A comparison of fishery models with and without cannibalism with implications for the management of the Cape hake resource off southern Africa

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An age-aggregated model that explicitly includes cannibalism of older fish on younger fish is developed. This model is used as the basis for determining the importance of including cannibalism in stock assessment and fishery regulation for the Cape hake stocks off southern Africa, stocks where cannibalism has been shown to be substantial. The cannibalism model is compared to a traditional Schaefer-type model in three ways. First, the two models are fitted to the catch-and-effort history for the Cape hake resource off northern Namibia. It is shown that the cannibalism parameters cannot be estimated from the catch-and-effort history alone, and must be obtained from other studies. Once the cannibalism parameters are specified, the two approaches provide similar fits and estimates of stock size and potential yield, although the non-cannibalistic approach is generally more optimistic. The second form of comparison involves fitting a cannibalistic model-estimation procedure and a non-cannibalistic model-estimation procedure to simulated data that contains differing levels of cannibalism. In general, both model-estimation procedures produce similar results, although the non-cannibalistic model-estimation procedure is more likely to result in outlying estimates of MSY when the data are uninformative. Finally, the performance of the two model-estimation procedures when combined with the f_{MSY} harvesting strategy is evaluated. The performance of the two approaches is similar as long as the data are relatively informative. It is thus argued that management agencies should not assume a priori that including cannibalism or multispecies interactions in assessment and management procedures will necessarily provide for better fisheries regulation. It is recommended that simulation studies similar to those described in this paper be performed prior to the introduction of the extensive data collection schemes required for assessments that include cannibalism or multispecies interactions.

Key words: cannibalism, hake, Schaefer model, management, population modeling, Monte Carlo simulation.

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Introduction

Most of the world's fisheries are currently managed on the basis of single-species assessments that do not consider cannibalism, predation, or environmental variability in any way except to treat these processes as random noise. A major trend in fisheries research is to attempt to model these processes, and some management agencies have embarked on major data collection programs to provide a basis for assessments that explicitly consider these processes. By far the most ambitious projects have been ICES's multispecies VPA (e.g. Anon., 1986, 1989; Pope and Knight, 1982) and the Norwegian MULTSPEC model (e.g. Bogstad et al., 1992). However, many other fisheries agencies now have some commitment to try explicitly to include variables describing these processes.

Two basic approaches have emerged, first are studies concentrating on cannibalism and predation, which attempt to estimate numbers-at-age for several species by utilizing stomach content data in order explicitly to consider how much each species/age eat of another (e.g. Lleonart et al., 1985; Anon., 1986, 1989; Punt, 1992). The second group of studies concentrate on understanding the physical and biological determinants of recruitment (e.g. Peterman and Bradford, 1987; Shannon et al., 1988; Frank et al., 1990). This second type of research has been criticized by Walters and Collie (1988) who

argue that the benefits of being able to predict recruit-
ment are often not particularly high, and that the
implementation of feedback-control harvesting strat-
egies may be a more effective, and less expensive, method
of managing in the face of recruitment variation.

The models used in most fisheries assessments are
so simple, and ignore so much biology, that it is
quite natureal to expect that adding cannibalism,
predation, or environmental determinants of recruit-
ment will provide better prediction and will hence
lead to improved resource utilization. However, this
has not been demonstrated, and indeed there is a
substantial body of literature that shows that very
simple models generally provide better prediction than
more realistic models (O'Neil, 1973; Ludwig and
Walters, 1985; Linhart and Zucchini, 1986; Walters,
1986; Punt, 1988).

The purpose of this paper is to explore the benefits of
considering cannibalism in stock assessments. As an
example, the assessments of the stocks of Cape hake
(*Merluccius capensis* Castelnau and *M. paradoxus*
Franca) off southern Africa are used; stocks for which it
has been argued that cannibalism should be included
when performing stock assessments (e.g. Lleonart *et al.*,
1985; Gasyukov and Dorovskikh, 1988). All of the
analyses conducted apply to the stock off northern
Namibia. However, because of the similar catch trajec-
tories and biology for the various stocks of hake off
southern Africa, the results are almost certain to be
insensitive to this particular selection.

The first step is to develop a variant of the Schaefer
model that explicitly includes two age groups and can-
nibalism of older fish on younger fish, and to fit it to the
actual catch-and-effort data for the northern Namibian
hake population. The model considered is non-age-
structured so that the traditional Schaefer model
(Schaefer, 1954, 1957) is a submodel of it. The model
utilized in this paper is deliberately simpler than the
models which might be applied to actual field data for
the resource under consideration (e.g. Lleonart *et al.*,
1985; Anon., 1986, 1989; Gasyukov and Dorovskikh,
1988; Punt, 1992) so that some generic conclusions
regarding modeling cannibalism use can be drawn.
Inevitably, the model will fail to capture some of the
peculiarities of the actual situation so that the numerical
results obtained from a more complex model might be
slightly different from those obtained using the age-
aggregated model. However, utilizing a more complex
model would complicate the interpretation of the results
substantially, to the extent that generic conclusions
might not be as clear as is the case when using a simple
model.

The next stage is to test the ability of cannibalistic
and non-cannibalistic model-estimation procedures to
estimate parameter values from simulated data with
differing levels of known cannibalism. Finally, the

performance of these model-estimation procedures
under feedback-control management is examined.

A "cannibalistic" model-estimation procedure

Gut content studies conducted in the south-east Atlantic
suggest that the major predators of juvenile Cape hake
are adult Cape hake (mainly the shallow-water species
Merluccius capensis Castelnau) (Chlapowski, 1977;
Botha, 1980; Prenski, 1980; Bergh, 1986; Andronov,
1987; Payne *et al.*, 1987; Roel and MacPherson, 1988;
Punt *et al.*, 1992). Therefore, for simplicity, only the
time-dependence of the predation mortality due to hake
has been modeled explicity – the natural mortality due
to other causes has been assumed to be time-invariant. A
further assumption which has been made to construct a
simple model of Cape hake dynamics is that the mature
and recruited components of the population and that
component which feeds on juvenile hake are all the
same. This is not a completely unreasonable assumption
because the age-at-50% maturity is about 4 years (Botha,
1986; Punt and Leslie, 1991), hake recruit to the fishery
between ages 2 and 3 (Punt, 1988), and start eating large
quantities of juvenile hake at age 4 (Botha, 1980). The
implication of these assumptions is that the dynamics of
the Cape hake resource can be modeled by the dynamics
of its two interacting components (adults and juveniles):

$$B_{i+1} = B_i - \Omega_1 B_i + \varphi J_{i+1} - \Gamma_i B_i$$

$$J_{i+1} = J_i - \Omega_2 J_i - \varphi J_i + g(B_i) - \psi J_i B_i / K \tag{1}$$

$$(C/E)_i = q \frac{B_i + B_{i+1}}{2} e^{v_i}, \ v_i \text{ from } N(0, \sigma^2). \tag{2}$$

where B_i is the adult (exploitable/mature) biomass at the
start of year i; J_i is the juvenile biomass at the start of
year i; g(B) is the contribution of births to the popula-
tion, as a function of adult biomass, $g(B) = rB(1 - B/K^*)$.
$(C/E)_i$ is the CPUE for year i; Γ_i is the fraction of the
adult biomass caught in year i ($\Gamma_i B_i = C_i$ – the catch in
year i); Ω_1 is the net change of the adult biomass due to
growth and mortality from natural causes; Ω_2 is the net
change of the juvenile biomass due to growth and all
causes of natural mortality *except predation by hake*; K
is the average pre-exploitation population size; r,K^* are
the parameters of the birth function. K^* should not be
confused with K. K and K^* are only equal when natural
mortality is not explicitly modeled; q is the catchability
coefficient; φ is the fraction of the juvenile biomass
which recruits each year; ψ is the coefficient of canni-
balism; and σ^2 is the variance of the (multiplicative)
observation error.

The model incorporates the effects of basal natural
mortality by means of the parameters Ω_1 and Ω_2. The
time-lag to recruitment is altered by varying the value of
the parameter φ, and the extent of cannibalism is varied

by changing the value of the parameter ψ. Cannibalism is scaled by the average pre-exploitation biomass (K) so that the parameter ψ has a natural interpretation – the fraction of the juvenile biomass which dies due to cannibalism when the resource is at its pre-exploitation level. In order for the size of the juvenile component of the population always to be non-negative, the parameters Ω_2, φ, and ψ must satisfy the constraint $\Omega_2 + \varphi + \psi \leq 1$. Note that Equation (1) does not include a term which allows for the beneficial effect of the consumption of juveniles on the size of the adult population because Cape hake are opportunistic feeders (Payne *et al.*, 1987; Punt *et al.*, 1992) – in years in which the diet of adult hake consists of large amounts of juvenile hake, there is a compensating reduction in the quantities of other species eaten so that the daily ration of adult hake is roughly independent of the abundance of prey species.

The relationship between the model parameters and the average pre-exploitation biomass is given by:

$$K^* = \frac{rK\varphi}{r\varphi - \Omega_1(\psi + \varphi + \Omega_2)}, \tag{3}$$

[i.e. K^* equals K when $\Omega_1 = 0$].

The effective surplus production [the equilibrium catch for various values of B] is given by:

$$C(B) = -\Omega_1 B + \frac{rB(1 - B/K^*)}{1 + \Omega_2/\varphi + \psi B/(K\varphi)}. \tag{4}$$

A special case of Model (1) [$\psi = \Omega_1 = \Omega_2 = 0$; $\varphi = 1$] is the standard non-cannibalistic model traditionally applied in the management of the Cape hake resource off southern Africa (e.g. Butterworth and Andrew, 1984).

In order to fit Model (1) to a time series of catch and catch rate data, the following sum of squares function is minimized:

$$SS = \sum_{i=1}^{n} [\ln(C/E)_i - \ln(C/E)_i]^2. \tag{5}$$

where $(C/E)_i = \hat{q}(\hat{B}_i + \hat{B}_{i+1})/2$.

As the number of estimable parameters is nine (Ω_1, Ω_2, φ, ψ, r, K^*, q, B_{1965}, and σ^2), it is infeasible (due to precision considerations) to attempt to estimate all of them from a time series of catch and catch rate data. Hence, when performing fits, four of the parameters (Ω_1, Ω_2, φ, and ψ) have been fixed. Further, the catches of hake off northern Namibia prior to 1965 were relatively small (less than 10 000 tons) (Punt, 1988), so it is reasonable to assume that this stock was at its average pre-exploitation level at that time (i.e. $B_{1965} = K$). Only two parameters (r and K^*) are included in the non-linear search because the other two (q and σ^2) can be obtained analytically (Cooke, 1983;

Table 1. Catch and catch rate data for the Cape hake resource off northern Namibia. Units: catches – 'tons; catch rate – tons per OTB-7 standardized hour. Source: ICSEAF statistical bulletins.

Year	Catch	CPUE	Year	Catch	CPUE
1965	93 510	1.78	1977	276 901	0.49
1966	212 444	1.31	1978	254 251	0.43
1967	195 032	0.91	1979	170 006	0.40
1968	382 712	0.96	1980	97 181	0.45
1969	320 430	0.88	1981	90 523	0.55
1970	402 467	0.90	1982	176 438	0.53
1971	365 557	0.87	1983	216 063	0.58
1972	606 084	0.72	1984	228 529	0.64
1973	377 642	0.57	1985	212 151	0.66
1974	318 836	0.45	1986	230 873	0.65
1975	309 374	0.42	1987	136 412	0.63
1976	389 020	0.42			

Punt, 1988). The current replacement yield (RY) is estimated by the surplus production during year n+1 [given by Equation (4)].

Results

Fits to actual data

Model (1) was fitted to the actual catch and catch rate data for the Cape hake resource off northern Namibia (Table 1) for various values of the parameters φ, ψ, Ω_1, and Ω_2 which satisfy the constraint that $\varphi + \psi + \Omega_2 \leq 1$. For all of the calculations in this paper, Ω_2 has for simplicity been taken to be equal to Ω_1 and these parameters are henceforth referred to as Ω. The estimates of the parameters r and K as well as the estimates of the management variables B_{1988}/K – the current depletion, MSY – the maximum sustainable yield, RY – the current replacement yield and B_{MSY}/K – the ratio of the adult biomass at which MSY is achieved to the average pre-exploitation biomass, are given in Table 2 for 34 of the variants considered. The results for $\varphi < 0.2$ have been omitted from Table 2 because they correspond to rather poor fits to the observed data. The set of results in Table 2 marked with an asterisk correspond to the fit of the traditional non-cannibalistic Schaefer model-estimation procedure (i.e. $\varphi = 1$, $\psi = \Omega_1 = \Omega_2 = 0$).

The results reported in Table 2 suggest that the assessment of the Cape hake resource off northern Namibia is not particularly sensitive to the selection of values for the cannibalism parameters. There are, however, some features in Table 2 which are worth noting.

The value of the parameter "r" (conventionally the intrinsic growth rate parameter) is highly dependent on the values of φ, ψ, and Ω. The value of r increases as the values of the parameters ψ and Ω are increased, and as the value of the parameter φ is decreased (if $\Omega > 0$). The trend in r with the former two parameters is a result of

Table 2. Summary of the results of the application of 34 variants of the "cannibalistic" model-estimation procedure to the catch-and-effort data for the Cape hake resource off northern Namibia. RY refers to the sustainable yield during 1988. The row marked by an asterisk corresponds to the fit of the traditional non-cannibalistic Schaefer model while the column SS refers to the value of Equation (5) corresponding to the results provided (multiplied by 1000 for presentational ease). Units for MSY and RY are '000 t.

φ	ψ	Ω	SS	r	K	B_{1988}/K	MSY	B_{MSY}/K	RY
0.200	0.000	0.000	306	0.319	3944	0.548	315.0	0.500	312.1
0.400	0.000	0.000	298	0.332	3352	0.526	278.3	0.500	277.6
0.600	0.000	0.000	295	0.356	3055	0.528	272.1	0.500	271.3
0.800	0.000	0.000	294	0.372	2906	0.534	270.0	0.500	268.8
*1.000	0.000	0.000	295	0.379	2836	0.539	268.6	0.500	266.9
0.200	0.200	0.000	301	0.426	3815	0.534	279.0	0.414	263.8
0.400	0.200	0.000	296	0.392	3348	0.522	265.2	0.449	259.7
0.600	0.200	0.000	293	0.395	3103	0.526	263.8	0.464	259.8
0.800	0.200	0.000	293	0.398	2974	0.531	263.7	0.472	260.1
0.200	0.400	0.000	299	0.539	3724	0.524	268.9	0.366	244.4
0.400	0.400	0.000	294	0.452	3349	0.519	259.7	0.414	248.8
0.600	0.400	0.000	292	0.433	3145	0.523	259.2	0.436	251.7
0.200	0.600	0.000	298	0.654	3663	0.516	266.1	0.333	234.6
0.400	0.600	0.000	294	0.511	3355	0.515	257.3	0.387	241.5
0.200	0.800	0.000	298	0.769	3621	0.510	266.0	0.309	229.0
0.200	0.000	0.200	319	1.314	2277	0.487	260.2	0.500	260.1
0.400	0.000	0.200	300	0.999	2274	0.512	265.0	0.500	264.8
0.600	0.000	0.200	296	0.881	2310	0.527	266.0	0.500	265.2
0.800	0.000	0.200	296	0.815	2353	0.536	265.9	0.500	264.5
0.200	0.200	0.200	312	1.427	2428	0.492	251.9	0.449	250.0
0.400	0.200	0.200	299	1.045	2411	0.512	257.9	0.464	255.6
0.600	0.200	0.200	296	0.909	2426	0.524	260.4	0.472	257.6
0.200	0.400	0.200	309	1.540	2549	0.495	249.2	0.414	242.9
0.400	0.400	0.200	299	1.094	2521	0.511	254.3	0.436	248.7
0.200	0.600	0.200	307	1.654	2644	0.495	248.8	0.387	237.8
0.200	0.000	0.400	314	2.931	1810	0.507	261.1	0.500	261.0
0.400	0.000	0.400	303	1.898	1918	0.525	263.3	0.500	262.7
0.600	0.000	0.400	301	1.542	2012	0.536	264.0	0.500	262.7
0.200	0.200	0.400	312	2.998	1970	0.507	254.4	0.464	252.5
0.400	0.200	0.400	302	1.928	2052	0.522	257.9	0.472	255.4
0.200	0.400	0.400	311	3.079	2103	0.505	251.0	0.436	246.3
0.200	0.000	0.600	312	4.951	1642	0.527	261.7	0.500	260.9
0.400	0.000	0.600	307	2.992	1761	0.539	262.8	0.500	261.2
0.200	0.200	0.600	310	4.990	1777	0.523	256.4	0.472	253.8

the model compensating for increased natural mortality by increasing the rate of reproduction. The dependence of r on the value of φ is related to a need to compensate for longer time-lags in the model. Both MSY and K decrease as φ, Ω, or ψ are increased. The sensitivity of MSY to the values of the cannibalism parameters is less than that of K, with the consequence that MSYR (the ratio of MSY to the biomass at which this yield is achieved, i.e. MSY/B_{MSY}) is an increasing function of φ, Ω, and ψ. For example, the MSYR for the ($\varphi=0.2$; $\psi=0.2$; $\Omega=0.6$) model is almost double that for the non-cannibalistic model ($\varphi=1$; $\psi=0$; $\Omega=0$).

Another feature of Table 2 is that if the value of ψ is larger than zero, the ratio B_{MSY}/K is less than 0.5 – when $\psi=0$, B_{MSY}/K is the traditional Schaefer model value of 0.5. The lowest value of this ratio in Table 2 is 0.309, which occurs when the cannibalism parameters are set to $\varphi=0.2$; $\psi=0.8$; $\Omega=0$. The dependence of B_{MSY}/K on the cannibalism parameters is due to higher

levels of natural mortality at higher biomass levels, resulting in the trade-off between natural mortality and reproduction being optimized at a lower fraction of the average pre-exploitation biomass. Figure 1 provides the estimates of the surplus production function for four combinations of the cannibalism parameters.

The estimates of current depletion (B_{1988}/K) are not very sensitive to the values of the cannibalism parameters (the range of estimates of this quantity in Table 2 is 0.487–0.548). Nevertheless, some trends in the estimates of B_{1988}/K with the values of the cannibalism parameters are apparent. For example, if $\psi>0$, the estimate of B_{1988}/K decreases as ψ is increased and when $\varphi>0.2$ and $\Omega>0.2$, B_{1988}/K increases as φ is increased.

There is little possibility of selecting amongst the various models in Table 2 on the basis of their fits to the observed data. This is because the values of SS [see Equation (5)] are relatively insensitive to the values assigned to the cannibalism parameters (see the fits of
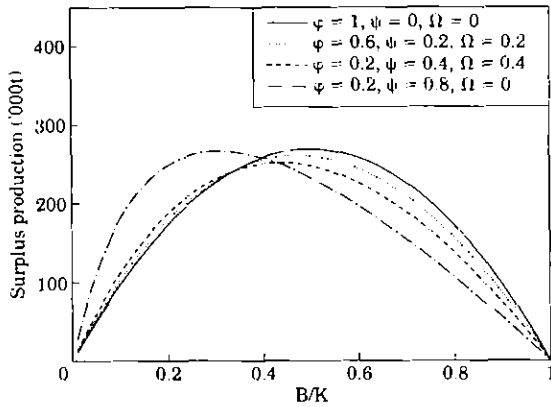
Figure 1. Estimates of the surplus production function for the Cape hake resource off northern Namibia provided by four alternative model-estimation procedures.
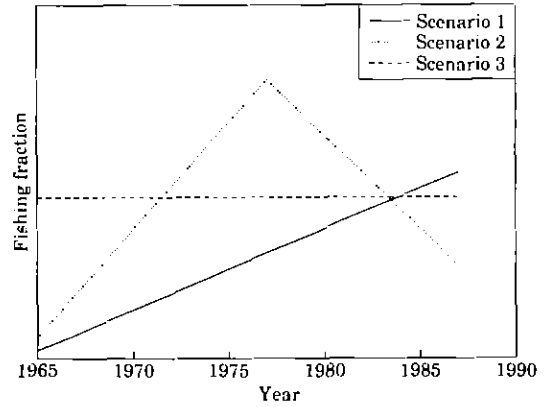

Figure 2. CPUE time series obtained from the fits of four variants of the cannibalistic model.

Figure 3. The three alternative fishing fraction (Γ_t) time series considered in the simulation exercises.

Estimation ability – a simulation exercise

The results of Table 2 suggest that the estimates provided by the non-cannibalism model-estimation procedure may overestimate MSY as well as the current replacement yield if the true situation involves cannibalism effects. This could, in turn, lead to overestimation of total allowable catches (TACs) and hence to biological overexploitation.

In order to investigate this problem further, a simulation exercise has been carried out. Four sets of cannibalism parameter values ($\varphi = 1$; $\psi = 0$; $\Omega = 0$, $\varphi = 0.6$; $\psi = 0.2$; $\Omega = 0.2$, $\varphi = 0.2$; $\psi = 0.4$; $\Omega = 0.4$, and $\varphi = 0.2$; $\psi = 0.8$; $\Omega = 0.0$), which may be representative of the dynamics of the Cape hake resource off northern Namibia, were used to generate 100 artificial catch and catch-rate data sets according to Equations (1) and (2). Using the nomenclature of Linhart and Zucchini (1986), the combination of Equations (1) and (2) and a set of cannibalism parameter values will be referred to as an operating model. The first three of these four sets of values were selected because they capture the range from no cannibalism to substantial cannibalism. The fourth set was selected because it corresponds to the lowest B_{MSY}/K ratio, and hence to the surplus production function most different from that of the traditional Schaefer model (see Fig. 1). In order to mimic the northern Namibian hake population, the value of σ [see Equation (2)] used in these calculations was 0.12 and each data series contained 23 data points. The selection of $\sigma = 0.12$ is based on the fit of the traditional Schaefer model to the CPUE data for the hake stock considered. Three alternative historic fishing fraction (Γ_t) trajectories are considered (see Fig. 3). All three of these series project a value of B_{1988}/K roughly equal to 0.52. They differ in their level of data contrast. Of these three fishing fraction time-series, that in which the fishing fraction increases and then decreases mimics most closely the actual situation for the hake stocks off southern Africa.

four of the models in Figure 2). This suggests that, were a model-estimation procedure to be used to estimate the cannibalism parameters (i.e. φ, ψ, and Ω) from catch and catch-rate data alone, such estimates would, in all likelihood, be very imprecisely determined. In order to obtain values for these parameters, therefore, it is necessary to collect additional data. Note, however, that some management quantities such as B_{1988}/K may be reasonably well determined, even though this is unlikely for the estimates of φ, ψ, and Ω.

Comparison of the results of the non-cannibalism model-estimation procedure (the row in Table 2 marked by an asterisk) with the results of the other model-estimation procedures suggests that the estimates of B_{1988}/K, MSY, and RY provided by this procedure are generally more optimistic than the corresponding "cannibalistic" estimates. This is of some concern because of the possible implications related to accidental overexploitation. This will be examined further below.
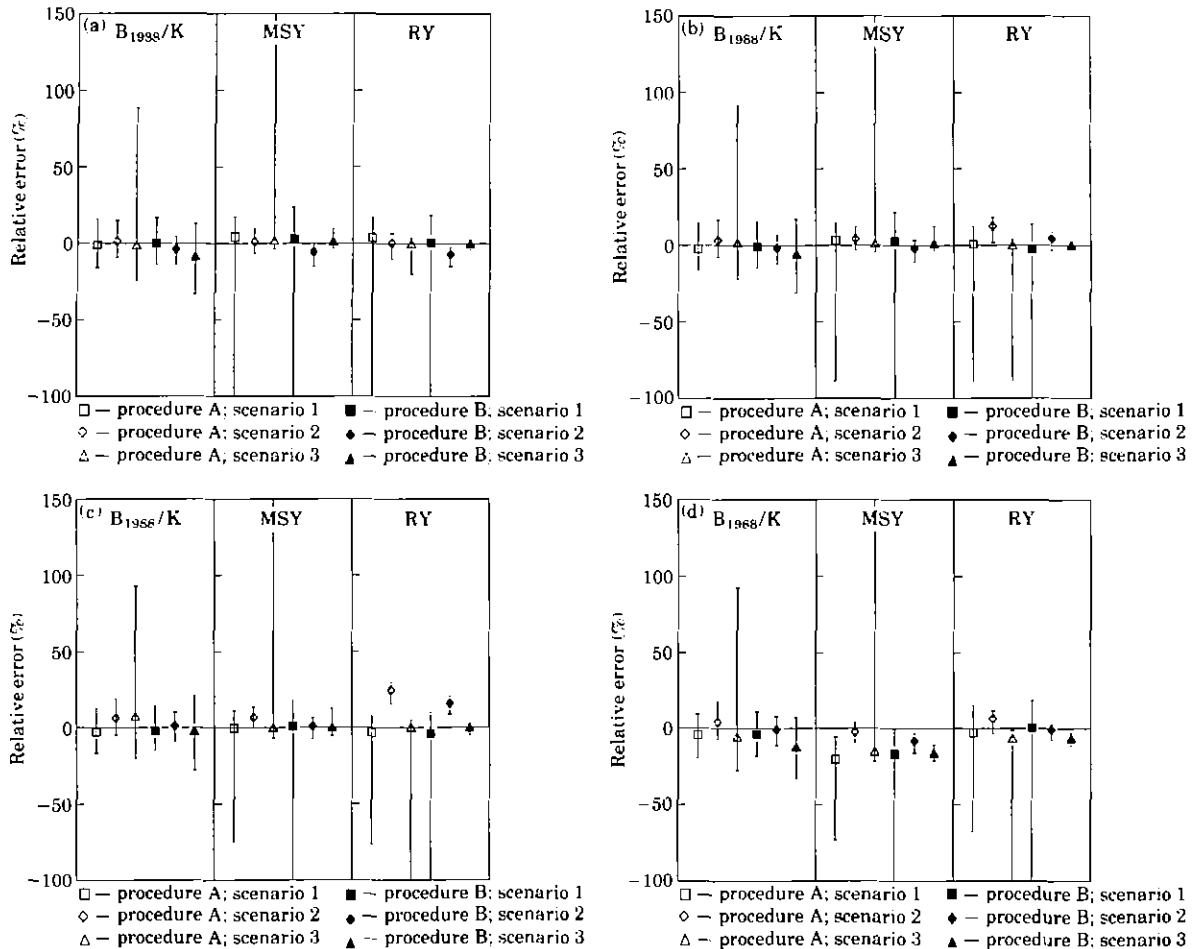
Figure 4. Comparison of the estimation performance of non-cannibalistic (procedure A) and cannibalistic (procedure B) model-estimation procedures for each of the three alternative fishing fraction time series and for each of four alternative models of Cape hake dynamics: (a) $\varphi=1$, $\psi=0$, $\Omega=0$; (b) $\varphi=0.6$, $\psi=0.2$, $\Omega=0.2$; (c) $\varphi=0.2$, $\psi=0.4$, $\Omega=0.4$; (d) $\varphi=0.2$, $\psi=0.8$, $\Omega=0$. Medians and 90% intervals of the relative error distributions of B_{1988}/K, MSY, and RY are shown.

Figure 4 contains plots of medians and 90% intervals for the relative errors of three management quantities: B_{1988}/K, MSY, and RY for two model-estimation procedures: procedure A, the traditional Schaefer model, and procedure B, the $\varphi=0.2$; $\psi=0.4$; $\Omega=0.4$ model, for each of the three fishing fraction trajectories (scenarios 1–3). Results are shown in Figure 4 for each of the four operating models mentioned above. Procedure B was selected for comparison because it is one of the "most cannibalistic" models considered. Note that the "r" and "K" values used in the generation process are those estimates obtained by fitting the model concerned to the actual catch-and-effort data for the Cape hake resource of northern Namibia (Table 2). The simulations are thus conditioned on a biology similar to that of Cape hake.

When the non-cannibalism model (i.e. $\varphi=1$; $\psi=0$; $\Omega=0$) is used to generate the artificial data sets (Fig. 4a),

the non-cannibalism model-estimation procedure (procedure A) provides estimates of the three management quantities which are close to their true values, at least on average – the absolute value of the largest median relative error for procedure A in Figure 4a is less than 5%. Although the median relative errors are close to zero, in some cases the distributions of relative error are wide because of the effects of outliers. One consequence of this is that the estimates of some management quantities are biased. For example, the estimates of B_{1988}/K and MSY for scenario 3 (constant fishing fraction) are positively biased, while those of MSY and RY are negatively biased for scenario 1 (linearly increasing fishing fraction).

Of the three management quantities considered, B_{1988}/K is estimated with the greatest precision. This is not very surprising; the CPUE data provide information on this quantity directly. The poor precision of B_{1988}/K

evident for scenario 3 is of some concern. As might have been expected, the results for scenario 2 are the least variable of the three scenarios considered. This is because the fishing fraction time-series for this scenario (increasing then decreasing) generates more data contrast than those for the other two scenarios.

The results for the cannibalistic estimator (procedure B) are qualitatively similar to those of procedure A. The estimates provided by procedure B are, however, somewhat less variable than those provided by procedure A (particularly for scenario 3), while the median relative errors differ from zero to a slightly larger extent (the absolute value of the largest median relative error for procedure B in Figure 4a is 9%). In general, the relative errors are more negative for procedure B than for procedure A (see, for example, the estimates of RY for scenario 2). This behaviour was to have been expected given that procedure B resulted in more pessimistic estimates than procedure A when it was applied to the actual data for the hake resource off northern Namibia (see Table 2).

When the artificial data sets are generated by models which incorporate cannibalistic dynamics (Fig. 4b–d), the results are qualitatively similar to those for the non-cannibalistic operating model (Fig. 4a). There are, however, some features of these figures worth noting. For example, both procedures A and B are more likely to provide overestimates of B_{1988}/K and RY for scenario 2 when the operating models used for Figure 4b and c represent the true situation than is the case for the operating model of Figure 4a – the extent of increase in the chance of overestimation increases with the extent of cannibalism. On the other hand, the estimates for scenario 1 are slightly more likely to be underestimates than is the case when the model used to generate the data does not incorporate cannibalism.

It is unclear exactly why the changes in performance occur when different operating models are used to generate the artificial data sets. Undoubtedly, the increased probability of overestimation evident in Figure 4b and c is related to the fact that the cannibalistic model-estimation procedures generally provide less optimistic appraisals than the non-cannibalistic model-estimation procedure. However, there is also some interaction between the values of the cannibalism parameters, the fishing fraction time series, and the estimator which complicates assessment of the causes of changes in performance.

Performance under feedback control

Although most of the biases in Figure 4 are not large, they are nevertheless of some concern. The presence of occasional outlying estimates (particularly of MSY) could lead to accidental overexploitation if TACs were based on them. The results of Figure 4 thus suggest that

it is possible for a management procedure based on the non-cannibalism model to perform poorly if the real situation incorporated cannibalism effects and that some knowledge of the extent of cannibalism may serve to prevent this. This question is examined by means of a further simulation exercise.

Each of the four operating models considered in the previous section were used to generate 100 artificial sets of historic catch and catch-rate data. The two model-estimation procedures, in combination with the f_{MSY} harvesting strategy, were then used to manage these simulated resources for a further 10 years. This type of simulation exercise was first considered for management procedures based on the Schaefer model by Hilborn (1979) and is similar to the extensive simulation exercise used by the Scientific Committee of the International Whaling Commission (e.g. IWC, 1989, 1992) to select a revised management procedure for baleen whales.

The f_{MSY} strategy seeks to stabilize the biomass of a resource at B_{MSY} by setting TACs according to the formula:

$$TAC_{n+1} = (\hat{B}_{n+1}/\hat{B}_{MSY})M\hat{S}Y, \qquad (6)$$

where TAC_{n+1} is the f_{MSY} strategy TAC for year $n+1$ based on data until year n; $\hat{B}_{n+1}$ is the model estimate of the adult biomass at the start of year $n+1$; $\hat{B}_{MSY}$ is the model estimate of the adult biomass at which MSY is achieved; and $M\hat{S}Y$ is the model estimate of the maximum sustainable yield.

Note that the use of the f_{MSY} harvesting strategy in this simulation exercise does not imply that it is a strategy which is appropriate for the management of the Cape hake resources off southern Africa, but rather that it is a strategy which is easily defined and implemented within simulation trials. Punt (1992) can be consulted for a discussion on appropriate management strategies for these resources.

The three performance attributes which have been selected to measure the performance of each management procedure for each simulation trial are:

1. P_f – the ratio of the adult biomass at the end of the 10-year simulation period to the pre-exploitation adult biomass (K).

2. P_{low} – the smallest ratio of (B_y/K) during the 10-year management period.

3. C – the average annual catch during the 10-year management period.

The performance of alternative management procedures has been represented by means of plots in Figure 5. These plots show the median and 90% limits of the three performance attributes over the 100 simulation trials. In addition, medians and 90% limits are provided for the relative error of the estimate of MSY at the end of the 10-year management period. The P_f and C attributes measure the ability of a procedure to utilize the resource – the P_f distribution should be compared to
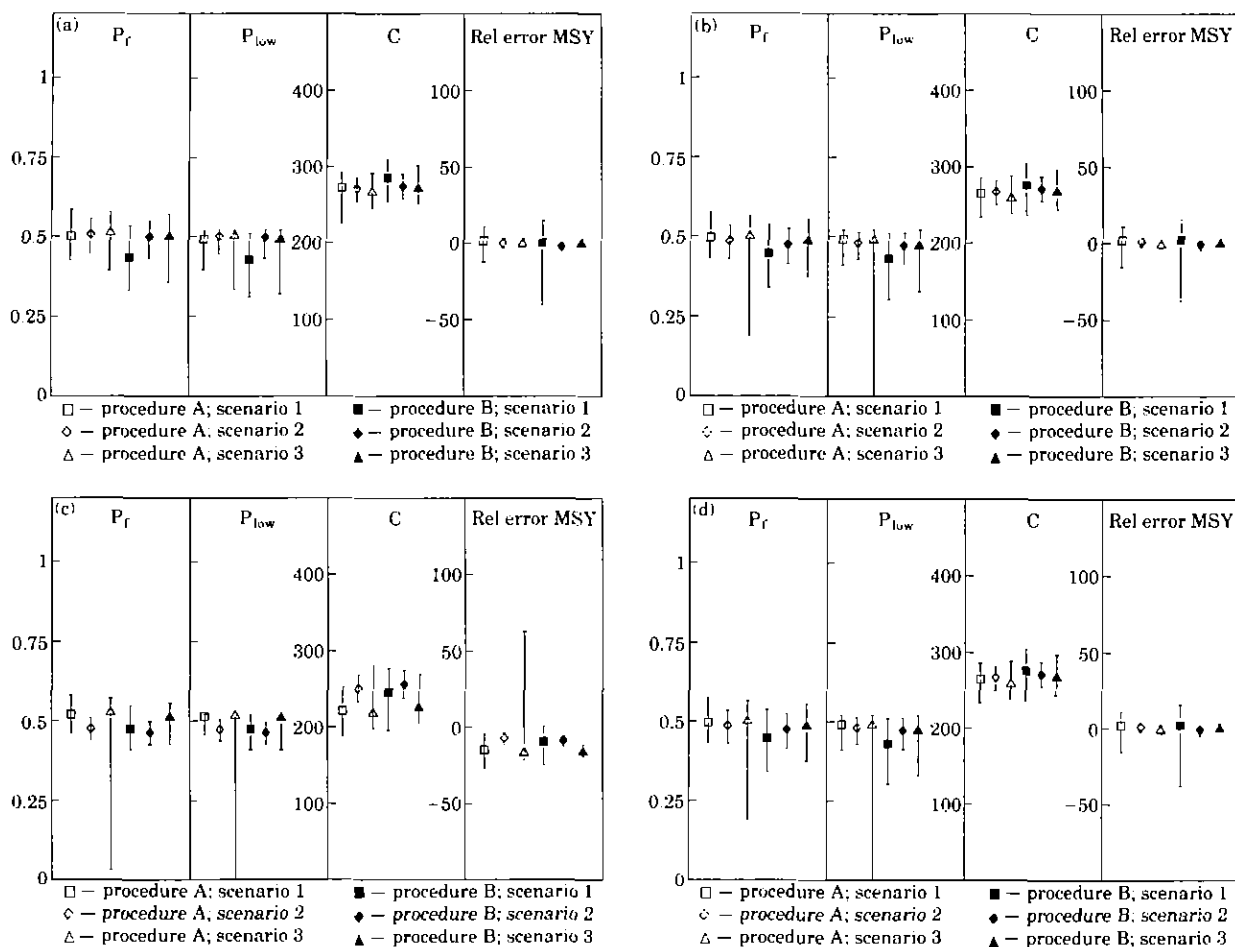
Figure 5. Comparison of the performance of two management procedures for four alternative models of Cape hake dynamics: (a) $\varphi=1$, $\psi=0$, $\Omega=0$; (b) $\varphi=0.6$, $\psi=0.2$, $\Omega=0.2$; (c) $\varphi=0.2$, $\psi=0.4$, $\Omega=0.4$; (d) $\varphi=0.2$, $\psi=0.8$, $\Omega=0$. Each plot shows the results for three alternative fishing fraction time series. The results for a trial are summarized by the median and 90% limits of the P_1, P_{low}, and C distributions (see text for definitions), as well as by the median and 90% limits of the relative error distribution of the estimate of MSY at the end of the 10-year management period.

the B_{MSY}/K of the operating model. The P_{low} attribute will be used to assess the risk associated with a management procedure. The relative error distribution for MSY is provided in order to determine the ability of a procedure to "learn" the true value of this parameter during the 10-year management period, and should be compared to the relative error distributions for this quantity in Figure 4.

For the non-cannibalistic operating model (Fig. 5a), the biomass is not left very far from B_{MSY} at the end of the 10-year management period. The non-cannibalistic management procedure (procedure A) with its B_{MSY}/K ratio of 0.5 tends to leave the biomass at a slightly higher level than the cannibalistic management procedure (procedure B) with its B_{MSY}/K ratio of 0.44. As a consequence of this, procedure B achieves higher average catches. The medians of the lowest depletion

distributions are not much lower than the medians of the final depletion distributions (maximum 2%), and in no case does the median lowest depletion drop below 0.4. These results thus suggest that within the 10-year management period, both management procedures are able to manage the resource satisfactorily (at least in some average sense).

When the operating model incorporates cannibalism (Fig. 5b–d), the performance of procedure A in terms of preventing overexploitation is very poor for scenario 3 (constant fishing fraction), even though the medians of the three performance attributes are not very different from their Figure 5a values even for this scenario. In more than 5% of the trials for scenario 3, procedure A drives the population to extinction in the first year because of an outlying estimate of MSY. As procedure B achieves similar values to procedure A for the P_f and C

performance attributes for this scenario, it is clearly superior to procedure A in this case. Note that the poor performance of procedure A may have been avoided had a restriction been placed on the extent to which the catch may vary from one year to the next. However, examination of alternative harvesting strategies is beyond the scope of this paper.

As the extent of cannibalism is increased, the actual (i.e. operating model) B_{MSY}/K decreases. However, the P_f distributions are almost independent of the values of the cannibalism parameters, except, of course, for the case of scenario 3. As a result, when the operating model incorporates cannibalism, overexploitation (i.e. $P_f < B_{MSY}/K$) is less likely. This increased resilience to overexploitation is also noted by Punt (1992).

The distribution of the relative errors of the estimate of MSY are much narrower after 10 years of management for the two operating models with the lowest extent of cannibalism. This suggests that the use of the f_{MSY} strategy over this period may lead to some notable increases in data contrast and hence in the ability to estimate the intrinsic growth rate parameter – a parameter which is often difficult to estimate using only a declining CPUE series (Hilborn, 1979). Not surprisingly, the estimate of MSY for scenario 2 is the best determined.

Discussion

The results reported above suggest that both of the model-estimation procedures considered are robust to the cannibalism behaviors investigated if a medium-term time horizon is considered and if the data contain a reasonable amount of contrast. At first this may appear surprising as the non-cannibalism and cannibalism model-estimation procedures are structurally different. However, when the cannibalism model is fitted to actual data, the fits are not very different from those of the non-cannibalism model (see Fig. 2). The data thus forced the simulation studies to consider only parameterizations which turned out to be dynamically similar to those of the non-cannibalism model. The above suggests that, if simulation studies are performed to test the ability of management procedures for a specific stock, the operating model should be parameterized as much as possible using the results of fits to real data. If this is not the case, spurious and unfortunate conclusions can be reached.

The results reported above have some bearing on the management of the hake resources off southern Africa as well as the direction in which future research effort should take. The results for scenario 2 suggest that the non-cannibalism procedure is robust to the true dynamics of the scenarios considered even for a relatively wide range of cannibalism-related parameter values and that the performance of a cannibalistic procedure is virtually identical to that of the non-cannibalistic procedure. This conclusion is sensitive to the exploitation history. In particular, the cannibalistic procedure performs much more satisfactorily than the non-cannibalistic procedure for the case in which the fishing fraction is constant.

However, as mentioned earlier, the exploitation pattern for the hake resources off southern Africa is similar to scenario 2. Thus, had considerable time and sampling effort been taken to obtain data which could be used to select values for the parameters φ, ψ, and Ω, the sampling effort expended would most likely have been in vain. This is because the non-cannibalism management procedure is likely to perform at least as well as most procedures which incorporate cannibalistic dynamics, at least in the short- to medium-term for scenario 2. This suggests that, for these hake resources, there seems little point in attempting to estimate the values of cannibalism parameters. A similar conclusion was reached by Punt (1992) for the Cape hake stock of the west coast of South Africa.

In a more general context, the results of this paper indicate that prior to the commencement of any large and expensive programs designed to collect stomach data for use in management, it is first necessary to determine whether the extra information that would be gained by using a management procedure that uses this information would lead to improved performance that is more than able to compensate for the associated increases in cost and sampling effort. For example, the results of this paper suggest that had it been likely that the fishing fraction time-series was similar to scenario 3, there would be a rationale for attempting to estimate the values of cannibalism parameters.

It should be noted that the results of this paper do not suggest that all stomach content collection programs should be stopped because they are "useless". Rather, the purpose of regular (and small-scale) data collection programs is to provide sufficient data so that it is possible to conduct analyses such as those in this paper to determine whether a large-scale data collection program (with its associated uncertainties) might lead to improved management. The results of the analyses of this paper suggest that in cases in which the data do not contain much contrast, the benefits of knowing something about cannibalism can lead to improved management. An issue not covered by this paper is whether it is in fact possible to estimate the parameters of a cannibalistic model with reasonable precision. Punt *et al.* (1992) examined the sampling variances associated with the stomach content data for Cape hake collected off the west coast of South Africa (the largest stomach content data collection program of its kind in that region) and found that estimates of consumption by prey species to be very poorly determined. Whether such data could be used to estimate the values of the parameters of a

cannibalistic model precisely is questionable (see Punt, 1992, for further details).

The results presented above relate to short- to medium-term management ability under an f_{MSY} harvesting strategy. It is possible that the ability to satisfy long-term management goals (such as optimum mesh sizes) might be enhanced by analyses based on models which incorporate cannibalistic dynamics. However, once again, the ability to make the correct decision depends not only on whether the optimum mesh size depends on cannibalistic dynamics (which it probably does), but also on whether the data could ever detect the correct mesh size with reasonable precision.

The extent to which it is possible to generalize the results of this study to multispecies models is unclear. It is possible in principle to perform the type of calculations reported in this paper to determine this. However, multiple-species systems are much more complex than a cannibalistic system and so this problem is beyond the scope of this paper. Nevertheless, the general point that it should not be assumed *a priori* that utilizing a multispecies model will lead to improved management still holds. If a multispecies model is to be applied in a particular case, simulation studies (based on existing data or data collected from a pilot study) should be conducted to assess the likely performance of management based on such a model.

Acknowledgments

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