preferred ratios that had applied previously were calculated from percentage allocations of directed sardine and anchovy TACs awarded under OMP-99 (De Oliveira, 2003). After February 2002, no further changes were to be allowed during the period for which the rights were allocated. The ratio of anticipated average directed sardine to anchovy catches was therefore chosen to remain the same from OMP-02 to OMP-04, to continue to reflect the relative preferences expressed by rights-holders. This is shown in Figure 4 as the preferred trade-off extrapolation (PTOE) line, which was projected to the new trade-off curve to determine the trade-off point for OMP-04.

Table 3. Average annual directed sardine, $\overline{C}^S$, and anchovy, $\overline{C}^A$, catch ('000 t) over the projection period from 2004 to 2023 for alternative two-tier thresholds (c^S_{tier} and c^A_{tier}, in '000 t), and alternative maximum proportions by which the TAC can be annually reduced (c^S_{mxdn}, c^A_{mxdn}).

c^S_{tier}	c^S_{mxdn}	c^A_{tier}	c^A_{mxdn}	$\overline{C}^S$	$\overline{C}^A$
None	0.15	None	0.25	332	278
None	0.20	None	0.30	340	285
222	0.10	330	0.25	357	299
240	**0.15**	**330**	**0.25**	**369**	**309**
250	0.20	330	0.25	373	312
240	0.15	309	0.20	369	309
240	0.15	354	0.30	369	309

The row shown emboldened corresponds to the control parameter values chosen for OMP-04.

A two-tier system for constraints on TAC decreases

Figure 4b shows the effect of introducing the two-tier system. For the same constraints on maximum interannual decreases in directed sardine and normal season anchovy TACs (of $c^S_{\text{mxdn}} = 0.15$ and $c^A_{\text{mxdn}} = 0.25$, respectively), the projected average directed sardine and anchovy TACs both increase by $\sim$11% for the two-tier control parameter values chosen (Table 3). Given the two-tier system, the effects of changes to these constraints were considered. If the maximum proportion by which the sardine TAC can be reduced annually (c^S_{mxdn}) is decreased, the projected average annual directed sardine catch also drops (Figure 4c), but the effect of reducing c^A_{mxdn} for anchovy is negligible (Table 3). The pelagic industry considered the estimated 1% decrease in average projected sardine catch resulting from a change in c^S_{mxdn} from 0.2 to 0.15 (as well as a similar reduction in projected anchovy catch) to be acceptable, given their preference for greater interannual stability during the periods of normal (i.e. not peak or trough abundance) years. They were able to accept this trade-off in part as a result of the average catch benefits provided by the move to the two-tier system. In addition, the industry was able to benefit from a decrease in c^A_{mxdn} from 0.3 to 0.25, with little change to the average projected catches.

Other changes in constraints on TACs

The increase in the maximum directed sardine TAC from 250 000 to 500 000 t, introduced because of the peak in sardine abundance, led to substantial increases of ~50% each for the projected average directed sardine and anchovy catches for the same level of risk. Supplementary Section B details these and some further results relating to the impact of changes to constraints.

Exceptional circumstances

The selection of the exceptional circumstance rules involved a trade-off between being sufficiently corrective that the resource is able to rebound above the threshold as soon as possible and avoiding the socio-economic disruption of near closure of the industry. As they were designed to protect the resource from severe depletion, simulation-testing of alternative potential provisions concentrated on those trajectories that attained low biomass levels under the proposed MP. Individual trajectories were tracked (results not shown), and summary statistics of the lower tails of distributions were compared. Performances of the MP with and without these additional exceptional circumstances rules are contrasted in Table 4. The rules chosen provide a means to reduce the TAC fairly rapidly once the threshold is crossed, with the aim of allowing the resource to recover.

Overview

In general, summary statistics fall into two conflicting groups: resource conservation, such as projected biomass relative to key reference points, and economic performance, such as average catch and variability. Table 4 shows that, on average, the 1+ biomass at the end of the 20-year projection period is estimated to be well above the biomass level used to define risk under OMP-04 for both anchovy and sardine.

The performance of OMP-04 was checked under a number of alternative robustness tests to the underlying operating models of sardine and anchovy population dynamics. The details of these tests and the performance of OMP-04 under each alternative are given in Supplementary Section C.

Implementation

The MP described in this paper was initially adopted as OMP-04 by the PSWG. OMP-04 was implemented from June 2004, but was subsequently revised twice. This paper contains results from the final revision of the OMP in August 2005. In addition, a revision to the sardine HCR was made towards the end of the period during which the OMP was implemented. These revisions and the reasons for them are described below.

Legal

The first revision to the OMP was in response to a Supreme Court of Appeal ruling which referred the matter of the distribution of the pelagic TAC for the 2005 season back to the Department of Environmental Affairs and Tourism for fresh determination (Supreme Court of Appeal, 2004). The second revision was in response to a Cape High Court ruling that the revised pelagic allocations for 2005 again be set aside (Cape High Court, 2005).

Rights-holders in the pelagic industry were afforded the opportunity to revise their preferred sardine/anchovy ratios at the beginning of 2002 (see above). Had the changes requested been granted in full, this would have resulted in the anchovy resource being wastefully underutilized at that time. A cap of a maximum change of 15% in favour of sardine (unrestricted changes in favour of anchovy) was subsequently (before any litigation) imposed on the extent to which individual rights-holders could change their preferred ratio (De Oliveira, 2003). The extent to which this cap should apply was considered in response to both court rulings, with the final revision allowing for a maximum change of 25% in favour of sardine.

The change in the individual rights-holders' preferred ratios resulted in only a small change to the MP's control parameters β, α_{ns}, and α_{ads}, and hence the trade-off point on the trade-off curve.

Biological

OMP-04 was developed based on assessments taking data up to November 2003 into account, a period ending when sardine biomass was at a peak (de Moor and Butterworth, 2009).

Table 4. The level of risk to the resources, $\text{risk}_S^{\text{OMP-04}}$ and $\text{risk}_A^{\text{OMP-04}}$, average annual directed catches ('000 t), $\bar{C}^S$ and $\bar{C}^A$, average proportional annual changes in directed catch, AAV^S and AAV^A, average biomasses at the end of the projection period as proportions of average pristine biomass, K^S and K^A, and as a proportion of the biomass levels used in defining risk, B^S_{risk} and B^A_{risk}, and average minimum biomasses over the projection period, B^S_{min} and B^A_{min}, as proportions of average pristine biomass and as proportions of $B^{S/A}_{\text{risk}}$, for the OMP-04 trade-off point.

	Sardine						Anchovy				
	All simulations		Lower 10%				All simulations		Lower 10%		
Parameter	With ECs	No catch	With ECs	No ECs	No catch	Parameter	With ECs	No catch	With ECs	No ECs	No catch
$\text{risk}_S^{\text{OMP-04}}$	0.098	0.010	[a]	0.100[a]	[a]	$\text{risk}_A^{\text{OMP-04}}$	0.280	0.028	[a]	0.410[a]	[a]
$\bar{C}^S$	368.7	0.0	260.7	259.0	0.0	$\bar{C}^A$	304.0	0.0	204.4	127.1	0.0
AAV^S	0.194	N/A	0.270	0.262	N/A	AAV^A	0.333	N/A	0.433	0.409	N/A
$\overline{\hat{B}^S_{2023}/K^S}$	0.725	0.982	0.455	0.423	0.929	$\overline{\hat{B}^A_{2023}/K^A}$	0.684	1.012	0.778	0.011	1.183
$\overline{\hat{B}^S_{2023}/B^S_{\text{risk}}}$	3.997	5.213	1.308	1.221	2.890	$\overline{\hat{B}^A_{2023}/B^A_{\text{risk}}}$	14.967	22.078	19.116	0.292	28.959
$\overline{\hat{B}^S_{\text{min}}/K^S}$	0.449	0.658	0.175	0.167	0.462	$\overline{\hat{B}^A_{\text{min}}/K^A}$	0.133	0.301	0.010	0.000	0.087
$\overline{\hat{B}^S_{\text{min}}/B^S_{\text{risk}}}$	2.435	3.423	0.527	0.499	1.458	$\overline{\hat{B}^A_{\text{min}}/B^A_{\text{risk}}}$	2.766	6.303	0.231	0.004	2.017

Summary statistics are given for the full distribution of results and those corresponding to the lowest 10% of future biomass trajectories (defined by considering the lowest biomasses reached by every trajectory over the period for which it is projected, and selecting the trajectories corresponding to the lowest 10% of those values). The lowest 10% of future biomass trajectories are compared with and without the exceptional circumstances provisions (ECs) in the HCRs. Results in the absence of any catch are also provided to aid interpretation. N/A, not applicable.

[a]Risk is calculated using all simulations, and also for the results shown for the lowest 10% of future biomass trajectories.

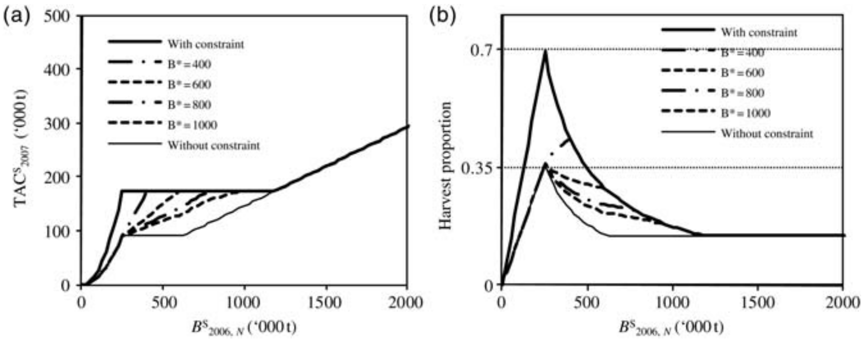

Figure 5. The (a) directed TAC and (b) harvest proportion for sardine in 2007 using OMP-04 (with constraint) and the effect of the choice of B^* in the metarule. The final value selected for B^* was 800 000 t. A comparison is made with the MP rule without any constraint on the maximum proportion by which directed sardine TAC can be reduced annually.

Below-average sardine recruitment was estimated by the hydroacoustic surveys in May of 2004, 2005, and 2006. The sardine 1+ biomass estimated by the survey in November 2005 was below the range of that predicted when simulation testing OMP-04 (Cunningham and Butterworth, 2006), although a conservative sardine stock–recruitment curve was assumed for future simulations (see the section on "Operating Models" and Supplementary Section A). In addition, a predicted distribution of 1+ biomass in November 2006, using data available up to May 2006, hardly overlapped with the distribution simulated for November 2006 1+ biomass during OMP-04 testing (Cunningham and Butterworth, 2006). In line with the review process for such unanticipated events outlined in Appendix 2 of Rademeyer *et al*. (2008), a metarule for the directed sardine TAC was developed and agreed before the November 2006 survey results became known.

The metarule adopted involved modifying the maximum amount by which the directed sardine TAC could be reduced inter-annually if the survey estimate of November 1+ biomass was less than a threshold, B^*. The metarule would respond to a decrease in the sardine 1+ biomass quicker for higher values of B^*, decreasing the directed sardine TAC sooner and/or to a greater extent than for lower values of B^* (Figure 5a). In the absence of this metarule, the harvest proportion (TAC as a proportion of survey estimate of 1+ biomass) could have reached 70% (Figure 5b). This was due to the extremely rapid decrease in survey-estimated 1+ biomass following three consecutive years of poor recruitment. Considering not only that harvest proportion, but also the performance of the MP in the short and medium term with the metarule under alternative pessimistic scenarios, a conservative value of $B^* = 800\,000$ t was chosen. This was to ensure that the harvest proportion at low biomass remained close to that at which it would be were no constraints enforced (Figure 5b). This metarule was adopted as part of OMP-04 in November 2006 to continue to apply until a full revision of the OMP was undertaken, which was scheduled at the time for (and subsequently took place in) 2008.

Application

The revision of OMP-02 undertaken to ensure resources were not underutilized is justified by the directed sardine TACs for 2004 and 2005, which far exceeded the maximum previously applicable under OMP-02 (Table 5). Given TACs above the two-tier threshold and an observed decline in sardine abundance, the TAC in 2006 was decreased to $(1 - c^{\mathrm{S}}_{\mathrm{mxdn}})c^{\mathrm{S}}_{\mathrm{tier}} = 204\,000$ t. The November 2006 1+ biomass decreased below the threshold of $B^* = 800\,000$ t, so the then recently accepted modification to the rule came into effect, allowing the directed sardine TAC to decrease more than the maximum of 15% from the previous year's TAC that would have applied in the absence of the review process for unanticipated events being instituted.

Table 5. The directed sardine and total anchovy TACs ('000 t) recommended by OMP-04 for the duration of its application, with the TACs that would have applied had OMP-02 remained in use given for comparison[a].

	Directed sardine TAC		Anchovy normal season TAC		Anchovy additional season TAC	
Year	OMP-02	OMP-04	OMP-02	OMP-04	OMP-02	OMP-04
2004	250.000	456.874	150.000	272.519	100.000	150.000
2005	250.000	397.000[b]	150.000	215.049[c]	63.895	81.951[d]
2006	200.000	204.000	150.000	212.251	100.000	150.000
2007	160.000	162.436	150.000	386.942	100.000	150.000
Total	860.000	1 220.310	600.000	1 086.761	363.895	531.951

[a]The higher directed sardine catches under OMP-04 compared with OMP-02 were the result not only of the high sardine recruitment and biomass at the turn of the century, but also of the revision in the hydroacoustic dataseries of 1+ biomass estimates upon which previous stock assessments had been based (de Moor *et al*., 2008; de Moor and Butterworth, 2009).

[b]Directed sardine TAC was initially set at 375 078 t, but this was revised in August 2005 with the revision of the OMP (the "Implementation" section explains why the TAC/Bs were revised).

[c]Normal season anchovy TAC was initially set at 204.750 t, but this was revised with the revision of the OMP.

[d]Additional season anchovy TAC was initially set at 92.191 t, but this was revised with the revision of the OMP.

The normal season anchovy TAC ranged between 215 000 and 387 000 t during the period for which OMP-04 was implemented. The TAC exceeded the two-tier threshold in the final year of OMP-04 implementation. By way of comparison, had OMP-02 remained in place, the lower value of the control parameter α_{ns} would have resulted in the minimum TAC being enforced and severe underutilization of the resource during a period of high abundance (Table 5).

OMP-04 therefore proved sufficiently flexible during its implementation to ensure that the sardine resource was not underutilized during a short period of peak abundance, while still being able to rapidly decrease TACs once a drop in the biomass became evident from surveys. Exceptional circumstances provisions were not invoked for either species. The MP process in South Africa has matured to the stage where TAC/Bs recommended by the OMPs are readily accepted by decision-makers and stakeholders (Plagányi *et al.*, 2007; De Oliveira *et al.*, 2008). As a result, all the recommendations arising from OMP-04 were endorsed by the responsible Minister.

Discussion

At the start, we posed the generic questions of whether the MP approach would be viable for small pelagic fish species because their abundances can change so rapidly and whether the constraints desired by industry on interannual TAC changes which are often justified through the use of this approach can be achieved for such resources without risk of unintended resource depletion.

First impressions are that the maintenance of a MP approach, including such constraints, for recommending TACs for the South African sardine and anchovy fishery during the boom then (for sardine) bust period immediately following the turn of the century argues for positive responses to these questions. On closer inspection though, one might question whether OMP-04, given the changes made after its acceptance in 2004, really was a true MP, rather than a complex approach to traditional annual assessment updates. Importantly, however, all modifications were agreed before the data needed for computing the TACs became available, and the outcomes from those calculations were not questioned in the subsequent decision-making process. Moreover, the alternative trade-off points chosen for legal reasons did not alter the risks to the resources. By definition, alternative points on the trade-off curve satisfy both sardine and anchovy risk criteria, and the changes in the control parameters and resulting summary statistics, including projected average catch, for these alternatives were not appreciable.

Butterworth (2007) lists one of the perceived disadvantages of the MP approach being an overly rigid framework and the fear of always maintaining a MP in "autopilot" mode. However, OMP implementation requires post-adoption checks of whether the resource has moved outside the range for which it was designed to operate. When the sardine resource unexpectedly moved outside that range, the regular four-yearly review of the OMP had only just commenced, with adoption planned for a year thereafter. Nevertheless, the HCR was immediately modified, based on some simplified simulation test checks, to ensure that risk to the sardine resource was not unduly increased. This was in line with the provisions for such unanticipated events in South African managed fisheries (Rademeyer *et al.*, 2008) and demonstrates that sound application of MPs should not be without "intelligence" (a concern raised in Rochet and Rice, 2009).

Constraints on interannual TAC changes were kept in place. Indeed, the maximum interannual TAC reductions were actually decreased from 30% for anchovy and 20% for sardine in OMP-02 to 25 and 15%, respectively, in OMP-04. Importantly, however, this benefit of increased stability for the pelagic industry during the periods of more typical biomass levels could be maintained only as a result of the increased flexibility introduced through the two-tier system. This allows for greater reductions after boom periods during which TACs are permitted to increase substantially, to take advantage of unusually large increases in abundance and, also to keep in check the risk of unintended depletion of a resource during subsequent bust periods. Moreover, exceptional circumstances provisions were modified to ensure that if a resource fell to an unacceptably low level, sufficiently corrective action would be taken that should enable it to rebound above the specified exceptional circumstances threshold reasonably quickly.

The lack of robustness of estimates of average pristine biomass, K, to updates in assessments, which became evident when incorporating the associated new data, led to risk being defined in terms of past abundance levels rather than fractions of K. Given also the changes in estimates of the extent of recruitment variability, it was found useful to link risk to the extent to which the pristine biomass distribution was moved to the left by fishing under the MP proposed.

This experience with the management of the South African fishery for small pelagic fish indicates that the MP approach, in the form of OMP-04 and its associated implementation framework, including the general protocol for OMPs for South African fisheries which cater for unanticipated events, was sufficiently flexible to

(i) allow good use to be made of the sardine resource during a period of peak abundance,
(ii) decrease the directed sardine TAC sufficiently rapidly once the resource began to decline, while
(iii) still maintaining reasonable stability for the industry at low to intermediate levels of abundance.

Therefore, OMP-04 introduced novel modifications which allowed responses to rapid and large changes in resource abundance levels, which are typical of pelagic resources worldwide, while still keeping the risks of unintended resource depletion under control.

Supplementary material

Supplementary material is available at the *ICESJMS* online version of this paper. Section A provides details of the framework used to develop and simulation test OMP-04, Section B provides technical details of OMP-04, together with some further results from the simulation-testing, and Section C provides details of the robustness tests conducted.

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