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Evolution of operational management procedures for the South African West Coast rock lobster (*Jasus lalandii*) fishery

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Abstract The commercial fishery for *Jasus lalandii*, the South Africa West Coast rock lobster, began in the late 1800s and at its peak in the early 1950s yielded an annual catch of 18 000 t. Although this annual catch has dropped to only some 2000 t over recent years, the fishery remains South Africa's third most valuable for landed value. The primary reason for the low total allowable catch (TAC) over these recent years has been a marked drop in somatic growth rate that occurred at the end of the 1980s, for reasons that remain unexplained. A key problem in formulating TAC recommendations with longer-term objectives in mind, has been uncertainties about likely future trends, particularly in somatic growth and recruitment. To address this problem, an "operational management procedure" (OMP) was adopted in 1997 and has twice been re-evaluated and modified (in 2000 and 2003) in the light of further data and changing perceptions of resource dynamics. The history of this process is reviewed, concentrating on the most recent modification. In particular, a summary is given of the process by which the merits of alternative management procedures were evaluated over a range of important uncertainties about the dynamics of the resource. This summary includes a discussion of the key trade-offs between resource rebuilding, future TAC trends and TAC variability, and the eventual choice that was made. The paper concludes by listing a number of lessons learnt concerning best practice for OMP development as this process evolved.

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INTRODUCTION

The West Coast rock lobster *Jasus lalandii* (H. Milne-Edwards) (a panulirid spiny lobster), is found in commercially exploitable densities from 25°S in Namibia to just east of Cape Point in South Africa (see Fig. 1). The commercial fishery for *J. lalandii* began in the late 1800s, and at its peak in the early 1950s yielded an annual catch of 18 000 t (Fig. 2). A review of the historical development of the fishery is given in Pollock (1986). Although the annual commercial catch has dropped to only some 2000 t over recent years, the fishery remains South Africa's third most valuable for landed value (currently worth c. US$40 million, Neville Brink, Oceana Ltd pers. comm.). The primary reason for the low total allowable catch (TAC) over these recent years has been a marked drop in somatic growth rate that occurred at the end of the 1980s (Fig. 3) (Melville-Smith et al. 1995), for reasons that remain unexplained (Mayfield et al. 2000; Hazell et al. 2001).

Early in the fishery hoopnets predominated but, over time, traps have become the primary gear. A number of management measures have been put in place over the history of the fishery. A minimum size limit was introduced in 1933 (89 mm carapace length (CL)), which protected a large proportion of the slower growing female component of the population, and a tail-mass production quota was imposed in 1946. Catches declined however over the 1950s to the 1970s, most likely because of over-fishing, particularly in the more northern areas. In 1979 the tail-mass production quota was replaced by a whole lobster quota. Management by means of TACs, subdivided for individual fishing areas and allocated

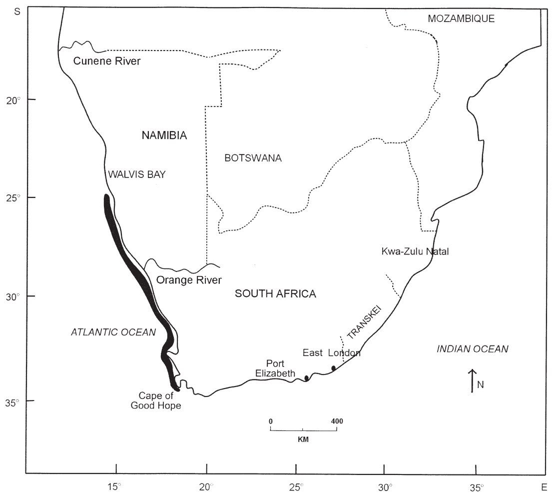


Fig. 1 Map showing the area of commercially exploitable densities of *Jasus lalandii*.

to individual operators, was introduced in the early 1980s. Other management controls applied include protection of berried females or soft-shelled lobsters, a closed winter season, and a daily bag limit for recreational fishers (Cockcroft & Payne 1999).

During the mid 1980s, scientists considered the resource to have stabilised and be capable of providing annual sustainable harvests in the 3500–4000 t range. However, in 1989 the somatic growth rate suddenly dropped (Fig. 3), resulting in decreased recruitment into the fishable portion of the population. Zero and even negative growth (shrinkage) at moulting were recorded under field conditions (Cockcroft & Goosen 1995). The lower somatic growth rate persisted, and clearly had a large effect on the productivity of the resource which required a management response. Catch rates of legal sized lobsters were poor because a large proportion of the lobsters caught were below the minimum size limit

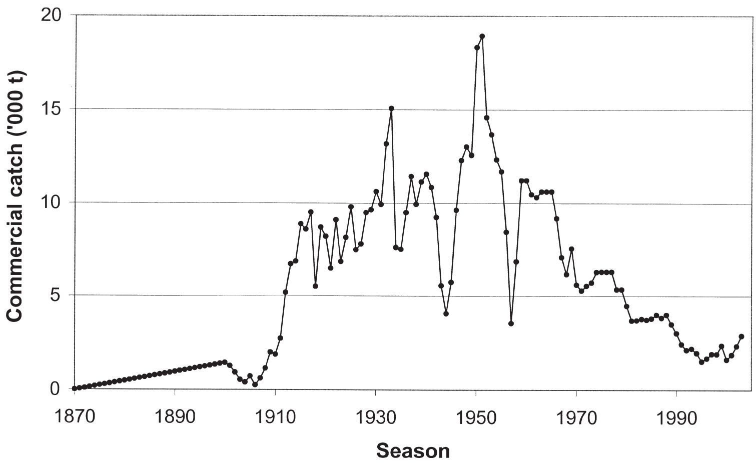


Fig. 2 Historic commercial catch history.

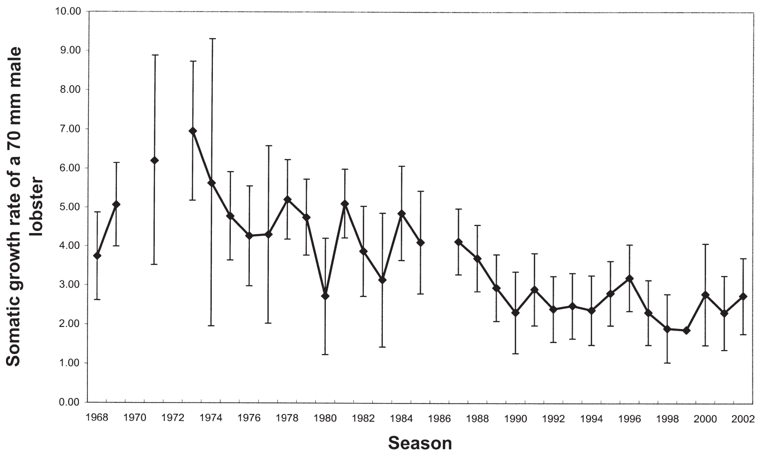


Fig. 3 Somatic growth of a 70 mm male West Coast rock lobster *Jasus lalandii* (Brandão et al. in press). Error bars show the 95% confidence intervals relative to the 1999 value which was incorporated in the intercept for the general linear model (GLM) analysis applied.

of 89 mm, and had to be returned to the sea. Early in the 1991 season, a temporary reduction of the minimum size from 89 mm to 75 mm CL was announced for scientific reasons as well as a relief measure to the industry. In 1992, the minimum size was initially set at 80 mm CL, but then reduced back to 75 mm CL in 1993 for economic reasons. This reduction aimed to improve catch rates as well as assist the industry in supplying the foreign market with smaller sized lobsters. Scientific arguments for reducing the minimum size included: (1) a reduction in discard mortality would result; (2) models showed that an agreed target for egg production could still be achieved with a size reduction; and (3) harvesting males >89 mm had resulted in the fishery being based on an unproductive "tip-of-the-iceberg", with a large pool of potentially harvestable lobsters below this size limit. During this period TACs were reduced from 3790 t in 1990 to 2400 t in 1992, and even further to 1500 t in 1995.

At this time the management process involved the development of recommendations by a working group of scientists, which were relayed to an advisory group (the then Sea Fisheries Advisory Committee, SFAC) appointed by the responsible minister, for transmission in turn to the minister for decision. The scientific working group was appointed by the research director of the marine section of government's Department of Environment Affairs and Tourism, and comprised government, university, and industry consultant scientists. Their advice was based on projections of resource assessments under different future levels of catch. However, increasing difficulty was experienced in reaching consensus, particularly because projection results and advice depended heavily on assumptions concerning whether and how rapidly somatic growth might recover to its pre 1990 levels, and on an appropriate target for recovery of the stock.

To try to resolve this difficulty, government made the decision to move to an Operational Management Procedure (or OMP) approach. The aim was to pre-specify how future scientific TAC recommendations would be calculated, given monitoring data that focused on catch-per-unit-effort (CPUE) derived from industry catches, a fisheries-independent monitoring survey (FIMS) (Dept. Statistics, University of Cape Town 2003), and annual assessments of somatic growth rate. (In South Africa, the prefix "Operational" is used to emphasise that a specific and immediately applicable formula, e.g., for a TAC, is specified, rather than a general concept only.)

Management procedures (MPs) have also been developed and implemented for the New Zealand rock lobster fishery (Starr et al. 1997; Bentley et al. 2003a,b). The first such MP was implemented in 1997 for the two most southern New Zealand sub-stocks, which were estimated to be fairly depleted (to c. 1/3 B_{MSY}) (Starr et al. 1997). The aim of this MP was to rebuild those sub-stocks to B_{MSY} level. The MP was based on comparisons between observed and model-predicted CPUE. Bentley et al. (2003a) reports how a new MP was implemented for these two sub-stocks in 2002. This MP was designed with a different target recovery level, based on CPUE and the history of the fishery, rather than a biomass-rebuild target estimated from stock assessment. Both Starr et al. (2003) and Bentley et al. (2003a) discuss the two main sources of uncertainty for these sub-stocks: the levels of migration between the two sub-stocks and of recruitment in each one. Candidate MPs were tested for a range of assumptions about these two processes.

Bentley et al. (2003b) describes the development of a MP for New Zealand rock lobster stocks that are not over-exploited and estimated to be above legislated minimum biomass levels. Bentley et al. (2003a,b) discuss how representatives from the commercial, recreational, customary, and conservation sectors were involved in agreeing on management objectives and associated performance indicators for these fisheries. Trade-offs among these objectives were clearly an important issue, and Bentley et al. (2003b) concludes that the ultimate choice of a MP will depend on the relative weight given to different objectives.

OMP DEVELOPMENT

An OMP comprises pre-specified monitoring data, together with a formula to be used to convert these to a TAC recommendation. A key aspect of the approach is computer simulation testing to check that the formula is adequately robust in the face of uncertainty about the dynamics of the resource (Butterworth & Punt 1999; Cooke 1999).

In the mid 1990s, this approach was already in use for South Africa's two most valuable fisheries (the primarily demersal trawl fishery for hake, *Merlucius* spp., and the purse seine fishery for sardine, *Sardinops sagax*, and anchovy, *Engraulis capensis*; Geromont et al. 1999). A particular motivation for choosing to use the OMP approach for the West Coast rock lobster was its feedback-control nature,

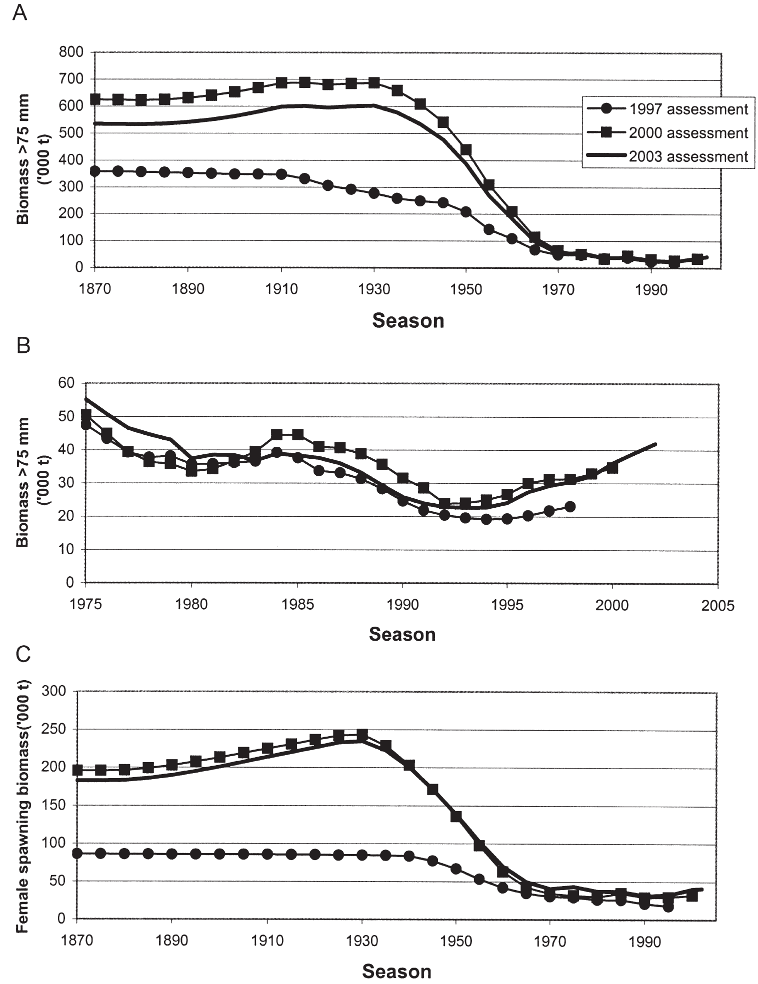


Fig. 4 Biomass trajectories as estimated by the best assessments of the resource at the time of the 1997, 2000, and 2003 Operational Management Procedure developments. **A**, B_{75} (biomass of both sexes for carapace length >75 mm; **B**, an enlargement for recent years of the upper panel; and **C**, female spawning biomass. (The 2003 results shown are for the RC1 Reference Case.)

i.e., as future information (data) become available, the OMP is able to self-correct for the consequences of having to base previous management decisions on unavoidably inexact assessments. Given uncertainty as to what the future somatic growth rate might be, the formula to be adopted needed to react adequately in adjusting future TACs so that resource-recovery objectives were not unduly compromised.

1997 operational management procedure

The first OMP for the resource was implemented in 1997, with the intention that it be applied for a period of three years. The underlying assessment model used for the West Coast rock lobster was (and currently still is) a size-structured model that takes annual variations in somatic growth, recruitment, and survivorship into account (Johnston 1998). A size-structured approach was necessitated because there had been several changes in minimum legal CL, as well as changes in somatic growth over time. Figure 4 shows the best assessment of the resource provided by this approach at that time, and the two subsequent revisions of the assessment in 2000 and 2003. This model, and variations thereof reflecting ranges of uncertainties, were used as the basis for simulation testing of candidate OMPs. These "operating models" represent the "truth" for the model simulations. The operating model generates "data", which the candidate OMP in turn uses to provide scientific TAC recommendations, whose implications are evaluated by projecting the operating model forward in time under these catches.

Before the development of the 1997 OMP, the SFAC was approached to provide some initial feedback about management objectives. They chose to: (1) endorse a resource re-building strategy (given that current biomass was indicated to be at a very low proportion relative to that for the pristine stock—see Fig. 4); (2) suggest that rebuilding targets of between 20% and 50% above the 1996 level for exploitable biomass (B_{75}—the biomass of lobsters with a CL >75 mm) over a 10-year period should be investigated; and (3) propose that the 1997 TAC level (which at that time applied only to the commercial component of the fishery, as distinct from the recreational component of a few hundred tonnes annually) should be set at between 10% and 20% above the 1996 level of 1700 t.

In response, scientists developed a number of alternate candidate OMPs (12 in all) which covered the ranges suggested above for management objectives. The objectives for each of the 12 in turn were achieved for the best assessment of the resource projected deterministically under baseline assumptions; the most important of these assumptions were that future recruitment would be maintained at the average level of the previous two decades and that somatic growth would continue to follow a first order auto-regressive time series as estimated from the 1975–95 data. The OMPs used three sources of input data (commercial CPUE, a FIMS index of abundance, and somatic growth rate). The rationale underlying the OMP was that if these inputs showed an increasing trend the TAC would be increased, whereas if a downward trend was observed, the TAC would be decreased. (Appendix 1 provides the formula for the OMP ultimately implemented.) The OMP thus had an implicit feedback structure, i.e., an ability to self-correct. The OMP also contained a maximum inter-annual TAC reduction constraint (15%) and "exceptional circumstances" were defined under which the OMP-generated TAC would be modified if necessary to offset the consequences of an unexpectedly "bad" (such as very poor recruitment or somatic growth) or "good" event.

Model simulations for each OMP candidate were run stochastically (i.e., taking account of future process error in the form of recruitment variability and observation error between abundance and somatic growth indices and their corresponding actual underlying trends), and a wide range of robustness tests were examined. Robustness tests involve changes to one or more of the assumptions or parameter values of the baseline operating model, which maintain compatability between model and data and reflect alternative plausible representations of the real underlying situation. The 1997 OMP showed particularly good robustness in meeting recovery targets in the face of uncertainties relating to the future somatic growth rate. Robustness was less satisfactory for situations where future recruitment (and hence resource productivity) was appreciably lower or higher than the baseline assumption. The final 1997 OMP recommended by the SFAC to the minister was the least conservative of the 12 candidate OMPs, and aimed for a 20% biomass (B_{75}) recovery over the 1996–2006 period with a 20% increase in the 1997 TAC over the 1996 level. This OMP was used by the scientific working group to recommend TACs, which were all subsequently duly implemented, over the 1997–99 period.

2000 operational management procedure

After the implementation of the 1997 OMP for a period of three years, the underlying size-structured model of the resource was refined and updated given the new data available, and the OMP simulation testing process repeated. Given the longer time-series of CPUE and FIMS data, the new OMP changed from an empirical to a population model basis (see Appendix 1) with a view towards making greater use of the available data and thereby perhaps reducing (unnecessary) variability in TAC outputs. The revised best assessment of the resource estimated current exploitable biomass (B_{75}) to be some 50% larger in absolute terms (though not relative to pristine) than it had been three years earlier (see Fig. 4). This result contributed to decision makers selecting an OMP with a lesser target rebuilding level of 14% from 1996 to 2006 (compared with the 20% of the 1997 OMP) and a 6% increase in the 2000 TAC compared with the 1999 level. (By this time, given other legislative changes, the TAC comprised the sum of commercial and recreational components, rather than the commercial component only.)

Current operational management procedure

The current (2003) OMP for the West Coast rock lobster fishery is similar to the 2000 OMP, although the process undertaken to choose between alternative candidates differed in some important respects. First, at the start of this OMP development phase, two alternate best or "reference case" (RC) assessment models for the resource were proposed. Although both these assessments were based on the size-structured model, RC1 placed no constraint on the recruitment estimates, whereas RC2 forced the recruitment estimates to lie on or not far below the

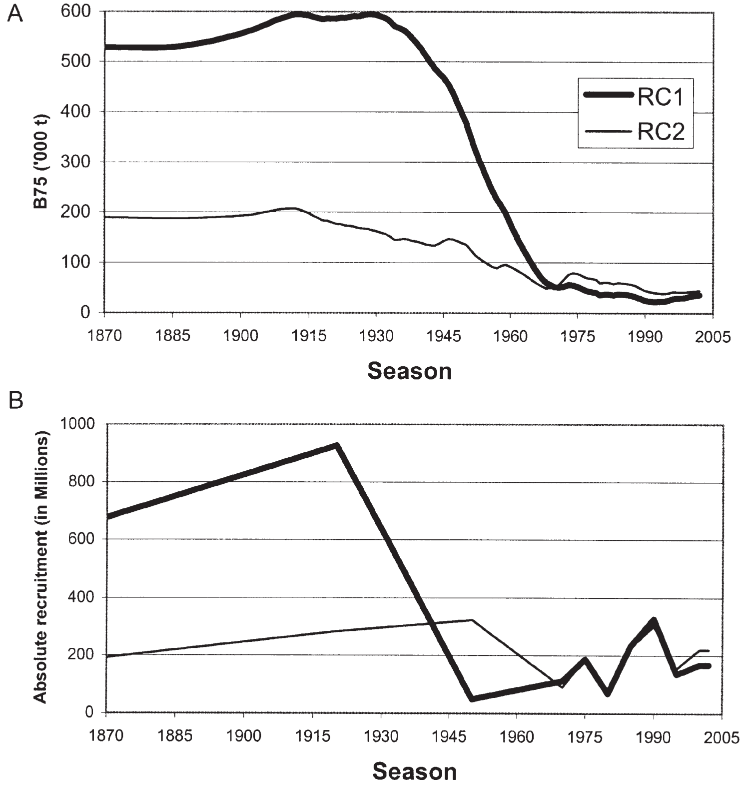


Fig. 5 Comparison between 2003 reference case assessments RC1 and RC2 estimated trends for **A**, B_{75} (biomass above 75 mm carapace length) and **B**, absolute recruitment.

replacement line. These two models resulted in very different perceptions of the current status of the resource and hence the need for, and extent of, rebuilding required. Essentially the RC1 model was similar to the preceding assessments in that it estimated current biomass levels to be low relative to pristine (see Fig. 4). The alternate model, RC2, estimated current biomass levels to be considerably higher not only in absolute terms, but especially relative to pristine (see Fig. 5). The two assessments yielded very similar results over the period after 1970 for which resource-related data (other than annual catches) are available, but differed in their estimates of abundance and recruitment before that time. RC2 is associated with a very low selectivity for larger female lobsters, i.e., it implies that a relatively large component of the female lobsters must be "cryptic", or unavailable to the fishery, the plausibility of which was questioned by the scientific working group.

Besides the two alternate assessments (RC1 and RC2), considerable uncertainty remained (as in 1997 and 2000), about likely future somatic growth rate and recruitment levels. The working group was able to agree on three scenarios as reflective of the possible ranges for each of these factors, as listed in Table 1. For each reference case assessment there were thus nine representative models to project the resource. In 1997 and 2000, the tuning of OMP candidates to achieve target recovery levels had been based on a single such "baseline" model, even though robustness of performance for alternative models was checked. Objections were raised to this approach in the working group because of the key role then played by the choice of the baseline model, which had typically been selected towards the conservative end of the spectrum on previous occasions. To instead integrate performance over the range of models considered plausible, taking account of their relative plausibilities, weights were agreed for each set of scenarios under consideration (2 assessments × 3 future somatic growth scenarios × 3 future recruitment scenarios). A 0.80:0.20 weighting was assigned to the RC1:RC2 models, and the weights agreed for the other factors are shown in the final column of Table 1; the weight for a specific trial then followed by multiplying together the weights for each of the three factors. When developing weighted ("integrated") combinations of the distributions of a performance statistic across such trials, the RC1 and RC2 results were kept separate because their combination would have led to difficulties in interpretation (e.g., because some rebuilding was desirable if RC1 reflected the true status of the resource, whereas some reduction in abundance was acceptable if RC2 applied). However, because of the much greater weight accorded to RC1, only results under this assessment are presented here.

The formulation of the final candidates for the current OMP is described fully in Appendix 2. It is similar to that of OMP 2000 in that a population model is fitted to the three sets of input data, although it also includes further features to allow refinement of the shape of the anticipated TAC trajectory, as well as time-dependence in the parameter constraining inter-annual TAC changes. This last feature was introduced in response to industry requests for options to allow the possibility of larger changes in TAC in the short term. Furthermore, at industry's request, investigations were restricted to candidate OMPs which placed an upper bound of 10% on the extent to which the TAC could change (up or down) from one year to the next. Results of a final set of six OMP candidates were presented to the working group for consideration. The OMP candidates differed in the extent of resource recovery and the shape of the TAC trajectory anticipated, and the parameters governing the level of likely inter-annual TAC changes. Table 2 specifies the differences in these performance features between the six candidates.

Comparative "integrated" results for each OMP were reported for a range of summary performance statistics, the most important of which were: (1) $B(13/03)$—the biomass above 75 mm CL at the start of 2013 compared with that at the start of 2003; (2) $C_{\text{ave}}(10)$—the average expected catch over the following 10-year period; (3) $V(10)$—the average inter-annual catch variation (expressed as a percentage) over the following 10-year period; (4) $FE(12/03)$—the fishing effort in 2012 relative to that in 2003; and (5) TAC(y)—the TAC (commercial plus recreational) in year y. TAC and biomass (above 75 mm CL) trajectories were also reported (see Fig. 6).

The three factors discussed above (assessment, future somatic growth, and future recruitment levels) were not the only ones subject to uncertainty. Trials were also conducted to investigate robustness of performance to aspects such as alternate levels of natural survivorship and of discard mortality, and

Table 1 Three representative scenarios for each of future somatic growth rate and future recruitment considered by the rock lobster scientific working group in 2003, with the associated "relative plausibility" weights accorded to each.

	Option	Weighting
Future somatic growth rate	Low (1989–2001 average)	0.50
	Increase to 1968–2001 average over the next 10 years	0.35
	Increase to 1968–2001 average over the next 3 years	0.15
Future recruitment	Lowest value over 1975–95 period	0.10
	Average value over 1975–90 period	0.60
	Highest value over the 1975–95 period	0.30

Table 2 Essential features of the six candidates considered for the 2003 Operational Management Procedure by the working group. (TAC, total allowable catch; B_{75}, biomass above 75 mm; RC1, reference case 1; CAND1, operational procedure candidate 1 etc.)

	Median final B_{75} level after 10 years under RC1: $B(13/03)$		
	Relatively large increase (27–30%)	Relatively small increase (15–17%)	Almost no increase (3%)
Parameter (w_y) constraining extent of inter-annual TAC change is modified over time	CAND1	CAND2	CAND3
Parameter (w_y) constraining extent of inter-annual TAC change is constant over time	CAND4	CAND5	CAND6

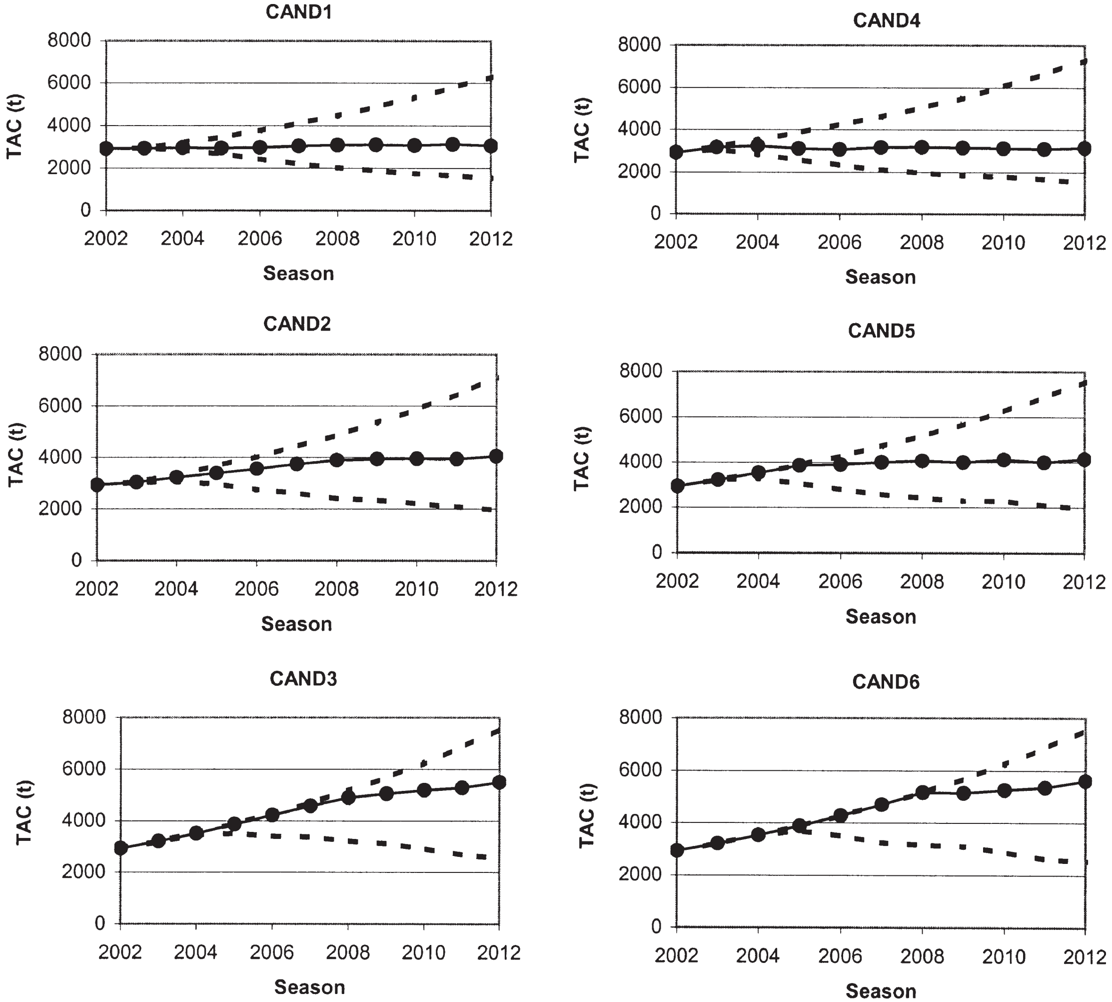
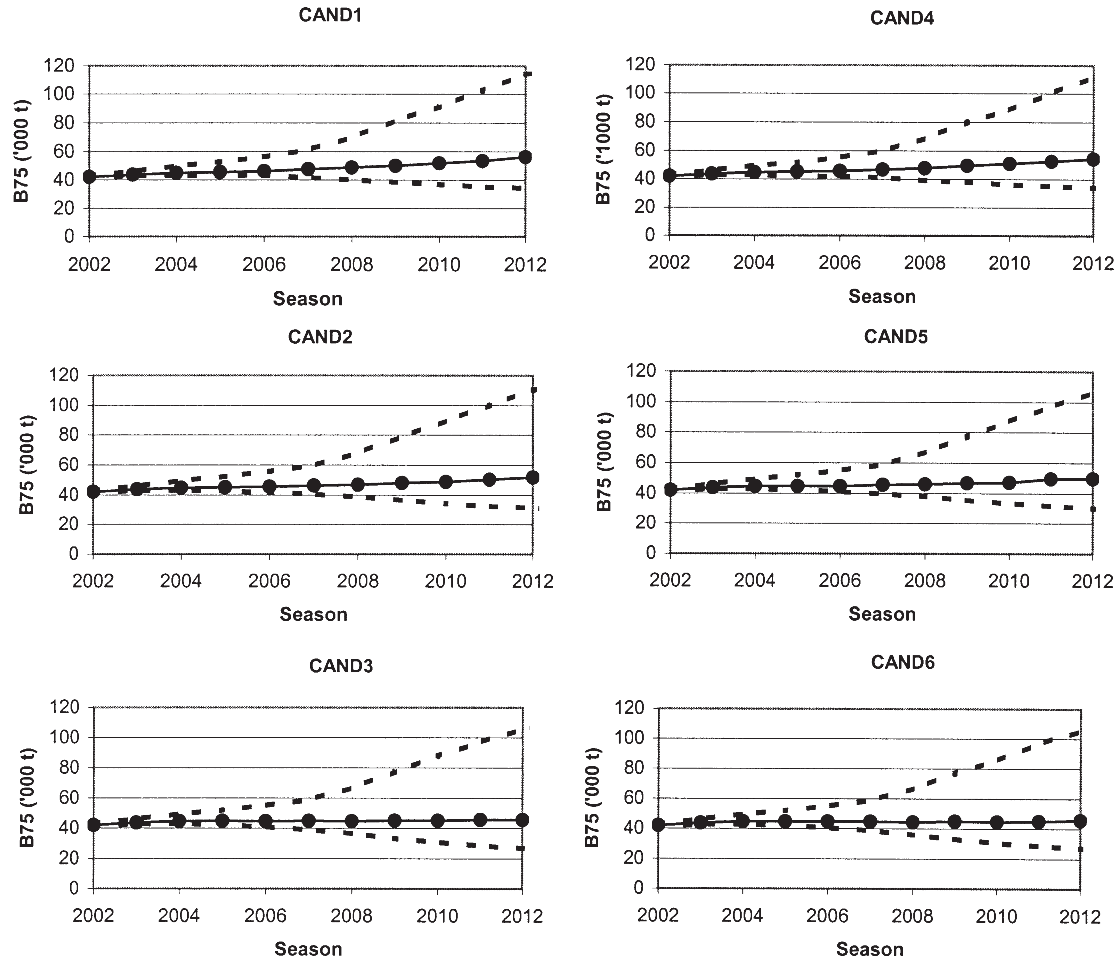


Fig. 6 **A**, Integrated TAC trajectory envelopes (medians and 80% probability intervals) for RC1 scenarios for each of the six operational management procedure (OMP) candidates considered in 2003. **B**, (*opposite page*) Integrated B_{75} trajectory envelopes (medians and 80% probability intervals) for RC1 scenarios for each of the six OMP candidates considered in 2003.

future "walkouts". (Walkouts refer to the phenomenon of mass strandings, which result from the lobsters moving into very shallow regions near the shore because of the occurrence of low oxygenated water (Cockroft 2002).) However, performance statistics showed much greater sensitivity to the first three factors. Thus, although in principle other factors could also have had plausibility weights accorded to different scenarios and been included in the integration process, this additional (and computationally onerous) complexity was not pursued—instead it was deemed sufficient to check that performance statistics did not change too radically under such further scenarios.

Choice of final OMP

Discussion of this choice took place in the context that the 2006 recovery targets set under the previous OMPs had already been achieved by 2003 (see Fig. 4). The integrated results (see Fig. 6 and 7) were examined closely by the working group. (It is evident from these plots that the trials conducted considered only future uncertainties, using best estimates of current resource status rather than taking account of estimation imprecision. Because of the large quantity of data available to the assessment, likelihood profile estimates of this imprecision suggest that it is



relatively small. Undoubtedly such estimates are negatively biased through their neglect of positive correlation amongst data which the likelihood formulation treats as independent. The extent of this bias is difficult to quantify. Nevertheless, the uncertainties related to future somatic growth and recruitment are so much larger than the likelihood-based assessment of estimate imprecision that it was considered safe to ignore the last factor in computations.)

Trade-offs between resource recovery ($B(13/03)$) and future catch levels (e.g., $C_{ave}(10)$) were a particular focus. Clearly the greater the resource recovery, the lower the catch levels over that period. Candidates 3 and 6 were dismissed immediately as not providing sufficient biomass recovery. Although many of the working group were concerned with the greater catch variability associated with candidates 4 and 5 (note for example the TAC(2005) panel in Fig. 7), the industry representatives were willing to accept this risk, in the hope that the future productivity of the resource would prove greater than expected. Candidates 4 and 5 were designed to allow for a faster response in the TAC to future changes in recruitment and somatic growth. Further desirable features seen in candidate 5 were not only the projected increase in TAC (for the distribution median, see Fig. 6A), but also the anticipated increase in fishing effort (see FE(12/03) in Fig. 7). In an economy where unemployment is a problem, options projecting a decrease in effort and hence unemployment over time are undesirable.

On this occasion, the working group recommended candidate 5 as the preferred OMP. This was adopted by the responsible minister, and this candidate OMP was then used to determine the TAC for the 2003/04 season.

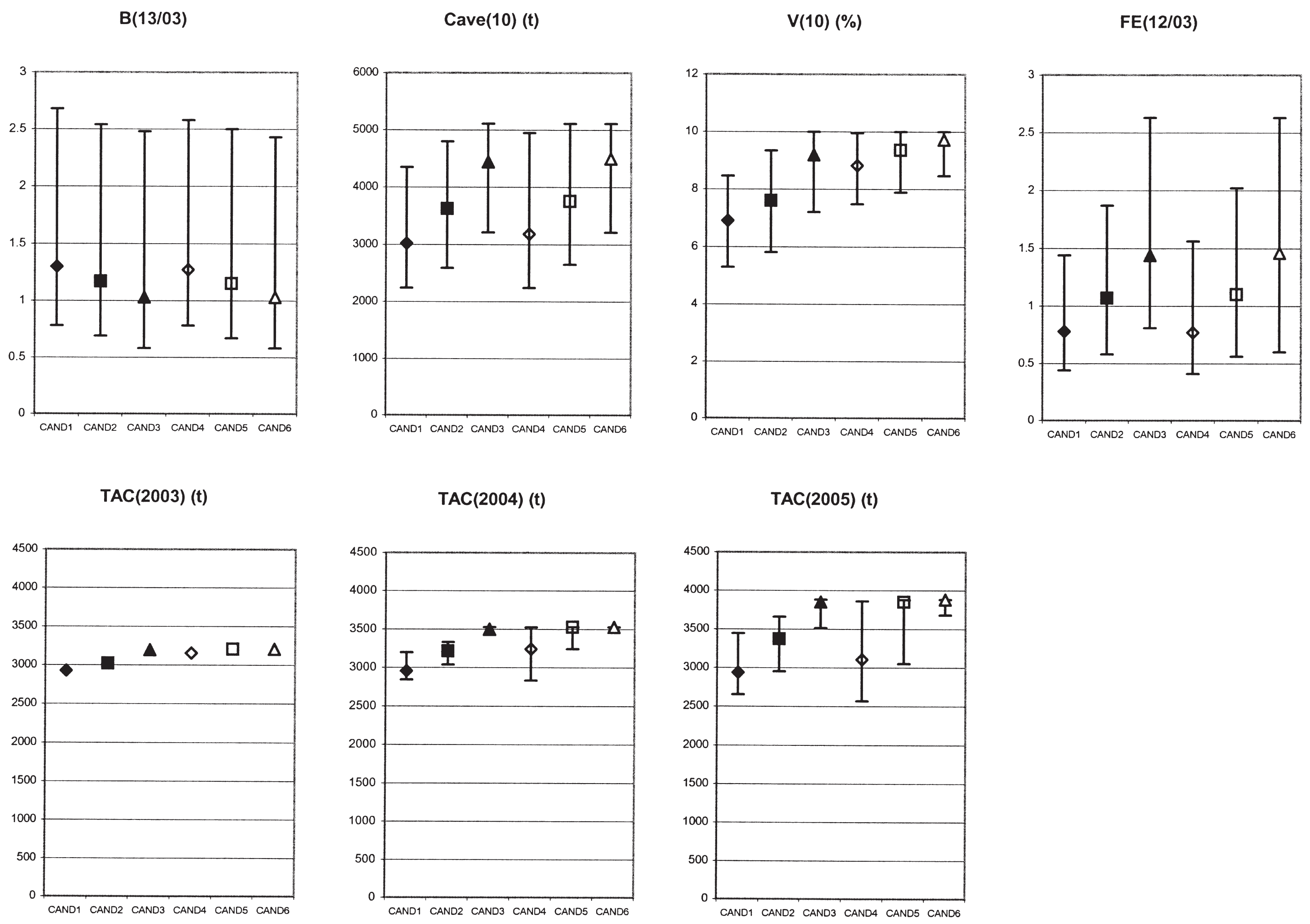


Fig. 7 Performance comparison plots for the six Operational Management Procedure candidates considered in 2003 under assessments for RC1. Each panel represents a particular performance statistic, in which the median (shown by a symbol) and the 80% probability interval (shown by the bar) are compared for the candidates. Catch statistics are in t, and inter-annual catch variability V is percentage.

DISCUSSION

The first two OMPs developed for the resource (1997 and 2000) were specifically designed to respond quickly to future changes in somatic growth rate. The lobsters had experienced a period of particularly low somatic growth since the late 1980s, and the industry was anxious to be able to benefit as soon as possible (from increased TACs) if and when the somatic growth rates improved. At this stage, the general linear models (GLMs) applied to the somatic growth data suggested that the annual somatic growth rate could be estimated with a fairly high degree of precision. In 2003 however, the GLM model was improved and extended to a mixed linear or "random effects" GLM which allowed for interactions between years and locations to be taken into account even though data were not available for every combination of these factors. This improved approach (Brandão et al. in press) revealed that the annual somatic growth estimates were much less precisely estimated than had previously been thought (the present estimated errors are shown in Fig. 3). Following this development, it was decided by the working group (and endorsed by the industry) that the 2003 OMP should down-weight the responsiveness of the OMP to the somatic growth rate data.

The 2003 OMP was also developed to contain a set of rules (also tested in the computer simulations) to be implemented if a situation arises in the future where a particular input datum value is unavailable. Essentially, if a particular index is missing in any year, the previous year's index is used. The implementation of the OMP 2000 had been caught short on this account, when in 2000 the somatic growth data were not collected from several of the key sampling areas, thus preventing the calculation of a comparable 2000 somatic growth input data value.

The development of the two alternate assessment models, RC1 and RC2, during the 2003 OMP development highlighted the problems of estimating past recruitment trends for the resource when it is treated as a single stock. These different assessments imply appreciably different extents of depletion of the resource below pre-exploitation levels, and accordingly confound discussions over the degree of resource recovery that is appropriate as a target for management. It is possible that the RC1 results, which suggest recruitment was well below replacement levels for much of the earlier part of the 20th century, are an artefact of treating the resource as a single homogenous stock in circumstances where there is clear evidence of sequential depletion from north to south along the west coast. Historical catches were originally largest in the north, unlike the current situation where most of the catch is taken in the vicinity of the Cape of Good Hope (Fig. 1). In consideration of analyses to date, the tacit assumption has generally been made that RC1 assessment type results, which suggest a heavily depleted resource, are quite plausible as they are consistent with the expected consequences of serial depletion. This, however, needs to be checked more carefully. Future work will thus concentrate on developing spatially disaggregated assessments of the resource, with the possibility of these leading to a movement away from single stock management towards the development of separate OMPs for perhaps three separate areas.

The 1997 OMP contained "exceptional circumstances" rules defining circumstances under which the OMP-generated TAC could be modified. These rules covered very optimistic as well as very pessimistic scenarios. Including such an "opt-out" in the OMP at this initial stage of OMP implementation appeared to alleviate fears, particularly amongst industry, that if the then current assessments were shown in the future to be substantially in error, the OMP-generated TAC could be superseded, i.e., they would not be locked into recommendations from a formula with a flawed basis. With time, confidence grew in the reliability of the operating model and the whole OMP approach in general, and it was not felt necessary to include such "exceptional circumstances" provisions explicitly for the following two OMPs. Nevertheless, the understanding has always been that the OMP-generated TAC would be reconsidered if future data or research indicated the resource behaviour to be outside the range of possibilities considered in the robustness trials of the OMP.

The West Coast rock lobster is a particularly slow-growing lobster. This impacts the trade-off between recovery and current catch levels. The slow somatic growth results in a low surplus yield:biomass ratio. This in turn demands a large sacrifice in catch to obtain resource recovery. Unsurprisingly, the nature of this trade-off led to strong opposition from industry interests to setting high recovery targets.

Lessons learnt

One of the most successful aspects of moving towards management using an OMP approach has been the substantial reduction in the time spent annually in haggling over TAC recommendations. Although the scientific processes of developing each of the three OMPs summarised here have not been without difficulties and extensive debate, when it came to implementing agreed TAC formulae, only minor questions related to input data have arisen, and the resultant TAC recommendations have, without exception although sometimes with some debate, been implemented without change by decision makers. The pre-specified TAC calculation rules have also resulted in an increase in transparency and improved understanding by all parties, and have allowed the focus of research to move towards other important management issues such as area-disaggregated assessments.

Other important lessons learnt have included: (1) "Bribery"—in one form or another, the TAC (or its possible range) in the first year of implementation of an OMP or OMP revision has served as an important axis in the suite of candidates considered; "sweetening the pill" proved a useful bargaining chip in acquiring industry consensus to buy into continued future application of the TAC formula in question, whose feedback nature then provided greater longer-term guarantees of continued sustainable usage and safeguarding of the resource. (2) Missing data—whatever assurances of certainty of future availability of resource monitoring data may be given at the time an OMP is developed, provision needs to be made in the TAC formula for defaults if this does not happen. (3) OMP complexity—that the assessment model within the 2003 OMP is somewhat complex has not been an issue; over time, stakeholders have come to greater acceptance that it is not the details of the OMP itself that matter, but rather the anticipated performance to be expected, as illustrated (for example) in Fig. 6 and 7. (4) TAC changes—placing bounds on the extent to which the TAC can change from one year to the next is important to stakeholders, and assists in achieving consensus on their acceptance of an OMP. (5) Recovery targets—given a biomass recovery target, considerable scientific debate can arise concerning under which of a number candidate Reference Case operating models this target is to be achieved (i.e., the OMP process provides no escape from the issue of "which is the 'best' resource assessment?"). It proved easier to gain acceptance of the approach adopted for the 2003 OMP of a Reference Case of "integrating" over some key uncertainty axes through a scenario weighting system than the earlier approach of selecting a single scenario. (6) Presentation of results—OMP testing provides a plethora of tabulations and plots. These have to be ruthlessly culled for final presentation of options to decision makers. The integrative approach set out in (5) above, assists in this.

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(*Appendices overleaf*)

Appendix 1 Summary of operational management procedure (OMP) total allowable catch (TAC) formulae for the 1997 and 2000 OMPs.

1997 OMP

An empirical approach was implemented for calculating the TAC each year as follows:

$$TAC_t^* = \left(\frac{CPUE_{t-1,t-2,t-3}}{CPUE_{93,94,95}} \right)^{0.5} \left(\frac{FIMS_{t-1,t-2,t-3}}{FIMS_{92,93,94,95}} \right)^{0.5} \frac{Y_{ARMA97}^Q}{Q} \tag{A1.1}$$

where Y_{ARMA97}^Q is the sustainable yield (assuming future recruitment to be the average of the recent past level) at the target biomass recovery level QB_{1996}, for the expected baseline (ARMA'97) somatic growth scenario (an AR(1) time series model fitted to the 1975–95 somatic growth data), where for this OMP the target biomass increase Q is 1.2 (reflecting a 20% increase); $CPUE_{t-1,t-2,t-3}$ and $FIMS_{t-1,t-2,t-3}$ are the average CPUE and FIMS values respectively for seasons t-1, t-2 and t-3; $CPUE_{93,94,95}$ is the average CPUE over the 1993–95 period; and $FIMS_{92,93,94,95}$ is the average FIMS index over the 1992–95 period.

The algorithm in Equation A1.1 needed to take into account that the somatic growth rate in the future might well deviate from the baseline ARMA'97 prediction. Equation A1.1 was thus modified as follows:

$$TAC_t^{**} = TAC_t^* \frac{Y_g^Q}{Y_{ARMA97}^Q} \tag{A1.2}$$

where Y_g^Q is the sustainable yield at the target biomass level, calculated for growth g, and is calculated as the arithmetic average over seasons t-1, t-2 and t-3. Given this adjustment, eventual attainment of the target biomass recovery level QB_{1996} is achieved whatever somatic growth scenario eventuates.

To allow flexibility in targets for the TAC in the short term, the algorithm was modified to include a number of tuning parameters: w, h, and k. The final TAC setting algorithm was thus:

$$TAC_t = \max \begin{Bmatrix} wTAC_{t-1} + (1-w)TAC_t^{**}\left[1 - h(t-1997)^{\gamma}\right]k \\ 0.85TAC_{t-1} \end{Bmatrix} \tag{A1.3}$$

Note: w is the weight given to the previous year's TAC and was set at 0.5; h is a parameter which can be tuned to produce a given biomass target (e.g., $1.2B_{1996}$) at the end of the 10-year period (2006); k is the parameter tuned to produce a specified expected 1997 TAC value; and γ is a parameter which determines the "shape" of the TAC trajectory. A value of 0.5 was found to lead to smooth and usually monotonic trends.

Furthermore, a maximum inter-annual TAC reduction constraint of 15% was imposed. The values of k and h for the selected 1997 OMP were 1.0066 and 0.9 respectively.

2000 OMP

The underlying approach was to fit a simple population model to available CPUE, FIMS, and somatic growth data to provide a basis to compute a catch that would see a target biomass achieved by the end of the 2000–06 period. The simple population model was identical to that used for the 2003 OMP and is described in Appendix 2. The only difference here is that the population model was fitted by minimising a sum-of-squares function involving CPUE and FIMS data, and that the trap and hoopnet catchability coefficients were estimable parameters. The penalty function for the "a" parameter (see Equation A2.2 below) was as follows:

$P = 1 - e^{-(a-3500)^2/2\sigma_a^2}$ for $a < 3500$
$P = 0$ for 3500 a 5000
$P = 1 - e^{-(a-5000)^2/2\sigma_a^2}$ for $a > 5000$
where $\sigma_a = 1000$

The population model was projected forwards to 2006, under the following catch strategy:

$$C_t^* = C_1 e^{\delta(t-2005)}$$

with C_1 being selected (using a bisection method) to achieve the biomass target level, and δ selected to achieve a certain TAC(2000) value. The final TAC formula was as follows, and included a 15% maximum inter-annual TAC reduction constraint:

$$TAC_t = \max\begin{pmatrix} wTAC_{t-1} + (1-w)C_t^* \\ 0.85TAC_{t-1} \end{pmatrix} \tag{A1.4}$$

where $w = 0.7$.

Appendix 2 Current 2003 operational management procedure (OMP) for the South African West Coast rock lobster fishery.

The underlying approach of this OMP is to fit a simple population model to available catch-per-unit-effort (CPUE), FIMS, and somatic growth data to provide a basis to compute a catch that will see a target biomass achieved by the end of the period under consideration (i.e., the start of the 2013 season) for the RC1 assessment model, coupled with the assumptions of continued low somatic growth and future recruitment at its average level over 1975–90.

A simple surplus production population model is used for this procedure to model the dynamics from 1992 to 2013:

$$B_{t+1}^p = B_t^p + G_t - (C_t + P_t) \tag{A2.1}$$

where B_t^p is the population model biomass in season t; G_t is the annual "growth" of resource in season t; C_t is the annual commercial + recreational catch in season t; P_t is the annual estimate of poaching for season t (poaching is also taken into account in the underlying operating models); and B_{1992}^p is a parameter estimated in fitting this model to data.

In the population model, the annual "growth" of the resource, G_t, is set to be:

$$G_t = a(\beta_t + b) \tag{A2.2}$$

The value of b is set externally by regressing against β the equilibrium sustainable yield for the model's estimate of the biomass in 2002 for different values of β (this relationship is near linear). This was done for both RC1 and RC2. The intercept of these regressions with the horizontal axis (β) was averaged over RC1 and RC2, and yielded a value of $b = -9.332$. Using a value derived from the underlying operating model in the OMP may seem to be providing the OMP more information on resource dynamics than is appropriate; remember, however, that though this gives the OMP an advantage in trials under the Reference Case operating model, it is also *dis*advantaged in robustness trials for which this assumed value for b will be incorrect.

The annual somatic growth rate parameter β_t is the GLM estimated somatic growth of a male rock lobster as extrapolated to 1 mm CL. For any season Y in the future ($Y \geq 2003$): β_t is known for $1992 \leq t \leq Y-1$, and β_t is set equal to the average of the values for the three preceding seasons for the balance of the projection period (for which β_t would not be known in practice in season Y), i.e.,

$$\left(\sum_{t=Y-3}^{Y-1} \beta_t\right)/3 \text{ for } Y \leq t \leq 2013.$$

Each season (from $y = 2003$), as new data become available, the population model (see Equation (A2.1)) is fitted by minimising the following negative log-likelihood:

$$-\ln L = \sum_{T=1993}^{t-1}\left\{\ln\sigma_{cpue} + \frac{1}{2\sigma_{cpue}^2}(\ln CPUE_T - \ln q_{cpue} - \ln B_T^P)^2\right\} \tag{A2.3}$$
$$+ \sum_{T=1992}^{t-1}\left\{\ln\sigma_{FIMS} + \frac{1}{2\sigma_{FIMS}^2}(\ln FIMS_T - \ln q_{FIMS} - \ln B_T^P)^2\right\} + Q$$

where $CPUE_T$ is the trap CPUE for season T; $FIMS_T$ is the FIMS CPUE for season T; q_{CPUE} is the trap catchability coefficient; and q_{FIMS} is the FIMS catchability coefficient. The parameters of the likelihood L estimated in the fitting process are B_{1992}^p and a (closed form expressions provide σ_{cpue} and σ_{FIMS}).

A penalty function (Q) is added to the negative log-likelihood function (see Equation A2.3 above) for the "a" parameter of the G_t relationship (see Equation A2.2) used. The penalty function is as follows:

$$Q = \frac{(a-4000)^2}{2\sigma_a^2}$$

where $\sigma_a = 1000$.

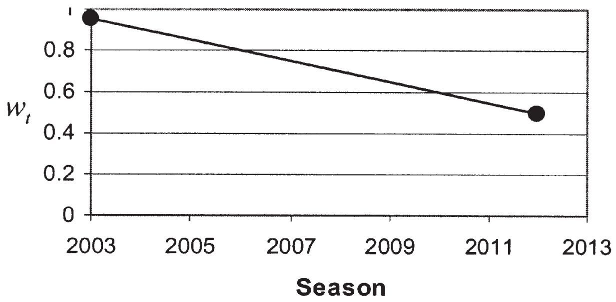
This penalty function was introduced to provide an appropriate trade-off between too little impact of the data upon a (which leads to an inability to show adequate reaction to a changed somatic growth rate), and too much impact (which causes TAC variability that is too large).

OMP formula

The final TAC-setting formula is as follows:

$$TAC_t = w_t TAC_{t-1} + (1-w_t)\alpha\left(1+\lambda(\beta_t^m - \bar{\beta}^m)\right)\frac{\hat{B}_t^p}{\hat{B}_t^p}\left[\left(\frac{CPUE_{t-3,t-2,t-1}}{CPUE_{93,94,95}}\right)^{0.25}\left(\frac{FIMS_{t-3,t-2,t-1}}{FIMS_{92,93,94,95}}\right)^{0.75}\right]^p$$

where α, γ, and p are three control parameters, and w_t changes as follows:



The vertical axis intercept (w_t for 2003) is a tuning parameter and termed W, and $w_{2012} = 0.5$. Here values of $W = 0.95$ and 0.50 (i.e., constant w_t over time) were considered for CAND1-3 and CAND4-6 respectively.

Note that the $W = 0.5$ candidates allow the TAC to increase (or decrease) at a faster level relative to the corresponding $W = 0.95$ candidates.

Allowing the w value to vary with time in this way created further control over how much the TAC is allowed to change in the short term compared with the 2002 TAC (of 2915 MT).

For all six candidate OMPs, the following control parameter values were fixed externally: $\lambda = 1$ and $P = 2$. Note that the reason for introducing the p factor and the term in the formula involving CPUE and FIMS was to attempt to render the OMPs more responsive (in TAC terms) to circumstances of either high or low future recruitment, which become manifest in the monitoring data only towards the end of the projection period. The rationale for the CPUE:FIMS weighting power of 0.25:0.75 was to secure a better reaction to changes in abundance index trends that would arise from changes in recruitment strength. The FIMS index reflects the biomass of lobster 60 mm and larger, whereas the CPUE reflects the biomass of lobster only 75 mm and larger.

Tuning of the six OMP candidates

The above OMP candidates were tuned as follows: CAND1 and CAND4—α selected so that the deterministically estimated $B(13/03) = 1.10$ ($\alpha = 580$ and 650 respectively); CAND2 and CAND5—α selected so that the deterministically estimated $B(13/03) = 1.00$ ($\alpha = 890$ and 920 respectively); and CAND3 and CAND6—α selected so that the deterministically estimated deterministic $B(13/03) = 0.85$ ($\alpha = 1520$ and 1505 respectively). These tunings were conducted for the scenario of low future somatic growth and average future recruitment (see Table 1). Deterministic projections were used (i.e., no account was taken of future process error in the form of recruitment variability and observation error between abundance and somatic growth indices and their underlying trends) to speed the tuning process.

Restrictions on inter-annual TAC variability

Candidates 1–6 were tested under a restriction of a maximum inter-annual TAC change of 10% (up and down).