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TOWARDS ADAPTIVE APPROACHES TO MANAGEMENT OF THE SOUTH AFRICAN ABALONE *HALIOTIS MIDAE* FISHERY

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The South African abalone *Haliotis midae* resource is widely perceived as being under threat of over-exploitation as a result of increased poaching. In this paper, reservations are expressed about using catch per unit effort as the sole index of abundance when assessing this fishery, particularly because of the highly aggregatory behaviour of the species. A fishery-independent survey has been initiated and is designed to provide relative indices of abundance with *CV*s of about 25% in most of the zones for which Total Allowable Catchs (*TAC*s) are set annually for this fishery. However, it will take several years before this relative index matures to a time-series long enough to provide a usable basis for management. Through a series of simple simulation models, it is shown that calibration of the survey to provide values of biomass in absolute terms would greatly enhance the value of the dataset. The models show that, if sufficient precision (*CV* 50% or less) could be achieved in such a calibration exercise, the potential for management benefit is improved substantially, even when using a relatively simple management procedure to set *TAC*s. This improvement results from an enhanced ability to detect resource declines or increases at an early stage, as well as from decreasing the time period until the survey index becomes useful. Furthermore, the paper demonstrates that basic modelling techniques could usefully indicate which forms of adaptive management experiments would improve ability to manage the resource, mainly through estimation of the level of precision that would be required from those experiments. The results of this study are particularly applicable to fishing zones for which there are insufficient other data to perform a standard stock assessment.

The South African commercial abalone *Haliotis midae* fishery began in 1949 and soon covered approximately 580 km of coastline from Cape Columbine to Quoin Point (Fig. 1). The catches in the 1960s were extremely high, and certainly greater than were sustainable, but fell dramatically in the 1970s. Although the fishery is small-scale, until very recently with a small Total Allowable Catch (*TAC*) of around 600 tons per year, it is economically important. Most abalone are found on reefs shallower than 10 m and are closely associated with kelp *Ecklonia maxima* beds. Only a few large individuals are found between 10 and 20 m deep, and virtually no abalone occur at greater depths. The biology of the resource is described in Tarr (1992, 1993, 1995).

In the past, a number of measures have been introduced to manage the resource. In 1953, a minimum size limit of 10.2 cm shell width was set. This minimum legal size was changed to 11.4 cm the following year, and still applies today. Also, various forms of catch control have been implemented. In 1969, six abalone factories were granted processing rights to a fixed percentage of an overall maximum production catch limit, which was subsequently replaced by a maximum whole-mass catch limit. In 1984, on the basis of individual historical performance, divers involved in the fishery were each granted fishing rights (termed an entitlement) to a fixed percentage of the overall catch limit, and they became legally obliged to deliver to specific factories. From the 1986/87 season, the overall catch limit was changed to a *TAC* for each of the seven specific fishing zones A–G (Fig. 1). This measure was introduced to balance the distribution of effort better over the fishing grounds.

Additional management measures implemented for abalone include effort control, in the form of closed seasons. From 1985, a three-month closed season from July to September was proclaimed. Closed seasons (of varying lengths, especially in recent years) are also used to limit recreational effort. Recreational divers are required to purchase a recreational abalone licence, which currently entitles them to catch four abalone each per day, using snorkel gear only. The recreational fishery has been increasing in recent years, but of greater concern is the large increase in illegal catches. Anecdotal information is that these illegal catches now approach half the level of the annual legal *TAC*. Furthermore, an estimated 55% of the abalone taken by the illegal fishery is smaller than the minimum legal size (Tarr in press).

A management system that can be expected to exhibit robust performance in the face of uncertainty

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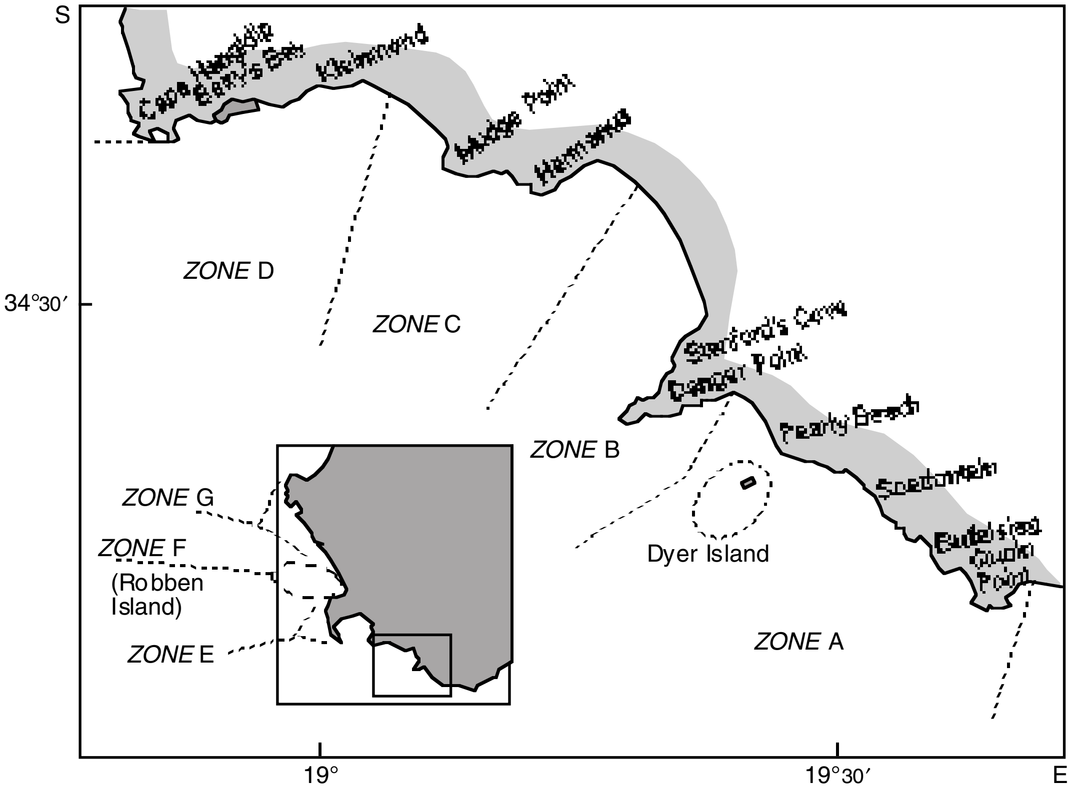

Fig. 1: Abalone commercial fishing zones and areas. The shaded area around Betty's Bay is a marine reserve. The inset shows the South-Western Cape region of South Africa

about both the status of the resource and the effectiveness of management measures is needed for the control of the resource as a whole. Until recently, a *TAC* was set for each zone, based on inspection of the catch per unit effort (*cpue*) trend and the size distribution of the catch for that zone. No specific model was applied to analyse the data objectively. To improve assessments of stock status, fishery-independent diver surveys were attempted in the 1980s, but the results were believed to be negatively biased, because the annual catches in some zones were greater than the corresponding biomasses estimated. Furthermore, there was a large *CV* of around 100% associated with each estimate. A new annual fishery-independent survey to estimate resource abundance, which was designed to overcome most of the problems associated with previous surveys, was started in 1995. The main difference between the new and past surveys was the intent to provide an index of relative abundance with better precision than was achieved earlier, rather than to attempt to estimate total abundance. Therefore, only the 0–5 m depth region of any zone was surveyed, with the same transects replicated each year. The design involved surveying 20 transects (30 m long) in each of six zones surveyed (A, B, C, D, F and Dyer Island, see Fig. 1). The transects ran perpendicular to the shoreline and were equi-spaced (except in areas devoid of kelp). This design was intended to provide a relative index of abundance for each zone with a *CV* of around 25%.

Intense spatial variation in demography seems characteristic of abalone populations worldwide (Breen 1986, Shepherd *et al*. 1992, Keesing and Baker 1998). As a result, the spatial and temporal patterns in the *cpue* data are also complex. These complexities have been best described in studies in South Australia (Keesing and Baker 1998) and Tasmania (Prince 1992) over small spatial scales in which catch varies spatially and temporally. These patterns were deemed to occur for various reasons, including habitat hetero-

Table I: Description of symbols used in the equations in the text. Equation number denotes the first equation in which the symbol is used

Term	Equation number	Description
y	1	Year
B_y	1	Biomass (tons) at the start of the year y
C_y	1	Catch (tons) in year y
r	1	Intrinsic growth rate parameter ($\cdot$year^{-1})
u	2	Simulation index
I_y^u	2	Relative abundance index from the survey in year y in simulation u
c	2	Multiplicative bias if the survey index is used directly to estimate absolute abundance
ε^u	2	Drawn from a normal distribution with coefficient of variance of about 0.25, i.e. $N[0.0.25^2]$
b	3	Slope of the log of the survey index plotted against time
n	3	Power index in *TAC* formula
S	4	Scenario
B_y^S	4	Biomass (tons) at the start of year y for scenario S
r^S	4	Intrinsic growth rate ($\cdot$year^{-1}) parameter for scenario S
C_u^y	4	Annual *TAC* (tons) for simulation u as set by the management procedure
c^*	5	True survey calibration factor
$\varepsilon^{u,c}$	6	Error drawn from $N[0,\sigma_c^2]$
σ_c^2	6	Calibration experiment squared coefficient of variation
B_y	7	Biomass (tons) for year y with estimate B_y^u for simulation u
r	7	Intrinsic growth rate ($\cdot$year^{-1}) with estimate r^u for simulation u
N	9	y^*+1
y^*	9	Present assessment year

geneity, temporal and spatial variation in diver behaviour, and trends in catchability. In particular, diver behaviour and temporal change in individual and aggregate diver efficiency were believed to add another level of complexity in the analysis. Only some of these problems can be overcome with appropriate *cpue* standardization techniques (e.g. generalized linear models).

The above leads to a more worrying problem, in that fishery assessment models assume that *cpue* is related (usually in a linear fashion) to the biomass of recruited animals. This assumption is justified only if the animals are distributed randomly, or if fishing is random over the habitat area. The more animals tend to aggregate, the more the *cpue* is likely to deviate from a linear relationship with biomass (Walters and Maguire 1996). This problem arises in abalone populations worldwide, for which high catch rates can be maintained even when the population is decreasing. This can lead to serial depletion of the resource while *cpue* remains fairly stable, as has been shown in abalone fisheries off Mexico (Prince and Guzmán del Próo 1993), California (Tegner *et al*. 1989) and Australia (Shepherd and Baker 1998). Therefore, stock assessments of abalone worldwide have seldom proved successful, because of the difficulties in obtaining appropriate indices of abundance (Breen 1992, Prince 1992, Shepherd and Baker 1998, McShane 1998, Keesing and Baker 1998, Worthington and Andrew 1998).

One option available to managers of the resource under those circumstances is to use a dynamic model tuned to *cpue* data as well as to a survey index. This approach should become more accurate as the length of the survey time-series increases. However, it would be several years before the survey index is long enough to be statistically informative. If this is the case, then a second option, intended to overcome the potential problems of initial heavy reliance on the *cpue* series, is to gain further information through carefully planned experimentation on the abundance of the resource, i.e. some form of adaptive management. If this option is feasible, it might be possible to put in place an alternative and more appropriate management procedure for setting *TAC*s sooner.

Given the problems described above, innovative approaches are required to attempt to supplement existing management practices for the South African abalone. In this paper, the effects of managing the resource using two approaches are investigated, through simulations over a 10-year time period. These two approaches are in the form of management based upon a survey index only, and coupled with calibration of the index to absolute abundance values. One of the aims is to investigate the usefulness of simple management models as tools to estimate the precision required for any proposed calibration experiment, e.g. a depletion exercise (Leslie and Davis 1939, DeLury 1947). Furthermore, the modelling approach allows estimation of the utility of the results, before committing to any major and potentially expensive and labour intensive fieldwork.

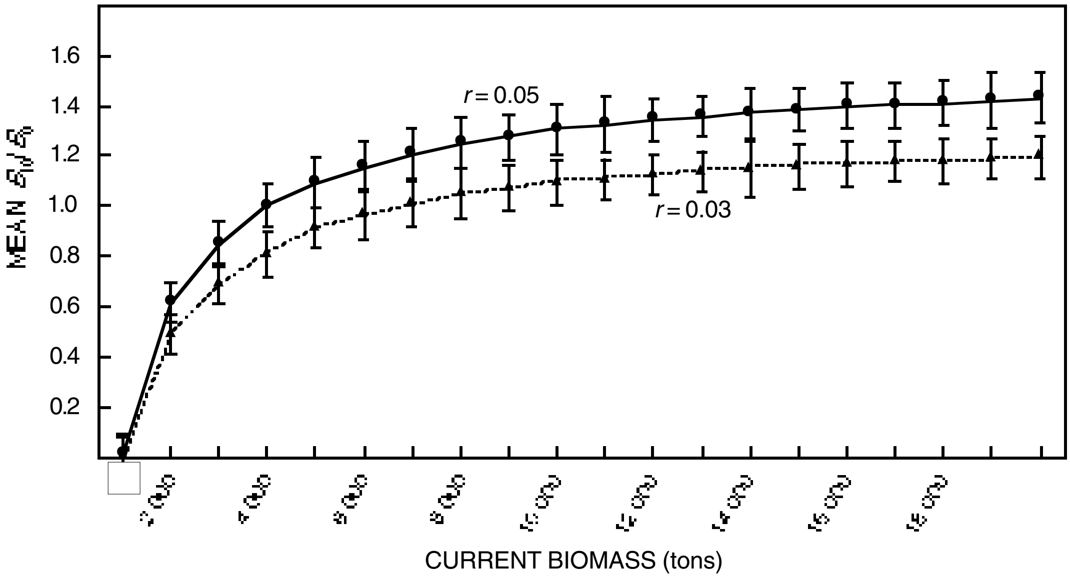

Fig. 2: Mean (±2 *SD*) final depletion, i.e. final relative to current biomass (B_{10}/B_0) for different values of the current biomass (B_0) and the intrinsic growth rate (*r*) for the management procedure based upon the survey index alone (setting n = 2 in Equation 3). The results shown are for a maximum permitted annual *TAC* decrease of 20%

MANAGEMENT BASED UPON A SURVEY INDEX ALONE

For the reader's convenience, the symbols used in the equations following are also listed and defined in Table I.

A simple Malthus model, which ignores density dependence so that the dynamics are specified by a single parameter (the intrinsic growth rate *r*), has been used to calculate the consequences of managing the resource over 10 years on the basis of the trend shown by the survey index alone. The model assumed for the underlying biomass dynamics is thus

$$B_{y+1} = B_y + rB_y - C_y \quad , \qquad (1)$$

where B_y is the biomass (tons) at the start of year y, C_y is the catch in that year, and r is the intrinsic growth rate parameter ($\cdot$year^{-1}).

The management procedure considered is that the *TAC* is kept constant at its current level (taken to be 200 tons) for the first three years (y = 0,1,2), and thereafter adjusted on the basis of the slope (b) of the log of the survey abundance plotted index against time, as evaluated by linear regression. Once more than five such indices are available, only the most recent five values are used in calculating b.

The survey index values (assumed to be log-normally distributed) for the simulation testing were generated from the formula

$$I_y^u = c\,B_y \mathrm{e}^{\varepsilon^u} \quad , \qquad (2)$$

where I_y^u is the observed relative abundance index from the survey in year y for simulation u, c is the multiplicative bias if the survey index (an areal density) is used directly to estimate absolute abundance by multiplying by assessed habitat area, and $\varepsilon^u \sim N[0, 0.25^2]$, as the survey is designed to result in a coefficient of variance of about 0.25 (for simplicity, the approximation that the standard deviation of ε is used, provided this is not too large, is equal to the *CV* of the survey index).

Two options were investigated for setting the *TAC* (C_y) from year y = 3, when deviation from the fixed level for years y = 0, 1, 2 is first permitted:

$$C_{y+1} = C_y(1+b)^n \quad , \qquad (3)$$

where values of 2 and 3 for n were considered.

The annual *TAC* increase was limited to a maximum of 20%, while limits on the annual decrease ranging from 20 to 90% were examined. These options for the

Table II: Performance statistics for the management procedures described in the section "Management based upon a survey index alone" (with $n = 2$ in Equation 3), and the section "Management using a calibrated survey index" (with $x = 0.5$ in Equation 12). In all instances, the *TAC* for the year before the management procedure is first implemented is assumed to be 200 tons, and interannual modifications are restricted to within a 20% increase and 40% decrease. Three scenarios for the initial biomass in tons (B_0) and intrinsic growth rate (r) per year are considered. *CV* refers to the coefficient of variation (σ_c) for the estimate of the calibration factor (c) obtained in the calibration experiment. Note that $CV = 0$ corresponds to a perfect result, whereas $CV = \infty$ gives results in the absence of any calibration experiment

Scenario	Management procedure		Depletion (B_{10}/B_0)		*TAC*	
$B(_0, r)$	Survey type	*CV* of calibration experiment	Mean	Lower 5%-ile	Average catch (tons)	Catch variability
(1 000, 0.03)	Relative survey index		0.19	0.07	96	0.27
	Absolute survey index	∞	0.19	0	94	0.24
		0.5	0.74	0.37	48	0.24
		0.25	0.76	0.56	47	0.22
		0	0.76	0.71	48	0.21
(5 000, 0.04)	Relative survey index		1.01	0.88	195	0.10
	Absolute survey index	∞	1.01	0.79	193	0.16
		0.5	1.02	0.67	187	0.14
		0.25	1.02	0.79	192	0.10
		0	1.01	0.95	200	0.09
(7 000, 0.05)	Relative survey index		1.22	1.12	215	0.10
	Absolute survey index	∞	1.21	1.05	222	0.17
		0.5	1.16	0.76	266	0.14
		0.25	1.14	0.89	280	0.11
		0	1.12	1.05	291	0.09

procedure were tested for a range of r (0.03–0.05·year^{-1}) and initial biomass B_0(1 000–10 000 tons) values. A range of plausible values of the parameter r was inferred from yield/biomass ratios for yield-per-recruit models. The inputs to these models were derived from equilibrium size-based models (based on measures of the somatic growth of abalone reported by Tarr 1995), which were fitted to known size frequencies.

The management procedure above was tested using the above-mentioned ranges of r and B_0 values, with an initial *TAC* of 200 tons. An important criterion was that the procedure should not result in severe reduction in biomass, even in the worst scenario considered (i.e. slowest growth and lowest current biomass[1]). The final to current biomass ratio (i.e. B_{10}/B_0) for a range of current biomass values and for the two extreme values considered for r are shown in Figure 2, where *TAC*s are set according to Equation 3 (with $n = 2$) and a maximum permitted annual decrease in the *TAC* of 40%. Some further results for this case are also listed in Table II. Under the worst scenario considered, the resource is reduced (on average) by more than 80% within 10 years (Figs 2, 3). Only a current biomass of $B_0 > 4\,000$ tons (for $r = 0.05$·year^{-1}) or $B_0 > 7\,000$ tons (for $r = 0.03$·year^{-1}) secures a better than 50% chance of resource stability or growth.

Figure 3 shows the mean final to current biomass for the worst scenario considered (i.e. $B_0 = 1\,000$ tons, $r = 0.03$·year^{-1}). Two choices for the parameter n in the formula were used to set catch limits (Equation 3), and a range of maximum allowed percentage *TAC* decreases from one year to the next was considered. A B_{10}/B_0 ratio <0.5, (i.e. an expected biomass in 10 years of less than half the size of the starting biomass), cannot be avoided, even if the maximum annual *TAC* decrease allowed is 90%. A maximum annual decrease in excess of 60% can maintain 30–40% of the initial biomass level B_0. If this worst scenario represents reality, then using the trend in the survey index alone in the manner described above to set future catches, could not prevent severe depletion of the resource.

[1] Biomass and catch figures used here have been expressed in absolute terms, so as to be more meaningful to those familiar with the fishery. This is not necessary for the analysis conducted, however, for which the critical parameter is the ratio of the current biomass to the present *TAC*. This ratio is 5 for the worst scenario considered here.

MANAGEMENT USING A CALIBRATED SURVEY INDEX

If the survey index could be calibrated so that it also

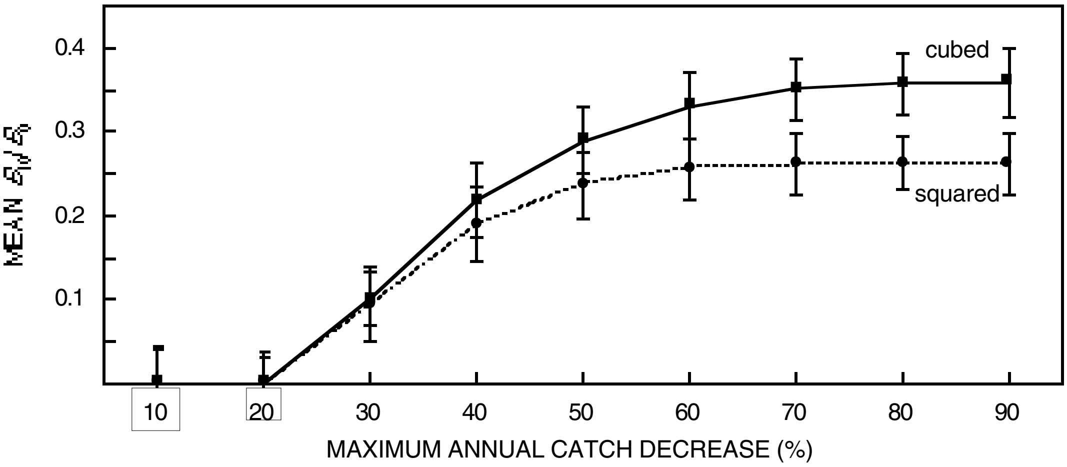

Fig. 3: Mean (±2 *SD*) final relative to current biomass (B_{10}/B_0) for the worst case tested in which r = 0.03 and B_0 = 1 000 tons for the management procedure based upon the survey index alone. Results are shown as a function of the maximum permitted annual decrease in the *TAC* for two values of the parameter n in the formula used to set the *TAC* (Equation 3)

provides an estimate of abundance in absolute terms, this might effectively narrow the range of possible present biomass values and hence allow better management of the resource. In particular, if the present biomass was shown to be low (e.g. around the 1 000 tons for the worst scenario, as above), *TAC* reduction could commence immediately, instead of waiting for at least three years, as implicit under the procedure above. This then might prevent the marked reduction in biomass for some scenarios, as shown in Figures 2 and 3.

A simulation exercise to investigate this possibility is described here. A management procedure is developed that incorporates the results of a calibration/depletion experiment in making annual adjustments to the *TAC*, and also defines statistics in terms of which the performance of the procedure over a 10-year period can be assessed. The procedure is tested for three scenarios:

(i) Worst: B_0 = 1 000 tons, r = 0.03·year^{-1} – continuation of current catch of 200 tons will reduce the biomass substantially;

(ii) Intermediate: B_0 = 5 000 tons, r = 0.04·year^{-1} – the current catch of 200 tons is sustainable (being exactly equal to the current replacement yield);

(iii) Good: B_0 = 7 000 tons, r = 0.05·year^{-1} – there is scope to increase the current catch of 200 tons to make better use of the resource.

The procedure should perform satisfactorily for all three of these scenarios. More specifically in the context under consideration here, it should reduce catches to avoid substantial reduction for the worst scenario, maintain the biomass and catches at their present level for the intermediate scenario, and increase catches for the good scenario.

Operating model

The potential value of a calibration experiment was investigated for various scenarios (S) for the actual status of the resource, by considering a range of r (0.03–0.05·year^{-1}) and B_0 (1 000–7 000 tons) values, where the dynamics of the biomass in a particular zone for each scenario is taken to be governed by a simple Malthus model:

$$B^s_{y+1} = B^s_y + r^s B^s_y - C^u_y \quad , \qquad (4)$$

where B^s_y is the biomass at the start of year y for scenario S, r^s is the intrinsic growth rate potential for scenario S, and C^u_y is the annual *TAC* for simulation u, as set by the management procedure detailed below.

A calibration experiment is assumed to be conducted to estimate the constant of proportionality (i.e. calibration factor c) between the survey index and biomass, for which the associated *CV* is taken to be σ_c.

The data generated by the operating model for each simulation are the annual relative indices of abundance obtained from surveys at the beginning of each year. These are provided by the formula

$$I_y^u = c^* B_y^s e^{\varepsilon^u} \quad , \tag{5}$$

where I_y^u is the measured index for year y for simulation u, c^* is the true survey calibration factor, and $\varepsilon^u \sim N[0, 0.25^2]$, as the survey coefficient of variation is taken to be 0.25.

The calibration experiment is not guaranteed to produce a value exactly equal to c^*, because there will be some estimation error. Results need to be integrated over the range of estimates of c^* that may result. This is effected by Monte Carlo integration, where the result of the experiment for simulation u is given by:

$$c^u = c^* e^{\varepsilon^{u,c}} \quad , \tag{6}$$

where $\varepsilon^{u,c} \sim N[0, \sigma_c^2]$.

The management procedure

THE ESTIMATOR

The potential value of a calibration experiment was investigated by considering the fishery for simulation u to be modelled by

$$B_{y+1} = B_y + rB_y - C_y^u \quad , \tag{7}$$

where B_y is the biomass (tons) for year y, with estimate B_y^u for simulation u, r is the intrinsic growth rate (·year^{-1}), with estimate r^u for simulation u, and C_y^u is the annual *TAC* (tons) for simulation u.

The data available to fit the model are (I_y^u : y = 0...y^*;c^u), where values of y^* (the most recent year for which data are available) range from 0 to 9. Errors are assumed to affect these data only, because the population model assumed in Equation 4 is deterministic, i.e. this is an observation error estimator. Estimates of the parameter values are obtained by maximizing the likelihood function:

$$L(r,c,\sigma,B_0) = \left\{ \prod_{y=0}^{y^*} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2\sigma^2}(\ell n I_y^u - \ell n\, c - \ell n B_y)^2} \right\} \times \frac{1}{\sigma_c\sqrt{2\pi}} e^{-\frac{1}{2\sigma_c^2}(\ell n\, c^u - \ell n\, c)^2} \times \frac{1}{0.02\sqrt{2\pi}} e^{-\frac{1}{2(0.02)^2}(r-0.04)^2} . \tag{8}$$

The final term in this function is not based upon data. It is introduced rather to allow:

(i) for more stable estimation until the survey index series is of sufficient length for r to be estimated with reasonable precision from such data; and
(ii) the catch control law (see below, Equation 12) to be implemented immediately by providing an initial estimate of r^u = 0.04·year^{-1}. This becomes modified as survey estimates accumulate, so providing information on the actual value of r.

By taking logarithms and omitting constants, maximizing this likelihood is mathematically equivalent to minimizing:

$$-\ell n L = N \ell n \sigma + \frac{1}{2\sigma^2} \sum_{y=0}^{y^*} (\ell n I_y^u - \ell n c - \ell n B_y)^2 + \frac{1}{2\sigma_c^2}(\ell n c^u - \ell n c)^2 + \frac{1}{2(0.02)^2}(r - 0.04)^2 \quad , \tag{9}$$

where $N = y^* + 1$.

Each year the resource status estimates are updated to take account of the new survey data. An analytical solution for c and σ can be attained by setting the respective partial derivatives of Equation 9 to zero, which provides the following estimates for simulation u:

$$\ell n \hat{c} = \frac{\frac{1}{\hat{\sigma}^2} \sum_{y=0}^{y^*} (\ell n I_y^u - \ell n B_y) + \frac{1}{\sigma_c^2} \ell n c^u}{\frac{N}{\hat{\sigma}^2} + \frac{1}{\sigma_c^2}} \tag{10}$$

$$\hat{\sigma} = \sqrt{\frac{1}{N} \sum_{y=0}^{y^*} (\ell n I_y^u - \ell n \hat{c} - \ell n B_y)^2} \quad , \tag{11}$$

where these two coupled equations have to be solved iteratively.

THE CATCH CONTROL LAW

The sustainable catch that could stabilize the resource is $C_{y+1}^u = r^u B_{y+1}^u$, so that the catch rule applied to set the next year's *TAC* was chosen to be

$$C_{y+1}^u = (1 - x)C_y^u + x \hat{r}^u \hat{B}_{y+1}^u \quad , \tag{12}$$

where the assumption is made that the catch in the year prior to the implementation of the procedure (y = -1) is equal to 200 tons.

The parameter x relates to the rate at which the

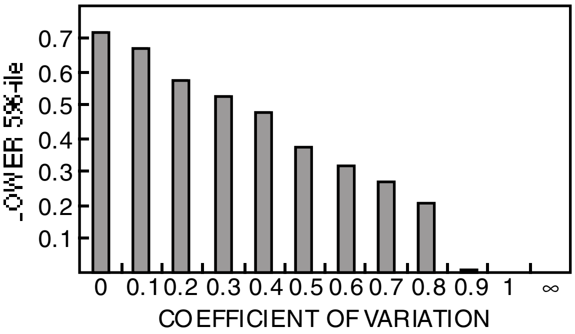

Fig. 4: Final depletion (B_{10}/B_0) lower 5%-iles for the worst scenario considered (B_0 = 1 000 tons, r = 0.03·year^{-1}) for different levels of the coefficient of variation (σ_c) of the calibration factor (c) for the management procedure based upon the calibrated survey index alone

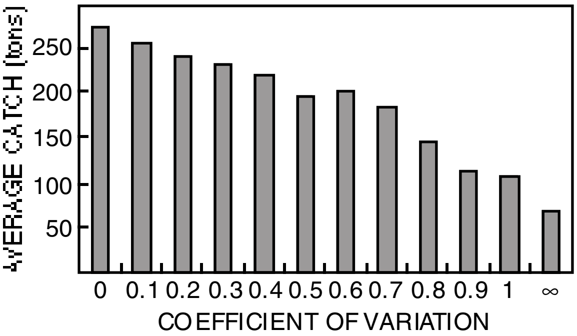

Fig. 5: Average catch over the period y = 0 to 9 for the B_0 = 7 000, r = 0.05·year^{-1} scenario for different levels of the coefficient of variation (σ_c) of the calibration factor (c) for the management procedure based upon the calibrated survey index alone

current catch is changed towards the desired level; the closer x is to 1, the faster the change. The results given in Table II are for the choice of x = 0.5, together with the additional restrictions that the change in *TAC* from one year to the next is limited to a maximum increase of 20% and decrease of 40%.

Note that, for the case of $\sigma_c = \infty$ (i.e. no calibration experiment), for which results are presented in Table II, there are insufficient data to estimate B^u_{y+1} from Equation 7 at the start of the 10-year management period. Therefore, in this limiting case, the *TAC* is kept unchanged at 200 tons for the first three years, with Equation 12 coming into play only thereafter.

Performance statistics

Procedure performance over a 10-year period for alternative scenarios and catch control laws was compared on the basis of four statistics: risk of serious reduction in resource abundance, given by the mean and 5%-ile of the B_{10}/B_0 ratio; average catch; and lack of stability, measured by the interannual catch variability (expressed as the average proportional change in catch from one year to the next).

Table II presents the results of these tests for a range of precision achieved by a calibration experiment ranging from perfect information ($CV = \sigma_c = 0$) to no experiment ($CV = \infty$). Comparative results for this last case are also shown for the procedure based upon the survey index trend alone, with n = 2 (see Equation 3). For comparability, both procedures include restrictions of 20 and 40% for the maximum and minimum change respectively in the *TAC* from one year to the next.

When a calibration experiment is not used, results are slightly better than when it is, as reflected by the lower 5%-iles for depletion (B_{10}/B_0) for the worst and intermediate scenarios. However, given the biomass reduction (on average) of more than 80% that results without calibration for both procedures for the worst scenario, neither can really be considered defensible.

Given perfect information from the calibration experiment, there are distinct improvements in performance. For the worst scenario, the lower 5%-ile for depletion reflects a reduction in biomass of some 30%. For the intermediate and good scenarios, interannual catch variability is reduced by some 50% of that achievable without a calibration experiment, and a catch increase of 30% is achieved for the good scenario.

Even for a calibration experiment with relatively poor precision (i.e. *CV* of 50%), there are marked improvements in performance. Compared to results without an experiment, the lower 5%-ile for depletion reflects a reduction of only 60% rather than 100%, whereas average catch for the good scenario increases by 20%. Figures 4 and 5 provide more details on how these two performance statistics are expected to vary as a function of the *CV* of the result provided by the calibration experiment.

The results show that, provided a reasonable level of precision (*CV* of <50%) could be achieved for a calibration experiment, a feedback control management procedure, based on a relative abundance index provided annually by surveys, could lead to substantial improvement in the management of the resource.

In logistical terms, the experiment would require that several "typical", but nevertheless small and isolated sites, are identified. After surveying these under the protocol for the present survey (though perhaps more intensively) to provide an index of relative abundance and associated *CV*, the density estimate to which this corresponds would need to be multiplied by a spatial assessment of the area covered by kelp. Comparison of that estimate with the total mass of abalone that could be removed from the site in an experiment would provide the calibration factor. However, the *CV* of the relative index obtained in this manner will be negatively biased as an estimate of the *CV* of the calibration factor for the zone concerned as a whole. This is because of the residual variance reflecting the variation of the calibration factor from site to site.

CONCLUSION

This paper highlights problems experienced in many fishery resources worldwide, especially those that are highly aggregatory and fished by several sectors. Well-designed, independent surveys in such cases are essential. However, the long-term nature of this investment can still leave a manager at risk in the short to medium term. The modelling exercise described here demonstrates that simple adaptive management techniques can greatly increase knowledge of the status of the resource in the short term. Arguments have been presented that past abalone catch and unstandardized *cpue* data (under the assumption of a linear biomass/*cpue* relationship) data should be treated with care, because its sole use as an abundance index for setting zonal *TAC*s cannot guarantee sustainable resource utilisation. In situations where past catch and *cpue* data are questionable or lacking, and where the survey index time-series is short, the results show that this prognosis could improve if an experiment were to be conducted in a limited area to calibrate the relative abundance index provided by the surveys. Such experiments (e.g. the depletion experiments, Leslie and Davis (1939) and DeLury (1947) are well cited in the literature, and it should be possible to investigate the feasibility of such an exercise for some components of the South African abalone resource.

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