The status and productivity of the Cape hake stock off the west coast of South Africa based on an age-structured production model with different stock-recruitment and fishing selectivity-at-age relationships

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CONTENTS

ABSTRACT

The surplus production model and *ad hoc* tuned VPA assessment methods currently used to provide the basis for scientific TAC recommendations for the Cape hake resource off South Africa provide rather different appraisals of the current status and productivity of this resource. The production model approach is based on the Butterworth-Andrew observation error estimator, and takes catch per unit effort (CPUE), as well as biomass survey data into account. The *ad hoc* tuned VPA is based on the Laurec-Shepherd tuning algorithm and utilizes catch-at-age and effort information. Applications of an age-structured model, which takes both CPUE and catch-at-age data into account, provides similar results to the production model if more weight is given to the CPUE data than the catch-at-age data and similar results to the *ad hoc* tuned VPA if more weight is given to the catch-at-age data rather than the CPUE data. This led Punt (1993) to conclude that the discrepancies between the various sets of results obtained from surplus production model and *ad hoc* tuned VPA methods are a consequence of a conflict between the catch-at-age data and the CPUE data and that they are not primarily a result of differences in the two assessment methods. However, the above two approaches are based on certain assumptions regarding recruitment, natural mortality and fishing selectivity. An attempt was made to obtain estimates of fishing selectivity-at-age from an age-structured production model. It is commonly assumed that selectivity-at-age has a slope of zero at older age classes. The estimates obtained all suggest that selectivity-at-age for older age classes (> 2 to 3 years) decreases with age. The results obtained in this study also indicate that the conflict between the observed trends in the catch-at-age data and the CPUE data can be basically resolved by assuming that for older age classes selectivity-at-age decreases.

INTRODUCTION

The Cape hake resource

The Cape hake fishery is of considerable social and economic value to South Africa. Cape hakes form the bulk (62% in 1991) of the catch of the South African demersal industry (Stuttaford 1993). The wholesale value of the hake catch exceeded 300 million rand in 1989. This was almost 30% of the wholesale value of all marine species harvested off the South African coast (Punt 1991). Annual hake catches by the South African fishing fleet over the period 1982-1991 remained fairly constant, averaging 138 000 tons per year. Payne (1989) provides a detailed history of the hake fishery off southern Africa, while Payne and Punt (1992) provide the rationale for the current management approach, which is based on an $f_{0.2}$ harvesting strategy.

Reviews of the biology of this resource are provided by Botha (1980), Crawford *et al.* (1987), Payne (1989) and Payne and Punt (1992). Cape hakes consist of two morphologically similar hake species, *Merluccius capensis and M. paradoxus* (Van Eck 1969). Since it is not easy to distinguish visually between the two species only the total combined species catch is recorded. The distribution of each species is depth-dependent; *M. paradoxus* occurs in deep water while *M. capensis* is a shallow water species (Botha 1973) (Figure 1). The distribution areas of the two species overlap in intermediate waters where small *M. paradoxus* occur together with medium to large *M. capensis* individuals as the size of fish of each species tends to increase with depth (Botha 1973). Consequently the adults of the two species do not mix and the species maintain their integrity by spawning at different depths (Botha 1973).

Earlier workers (*e.g.* Roux 1949) were convinced that there was some form of horizontal annual hake migration, but such conclusions were drawn on the erroneous premise that only one species existed. Van Eck (1969) later confirmed the presence of two hake species in local waters. There is a tendency for hake to move offshore into deeper water as they grow older and there appears to be some seasonal movement of adults inshore and offshore (Payne *et al.* 1989), but apart from that, there is no firm proof of extensive horizontal migration (Botha 1973, 1980). Vertical migration, which is characteristic of all hake species, takes place in the local species. Cape hakes have a regular and pronounced diurnal vertical migration pattern, being concentrated near the sea bed during the day (where they are in reach of the bottom trawls) and scattering into midwater at night (Botha 1973). There is a marked decline in vertical migrations during the spawning season. As far as their trophic relationship is concerned, there is no doubt that hake are an important link in the Benguela trophic chain, both as predator and prey (Payne *et al.* 1987a). Hake are generally opportunistic predators, with young hake preferring crustaceans, but with older hake tending towards piscivory (Payne *et al.* 1987a). Extensive cannibalism has been found to exist in the species. Botha (1980) noted that *M. capensis* was highly "cannibalistic" on juvenile *M. paradoxus* with other food organisms of very large *M. capensis* individuals may constitute less than 2% of the diet of these fish.

Management of the fishery

Since the turn of the century Cape hakes have formed the basis of a substantial local trawl fishery. This fishery was initially based at Cape Town, but later (in the 1960s) became established at Saldanha. Only a thousand metric tons was caught in 1919, but catches steadily increased to 30 000 metric tons before the Second World War. Later catches of Cape hakes in the southern Benguela increased from 50 000 tons in 1950 to about 160 000 tons in 1960 (Crawford *et al.* 1989). After 1962, Cape hakes also became a sought-after target for foreign trawlers from several countries. By 1973, some 14 different countries achieved a catch of just under one million tons with more than 300 large vessels (Botha 1985). The increasing fishing effort made a substantial impact on stock densities and catch rates decreased by 47% between 1940 and 1966, and a further 50% between 1966 and 1975 (Jones and Van Eck 1967).

The local fishery has traditionally confined its activities to the fishing grounds around Cape Town and to a lesser extent off the southern coast of South Africa. Foreign vessels concentrated in areas further north, off the coast of Namibia. The International Commission for the Southeast Atlantic Fisheries (ICSEAF) was established in 1972 to investigate and control the international fisheries for hake off South Africa and Namibia (Andrew and Butterworth 1987). Since 1978, total allowable catches (TACs) off South Africa were set to rebuild the stock, by applying an $f_{0.1}$ or an $f_{0.2}$ harvesting strategy. The fishery off South Africa has been managed exclusively by the nation since the declaration of a 200-nautical-mile exclusive fishing zone in 1977. However, the ICSEAF Scientific Advisory Council continued to consider assessments for the hake stocks in SA waters, and to allocate quotas for hake off Namibia until ICSEAF was dissolved in 1990 following the independence of Namibia. More recently effort has concentrated on the investigation of alternative management procedures for the Cape hake resource off the west coast of South Africa (see Punt 1991).

For management purposes ICSEAF divided the area under its management into Divisions. Off South Africa Division 1.6 corresponds to the west coast, and Divisions 2.1 and 2.2 correspond to the south coast (see Figure 1). In all four ICSEAF Divisions, catch per unit effort (CPUE) figures indicate a steady decline up to the late 1970s, when catch rates reached their lowest recorded levels. However, subsequent reductions in catch have led to a slow increase in CPUE. The increasing trend in CPUE in the South African hake fisheries over the past 15 years indicates that these resources have recovered since the mid-1970s (Butterworth *et al.* 1992). From 1976 to 1983, the ICSEAF Scientific Advisory Council used the Gulland form of the steady-state Fox production model for hake stock assessment (Butterworth and Andrew 1984). However, this model produced inadequate fits to the data, and biases in the estimation of maximum sustainable yield (MSY) and $f_{0.m}$ quota values (Andrew 1986). As a result a dynamic production model was introduced for managing the resource using CPUE data (Andrew and Butterworth 1987). A more detailed description of the dynamic model and the procedures used to obtain parameter estimates is given in Butterworth and Andrew (1984). Although a global TAC is set, for management purposes, the hake resource off South Africa has been divided into two stocks, and scientific TAC's are formulated for each stock, under the assumption that the stocks of hake off the south and west coasts are biologically isolated (Payne and Punt 1992). However, Payne *et al.* (1987b) suggests that there may be some interaction between the *M. paradoxus* stocks on the south and west coasts.

Current stock assessment techniques and the catch-at-age data

Current scientific TAC recommendations for the South African hake fishery are based on the results of two different assessment methods. The first is a dynamic production model estimation procedure which utilizes catch, CPUE and survey biomass data. The version used for Cape hakes is the Butterworth-Andrew ($B_1 = K$; Schaefer form) observation error estimator (production model). The choice of the Schaefer form and the assumption that $B_{1917} = K$ (*i.e.* the biomass immediately preceding exploitation is equal to its unexploited equilibrium level) is made because this combination was shown to give the best results out of a number of possible selections of models for the hake resource off northern Namibia (see Punt 1988, 1990, 1992). It is possible to vary a number of the assumptions of the production model (Andrew 1986, Punt 1991b). In most cases (*e.g.* taking account of some environmental indices, estimating the biomass at the start of exploitation), the results are not qualitatively very different from those provided in Table 1, taken from Punt (1993).

The second assessment technique used is an *ad hoc* tuned VPA based on a Laurec-Shepherd tuning algorithm which utilizes catch-at-age and effort data (Punt 1991a, 1991b). The results from the two approaches differ. The *TAC* estimates provided by the *ad hoc* tuned VPA are substantially lower than those from the production model-estimation procedure. Overall, the VPA assessment for the South African west coast indicates that the hake resource is less productive, smaller and more depleted than indicated by the production model. If one considers the common management quantities (Table 1 and 2), the differences are substantial. VPA estimates for MSY are slightly lower than the estimate from the production model, but the estimates of B_{MSY} and B_{90}/K are far lower in the case of the VPA. Production models have continued to be the preferred assessment approach both because simulation analyses (Punt 1991) have suggested that estimates provided by VPA may be subject to considerable imprecision, and because of the sensitivity of VPA *TAC* estimates to the value assumed for natural mortality, M (Punt 1993). For $M = 0.5$ yr^{-1} the discrepancy between the estimates of current depletion from the VPA and surplus production methods, is less than for $M = 0.3$ yr^{-1}. Irrespective of the value assumed for M, there are still substantial differences between the estimated trajectories of exploitable biomass provided by the two approaches (Payne and Punt 1992). For example, the VPA assessment still suggests that there has been little increase in exploitable biomass since 1978.

Even in a crude sense it is important to consider the discrepancies that exist in the data that these two methods utilize, especially the catch-at-age data. Even a cursory examination of the catch-at-age data (Table 3) indicate that even if M=0.5 the values of fishing mortality, F computed for the older age classes lie between 0.3 and 1.2, averaging about 0.8. This must be compared to an estimate of F of 0.2 from the surplus production model. Therefore the catch-at-age data suggest that harvest proportions average around 80%, whereas the surplus production model suggests that the harvest proportion is more in the region of 20% - a major discrepancy which is often ignored.

This discrepancy could be either due to: i) decreasing selectivity for older ages, and/or ii) very high natural mortality for these ages, and/or iii) consistently increasing annual recruitment levels, and/or iv) biases in the CPUE due to changes in the catchability coefficient. In this study, selectivity (i) is considered as the most likely possibility for the discrepancy. An assumed decrease in selectivity-at-age for the older age classes would explain why the catch-at-age data shows lower numbers of fish in older ages than that which is expected under the present fishing pressure. The idea of fishing selectivity decreasing in older age classes is not new. Andrew (1986), for example, suggested that emigration of older fish (into deeper, unfished waters) will lead to selectivity decreasing with age at older age classes. To investigate this possibility in more detail both the CPUE data (basis of production-based) and the catch-at-age data (basis of VPA analysis) need to be incorporated into a new assessment approach which has the flexibility of incorporating different selectivity-at-age relationships.

Aim of study

The aim of this study is to construct an age-structured production model (Hilborn 1990, Punt 1993) in order to reconcile some of the discrepancies that exist between the catch-at-age data and the surplus production model by considering that selectivity-at-age could be decreasing in older age classes. The strength of the age-structured production model assessment method is the flexibility for varying input information such as fishing selectivity-at-age (Hilborn 1990). The original feature of the work reported here is thus the estimation of fishing selectivity-at-age considering the possibility of more complex fishing selectivity patterns than those that have been considered in past assessments in which selectivity-at-age is not assumed to decrease with age at older age classes (*e.g.* Butterworth *et al.* 1986a; Hilborn 1991; Punt 1993). In the process the productivity and status of the west coast stock is also estimated, and is compared to the VPA and surplus production model results. The results produced here are also compared to those obtained by Punt (1993) who used a slightly different version of the age-structured production model (Table 4). Furthermore, in this study, estimates are computed two different stock-recruitment relationships.

METHODS

Age-structured production models

The age-structured production model (Hilborn 1990; Butterworth and Punt 1992; Punt 1993) is an assessment technique which can take account of the age-structured nature of fish populations, but does not necessarily require estimates of the age-composition of the catches (although the option to incorporate catch-at-age data exists). This approach involves constructing a deterministic age-structured population model and fitting it to the available abundance indices by maximizing the likelihood function for CPUE. The model requires only total catch mass data for each year, commencing at the start of the fishery. It assumes further that recruitment is deterministically related to spawner biomass. These simple age-structured models include numbers of individuals at each age, age-specific mass, age-specific fishing selectivity, as well as natural mortality rates and stock-recruitment parameters.

The basic age-structured production model

The basic structure of the age-structured production model is given below (the full method and equations are given in Appendix I). Generally age-structured models can be written a variety of different ways. The choices that must be made are whether the fishing and natural mortalities are assumed to be continuous processes acting simultaneously, or separate discrete time events. The model used here is a discrete time model based on Hilborn (1990). The general age-structured production model can be written simply as:

$$N_{y+1,a+1} = N_{y,a}\, e^{-(M_a + S_a F_y)} \qquad \text{(E.1)}$$

where $N_{y,a}$ is the number of fish of age a at the start of year y,

M_a is the rate of natural mortality on the fish of age class a,

S_a is the selectivity of the fishery on fish aged a years ($0 \leqslant S_a \leqslant 1$),

F_y is the fishing mortality for fully vulnerable individuals in year y, *i.e.* fish with $S_a = 1$ (the year effect for the fishing mortality).

To take age effects into account fishing mortality-at-age ($F_{y,a}$) is separated into an age-component which is common to all years (age-specific selectivity - S_a) and a year-component which is common to all ages within a particular year (year effect of fishing mortality - F_y). This assumption is justifiable if the distribution of fish and fishing vessels does not vary substantially from one year to the next. Two scenarios in which the separability assumption would not be justified, and which might be pertinent to the hake fishery (Punt 1991) are:

a) if the mesh size changes, and

b) if the distribution of the fishing fleet across the fishing grounds changes as a result of changes in market demand for different sizes of fish (fishermen seek out particular sizes of fish which are more profitable or required for the market at a particular time).

The separability assumption is based on the following relationship:

$$F_{y,a} = F_y S_a \qquad \text{(E.2)}$$

where $F_{y,a}$ is the instantaneous rate of fishing mortality on fish aged a during year y,

The total exploitable biomass at time y, $B^E{}_y$ is therefore:

$$B^E{}_y = \sum_{a=1}^{Max} N_{y,a} W_{a-0.5} S_a e^{-((M_a + S_a F_y)/2)} \qquad \text{(E.3)}$$

where

$B^E{}_y$ is the exploitable biomass for year y,

Max is the maximum age considered, and

$W_{a-0.5}$ is the mass-at-age for a fish of age a-0.5.

This is computed at mid-year, rather than at the beginning of the year because, as will be seen below, B^E_y is included in the objective function and compared with CPUE.

The spawning biomass SB_y can be calculated as:

$$SB_y = \sum_{a=m}^{Max} N_{y,a} W_a \qquad (E.4)$$

where SB_y is the spawning biomass at the beginning of the year y,

W_a is the mass-at-age for a fish aged exactly a-1

m is the age at sexual maturity. In this model all fish greater than four years old are assumed to be sexually mature.

It is assumed further that there is a relationship between the spawning biomass SB_y in one year, and the average recruitment in the following year:

$$N_{y,1} = R(SB_y) \qquad (E.5)$$

where R is the function for average recruitment.

The two most common stock-recruitment relationships are the Beverton and Holt (1957) (E.6) and Ricker (1954) (E.7) forms:

$$N_{y+1,1} = (\alpha SB_y) / (SB_y + \beta) \qquad (E.6)$$

$$N_{y+1,1} = \alpha \, SB_y \, e^{-\beta SB_y} \qquad (E.7)$$

where α, β are the stock-recruitment relationship parameters.

Equations (E.1) - (E.7) define the dynamics of both numbers-at-age and biomass-at-age.

In order to relate the model to observed data, additional relationships need to be defined. It is assumed that the available indices of population abundance, A_y, are proportional to stock biomass (where the abundance index is either CPUE or survey biomass):

$$A_y = \upsilon B^E{}_y \qquad \text{(E.8)}$$

where A_y is an index of population abundance, and
υ is a proportionality constant.

When CPUE is assumed to be an index of population abundance (*e.g.* A_y), then

$$A_y = C_y / E_y \qquad \text{(E.9)}$$

where E_y is the fishing effort in year y.
C_y is the catch in year y.

Based on Equations (E.8) and (E.9), the following relationship will now hold:

$$C_y / E_y = q\, B^E{}_y \qquad \text{(E.10)}$$

where q (the catchability coefficient) has replaced υ as the proportionality constant.

In the model a choice must be made whether to use fishing effort or the observed catch pattern to calculate F_y. Punt (1988) refers to this choice as 'conditioning on effort' or 'conditioning on catch'. The use of the term 'conditioning' implies that the predicted dynamics are conditional (in the statistical sense) on a specific catch or effort sequence (Hilborn 1990).

Although conditioning on effort is the easiest, effort is not as accurately measured as catch. Secondly, by conditioning on catch one can see whether the observed catch sequence can actually have been taken from the population model without driving it extinct. To condition the simulation on catch, the model is tuned by allowing the model to choose a value of F_y (see

Equation E.2) which satisfies the condition that total model-predicted catch, obtained by summing across age classes is equal to the total observed catch. The equation for model-predicted catch is:

$$C_y = \sum_{a=1}^{Max} W_{a-0.5}\, S_a\, F_y\; N_{y,a}\, (1 - e^{-(Ma + Sa\, Fy)})/(M_a + S_a\, F_y) \qquad \text{(E.11)}$$

Data Utilized

Annual recorded catch and CPUE data for the South African west coast hake stock are listed in Table 5. The CPUE is calculated from the directed effort of only part of the fleets involved in the fishery (Punt 1993). The adequacy of the power factors of fishing vessels used in the calculation of these data is currently a cause for concern. Although Cape hake in Division 1.6 have been fished since the turn of the century, comprehensive CPUE are only available from 1955. The catch statistics are usually reported in tonnes landed weight. Fish are headed and gutted before being weighed and therefore catch figures were converted to tonnes whole (nominal) weight by multiplying by a factor of 1.46 (Chalmers 1976). Nominal catches prior to 1972 were increased by 39% to account for discarding of small hake (Andrew 1986).

The collection of otoliths for ageing purposes and catch-length frequency data permits the breakdown of the total catch-by-mass into catch-at-age estimates (see Table 3 for the catch-at-age data for the period 1978 to 1990). Length frequency data also exist for the years 1964 to 1977 for the west coast. In principle, these data can be used to estimate catch-at-age for these years. Punt (1993) suggests however that the data may not reflect the length structure of the entire catch because the data were collected from the South African fleet only, during which substantial catches were being made by foreign fleets. In addition, reliable age-length keys do not exist for the years prior to 1978. Therefore catch-at-age estimates based on the pre-1978 catch length frequencies are unreliable.

Although survey biomass data are available from 1983, they are not utilized here. Punt (1993) incorporated survey biomass data in his age-structured production model assessments and found in his sensitivity tests that the results scarcely changed when survey biomass data were not taken into account. Andrew *et al.* (1989) incorporated biomass survey data into their assessment and found that fits to the relative indices of survey biomass and CPUE data hardly changed from fits to the CPUE data alone. Although the biomass estimates have fluctuated over the period since 1983, they show no significant trend.

Estimation of parameters

a) Input parameters

Four age-specific parameters are needed before the population can be simulated. These include selectivity-at-age (S_a), mass-at-age (W_a), and mortality-at-age (M_a) (see Appendix II). The remaining parameter is age-at-maturity. The estimates of selectivity-at-age, mass-at-age and age-at-maturity were obtained from other sources (except in the case where selectivity-at-age is estimated). The parameter values for the logistic selectivity function (see Appendix II) are based on the analysis of selectivity-at-age conducted by Punt (1991). The values for the parameters related to growth and maturation were taken from Punt and Leslie (1991) (see Appendix II). The natural mortality-at-age was assumed to be constant over the age classes considered for the "base case" models, however in one of the sensitivity tests, natural mortality is assumed to be age-specific (the relationship is given in Appendix II). There are rarely any data to justify the assumption that mortality is age-specific and it is normally assumed to be the same regardless of age. In must be borne in mind that the hake size mix in the population is dynamic and affected by the survival of the different age classes. As Botha (1980) pointed out, enhanced survival of both species to a large size will increase the rate of cannibalism on younger age classes. However, increased fishing pressure on large hake will correspondingly increase the survival of younger age classes. Therefore it would be important to consider the effects of cannibalism on the age-specific mortality as well, however the paucity of data, precludes such a study.

b) Parameters estimated by the model

The parameters which are obtained by fitting the model to the available data are the catchability coefficient (q), the relationship between the biomass and index of abundance (CPUE) and the two stock-recruitment parameters α and β. The first step in the regression is to obtain a set of initial age-class numbers, $N_{y,1}$. This is done by setting the initial age-distribution equal to that of the deterministic unexploited equilibrium (denoted by *) level for the stock (*i.e.* the age-structure corresponding to $F_y = 0$, for $y<1917$), therefore:

$$N^*_{y,a} = R^*_1 \, e^{-\sum_{r=1}^{a-1} M_r} \qquad \text{(E.12)}$$

and

$$SB^*_1 = \sum_{a=m}^{Max} N^*_{y,a} W_a \qquad \text{(E.13)}$$

where $N^*_{y,a}$ is the equilibrium number of fish of age a at the start of year y

R^*_1 is the average equilibrium recruitment

SB^*_1 is the spawning biomass at equilibrium.

By substituting equation (E.12) into equation (E.13) it is possible to obtain a relationship for spawning biomass at equilibrium (SB^*_1) in terms of average equilibrium recruitment (R^*_1):

$$SB^*_1 = R^*_1 \sum_{a=m}^{Max} W_a e^{-\sum_{r=1}^{a-1} M_r} \qquad \text{(E.14)}$$

setting

$$\gamma = \sum_{a=m}^{Max} W_a e^{-\sum_{r=1}^{a-1} M_r} \qquad \text{(E.15)}$$

gives

$$R^*_1 = SB^*_1 / \gamma \qquad \text{(E.16)}$$

For the Ricker stock-recruitment relationship:

$$R^*_1 = \alpha \, SB^*_y \, e^{-\beta SB^*_y} \qquad \text{(E.17)}$$

Equations (E.16) and (E.17) can be solved for the average equilibrium recruitment (R^*_1) and the equilibrium spawning biomass (SB^*_1). The result is:

$$R^*_1 = ln\,(\alpha\gamma)/(\beta\gamma) \tag{E.18}$$

A similar derivation can be done for the Beverton-Holt stock-recruitment relationship giving the following relationship for the average equilibrium recruitment (R^*_1) level:

$$R^*_1 = ln\,(\alpha\gamma)/(\beta\gamma) \tag{E.19}$$

Equation (E.18) and (E.19) can be substituted into equation (E.12) to compute the initial conditions for both stock-recruitment relationships:

$$N_{1917,a} = R^*_1\, e^{-\sum_{r=1}^{a-1} M_r} \tag{E.20}$$

The assumption that the hake stock was at equilibrium at its carrying capacity at the start of 1917 would seem to be realistic, because catches prior to 1917 were negligible.

The regression approach

Once the input parameters and the necessary starting conditions specified, an exploitable biomass sequence can be calculated and compared to the observed index of exploitable biomass (*i.e.* CPUE). The simulated and observed indices of abundance (CPUE) are incorporated into an objective function of the form:

$$SS = \sum_{y=1955}^{1990} [ln\,(q\,B^E_y) - ln\,(C_y / E_y)]^2 \tag{E.21}$$

The use off logarithms in the objective function is based on the assumption that the dominant noise in the model is in Equation (E.10), *i.e.* the choice of the error in the model is "observational error", and that this noise may arise from catchability fluctuations. Changing environmental factors, seasonal migration and behavioral/distributional changes tend to produce inter-annual catchability fluctuations. One would expect catchability to be influenced by a large number of these factors, each of which may well be independent and have a multiplicative effect. The central limit theorem implies that the sum of the logarithms of the magnitudes of these factors approaches a normal distribution, and therefore taking logarithms is the most appropriate transformation to use in the objective function.

The minimization procedure AMOEBA (Numerical Methods, Cambridge 1988) was used to find the parameter values which would provide the best fit. Two variations of the model were used throughout the assessment. The Ricker stock-recruitment relationship was incorporated into the Model 1 "base case". However, in order to be consistent with previous applications (Hilborn 1990; Butterworth and Punt 1992; Punt 1993) of this method the Beverton-Holt form of the stock-recruitment relationship was also studied (Model 2 "base case"). In the "base case" models, q and the parameters of the stock-recruitment relationships α and β, (for Ricker and Beverton-Holt) were estimated.

Specification of "base case" assessments and sensitivity tests

The specifications of the "base case" model and of the various sensitivity tests are given in Table 6. The selection is based on choosing a "base case" assessment and then varying each factor of the "base case" specification in turn to determine sensitivity. Due to the computational demands of the estimation process, the effects of varying more than one factor at a time has not been considered.

Incorporating catch-at-age information

As noted before, there appears to be a fundamental conflict between the results of the production model-based and catch-at-age-based assessment techniques. Punt (1993) found that although it was possible to reconcile some of the conflicts by adjusting the value of M, it was not possible to reconcile the point estimates of biomass, depletion and MSY for the west coast hake stock. This dichotomy could be indicative of model mis-specification and merits special attention. Although the model underlying the assessment is age-structured, no attempt is made to take catch-at-age data into account in the "base case" assessments, so only the information on annual catches and abundance indices (CPUE) is utilized.

In an attempt to detect the reason for the discrepancies between the catch-at-age-based assessments and production model-based approaches, applications of the age-structured production model were conducted in which a term incorporating catch-at-age information was added to the objective function. A weighting factor (ø) was then assigned to this term. The equation for the sum of squares becomes:

$$SS = \sum_{y=1955}^{1990} [\ln (q\, B^E{}_y) - \ln (C_y / E_y)]^2 + ø \sum_{y=1978}^{1990} \sum_{a=2}^{7} [\ln \; (C_{y,a}(\mathrm{mod}))/C_{y,a}(\mathrm{obs}))]^2 \quad (E.22)$$

where $C_{y,a}$ (obs) is the actual estimate of the number of fish of age a caught during the year y,

$C_{y,a}$ (mod) is the model estimate of the number of fish of age a caught during the year y and,

ø is the weighting factor used to change the relative influence of the CPUE and catch-at-age data in the objective function.

There are other ways of incorporating the contribution of the catch-at-age data in the objective function. The particular form of (E.22) has been selected because of numerical simplicity. The form gives equal weight to equal relative differences, and is appropriate if the catch-at-age data are log-normally distributed about their expected values. The summation on catch-at-age was restricted to ages 2 to 7 in this study. Punt (1993) restricted his summation to ages 2 to 6 on the basis that the estimates of the catches of 1-year-old and 7-year-old fish are probably very imprecise (the numbers involved for these ages are rather small, and hence may be subject to considerable sampling error). Therefore, the results obtained will not be totally comparable with Punt (1993).

In order to examine the effect of the catch-at-age data, values of the weighting factor (ϕ) between ϕ=0.001 and ϕ=4 were considered. The choice ϕ=0.001 corresponds to putting nearly all the weight on the CPUE data (essentially the "base case" scenario), while ϕ=2 or 4 reflects the opposite extreme where most weight is placed on the catch-at-age data.

Estimating selectivity-at-age from the model

The main aim of this report was to consider the possibility of an age-specific selectivity function with a negative slope for older age classes. The main reason for postulating that selectivity has a negative slope at older age classes is because of the observed trends in the catch-at-age data (see Introduction). Hake age tends to increase with depth and large *M. paradoxus* are found in deeper water than that in which trawlers normally operate (Punt 1993). This could lead to a smaller selectivity on older fish and hence a negative slope for older age classes in any assumed selectivity function. It may also be the case that older fish are avoiding the net and swimming ahead of the gear. In order, to obtain estimates of selectivity-at-age, an attempt was made to estimate the selectivity-at-age values. Since catch-at-age data exist for age classes 1 to 7, the maximum number of age classes was set at 7 in this version of the model. In the first analysis, selectivity-at-age was estimated for age classes 2 to 7, the selectivity-at-age value for age class 1 was set at 0.02 and the selectivity value for age class 2 was set at the value half way between 0.02 and selectivity at age class 3. In the second analysis, selectivity-at-age was estimated for age classes 1 to 7, and the selectivity-at-age value for age class 1 was set at half way between 0 and selectivity at age class 2. It is important to note that because of the assumption that the catch is taken at mid-year and the equations for exploitable biomass (E.3) are computed at mid-year, selectivity at a particular age is being estimated at mid-year of a particular age. In all the above analysis, where selectivity is being estimated the CPUE and catch-at-age data are weighted equally in the objective function (*i.e.* ϕ=1.0).

Non-parametric estimation of parameter uncertainty

The estimates of the coefficient of variation (C.V.) of the model parameter estimates are obtained using a non-parametric bootstrap procedure. The details of the bootstrapping procedure are presented in Appendix III, while a brief summary describing its implementation follows.

The bootstrap method (Efron 1981, 1982) assumes that the empirical probability distribution $\hat{F}$ is equal to the unknown distribution F for particular sample values. To calculate the variance of a statistic for the "base case" model, the model CPUE sequence was used as a basis for generating new CPUE values. A residual data set was first constructed from the differences between the observed *ln* CPUE values and the best model-predicted *ln* CPUE estimates obtained from the initial fitting procedure. A new sequence of residuals is obtained by randomly selecting residuals from the original residual set with replacement. The new sequence of residuals is then added to the original best model-predicted CPUE estimates to obtain a new set of "pseudo" observed CPUE data. The model was then fitted to this new CPUE sequence and the process was repeated a number of times. Each bootstrap procedure yielded an associated set of parameter estimates. Referred to as "bootstrap samples", these estimates constitute a randomly constructed hypothetical sampling distribution, from which the variance of the various parameters and variances of management quantities such as MSY and B_{MSY} estimates can be estimated.

The chief measurement of precision used for comparison of the various applications of the model is the coefficient of variation (C.V.), defined as the sample standard deviation (S) expressed as a percentage of the sample mean ($\overline{Y}$):

$$C.V. = S/\overline{Y} \times 100 \qquad (E. 23)$$

Variance estimation for this approach is extremely computer time intensive (Butterworth and Punt 1992), so that it was only possible in the time available to provide C.V. estimates for the "base case" implementation. However, an attempt was made (in one case) to obtain variance estimates of the estimated selectivity-at-age values obtained from the model. The model which estimates selectivity-at-age for ages 1 to 7 and assumes a Beverton-Holt stock-recruitment relationship was used. In this model, where both the CPUE and the catch-at-age data are used in the objective function, the residuals of the CPUE fit are used to obtain "pseudo" observed CPUE data and the residuals obtained from the differences between the observed *ln* catch-at-age values and the best model-predicted *ln* catch-at-age estimates obtained from the initial fitting procedure are used to obtain a new catch-at-age data matrix. The model was then fitted to this "pseudo" observed CPUE sequence and new catch-at-age matrix and the process was repeated a number of times.

RESULTS

"Base case" models and sensitivity tests

Figure 2 shows actual and model-predicted CPUE time series for the "base case" age-structured production model assessments for the Ricker (Model 1) and Beverton-Holt (Model 2) stock-recruitment relationship models. The fits of the model in both cases are slightly mis-specified. Plots showing the exploitable biomass series for each "base case" assessment are provided in Figure 3 (the absolute biomass values are very similar to the exploitable biomass values). The exploitable biomass estimates obtained from the "base case" model assuming a Ricker stock-recruitment relationship are smaller than that obtained assuming a Beverton-Holt stock-recruitment relationship for the time range considered.

The results of the applications of different variations of the assessment method are presented in a common format. Two tables (one for each assumed stock-recruitment relationship) containing the estimates of 8 management quantities and their bootstrap C.V.s are given for the different applications of the method. The values of the estimated parameters (α, β and q) and their associated C.V.s are also included. The 8 management quantities are:

a) MSY	the maximum sustainable yield,
b) B_{MSY}	the absolute biomass, not selectivity weighted, at the MSY,
c) B^E_{90}	the exploitable, selectivity weighted, biomass in the middle of 1990,
d) K^E	the unexploited, but selectivity weighted, equilibrium biomass,
e) B^E_{90}/K^E	the exploitable, selectivity weighted, biomass in the middle of 1990 as a fraction of the corresponding unexploited, but selectivity weighted, equilibrium biomass,
f) B_{90}	the absolute estimated, not selectivity weighted, biomass in the middle of 1990,
g) K	the absolute, not selectivity weighted, unexploited equilibrium biomass,
h) B_{90}/K	the estimated absolute biomass, not selectivity weighted, in the middle of

1990 as a fraction of the corresponding unexploited, not selectivity weighted, equilibrium biomass.

The results of the two "base case" assessments are shown in Table 7 and the results of the sensitivity analyses for the two "base case" models are summarized in Table 8. The estimates of four of the management quantities are shown [MSY, B_{MSY} , $B^E{}_{90}$ and $B^E{}_{90}/K^E$]. In addition, model estimates for catch-at-age are shown in Table 9.

Incorporating catch-at-age information ("base case" selectivity assumption)

Table 10 presents the estimates of MSY, B_{MSY}, $B^E{}_{90}$ and $B^E{}_{90}/K^E$ for each of the applications incorporating catch-at-age data. For each application a different weight was assigned to the catch-at-age data in the sum of squares function (see Equation E.22). The results are presented for both the Ricker and Beverton-Holt forms of the model. The model catch-at-age data are shown in Table 11 (for ϕ=1.0) and these can be compared with the observed catch-at-age data (see Table 3). The residuals of the fit of the model catch-at-age to the observed catch-at-age data are shown in Table 12 (for ϕ=1.0). The exploitable biomass trajectories are shown in Figure 4. Results are shown for the "base case" and variants (ϕ = 0.001, 0.01, 0.1, 1.0 and 2) which utilize catch-at-age data when estimating the model parameters. As the weight assigned to the catch-at-age data is increased from ϕ=0.001 to ϕ=2 or 4, the expected quality of the fit of the model to the CPUE data deteriorates (Figure 5, for ϕ=1.0).

Incorporating catch-at-age information and estimating selectivity-at-age

In the first analysis in which selectivity-at-age was estimated (for age classes 2 to 7) the selectivity-at-age value for age class 1 was set at 0.02 and the selectivity value for age class 2, was set at half way between 0.02 and the estimated selectivity for age class 3. In all these analyses the weight factor assigned to the catch-at-age data in the objective function was the same (*i.e.* ϕ = 1.0). The results are presented in Table 13. In both cases (Ricker and Beverton-Holt) the estimates of the absolute biomass of the resource, B_{90} and K are larger than the estimates of the exploitable biomass, $B^E{}_{90}$ and K^E (Figure 6). In the case of the Beverton-Holt results they are 2 to 3 times larger. The estimates of selectivity-at-age are shown in Figure 7. The model-predicted and observed CPUE time series are shown in Figure 8. The model catch-at-age data are shown in Table 14 (note $\o=1.0$) and these can be compared with the observed catch-at-age data (see Table 3). The residuals of the fit of the model catch-at-age to the observed catch-at-age data are shown in Table 15 (note $\o=1.0$).

In the next set of analyses, selectivity-at-age was estimated for age classes 1 to 7 - the selectivity-at-age value for age class 1 was set at half way between 0 and the estimated value of selectivity at age class 2. The results for the second analyses are presented in Table 16. As for the first analysis, in both cases (Ricker and Beverton-Holt) the estimates of B_{90} and K are larger than the estimates of $B^E{}_{90}$ and K^E, respectively. Again this is shown clearly in the biomass trajectories showing exploitable biomass and absolute biomass of the resource in Figure 9. The estimated selectivity-at-age values are shown in Figure 10 and the model-predicted and observed CPUE time series are shown in Figure 11. The model catch-at-age data are shown in Table 17 (note $\o=1.0$) and these can be compared with the observed catch-at-age data (see Table 3). The residuals of the fit of the model catch-at-age to the observed catch-at-age data are shown in Table 18 (note $\o=1.0$).

Additional tests of the sensitivity of the estimated selectivity-at-age values to the value of M and the weighting factor ($\o$) were carried out. In all the assessments where selectivity was estimated, the assumption was made that $M=0.3\ yr^{-1}$ and $\o=1.0$. The model chosen was the Ricker form where the selectivity-at-age was estimated for age classes 1 to 7. In the first trial the assumption was made that $M=0.5\ yr^{-1}$ and in the second trial M was set equal to $0.5\ yr^{-1}$ but the weighting factor ($\o$) was varied. Figure 12 and 13 show the estimated selectivity-at-age values for these two trials, respectively.

Since it was obvious from the initial results of fitting selectivity-at-age (Figures 7 and 10) that selectivity decreases for older ages a selectivity-at-age function which allows for this behaviour was used to do a re-assessment of the analysis where the catch-at-age data in the objective function were assigned different weights. The parameters of this new function and the selectivity function are given in Appendix II (Equation A.2.2) and Figure 14 (Function 2). The results are shown in Table 20. The aim was to compare these results with those in Table 10, where the selectivity-at-age relationship has a slope of zero at older age classes (see Figure 14, Function 1).

DISCUSSION

"Base case" models

Examination of the residual pattern for the age-structured production model (CPUE data only/selectivity is given) reveals that biases are evident in both Model 1 (Ricker) and Model 2 (Beverton-Holt) (see Figure 2). There are non-random runs of negative residuals in the early 1970's, followed by positive residuals in the early 1980s. It is possible that this is due to biases in the CPUE data rather than in the model.

One assumption of production models which, if incorrect, can lead to markedly different results is that of constant (time-invariant) catchability. The effects of improving technology can lead to increase in the catchability coefficient, however this may be balanced by an increase in the targeting of other species (Payne and Punt 1992). For example, post-1985 increases in CPUE could be due to changes in fishing strategy rather than increases in the resource biomass or a combination of the two. The demersal fishery which in the past targeted hake has become a more mixed fishery. With a recovery in the resource, it is postulated that vessels have recently been able to concentrate more on other species without prejudicing their ability to reach their hake quotas (C.A.R. Bross, pers comm., quoted in Punt, 1993). However, assuming that the pre-and post-1985 CPUE data are not comparable does not remove the model mis-specification. Payne and Punt (1992) suggest that further consideration should be given to the method of defining hake-directed effort. The catch trends show that hake have become a smaller proportion of the demersal catch (from 80% in 1986 to 60% in 1991). This will affect the measurement of effort, as only hake-directed effort should be considered. Incorrect measurement of effort could lead to a decrease in the catchability coefficient which is the reverse of the effect of improving events in technology which would tend to result in an increase in the catchability coefficient.

The biomass trends for the hake stock for Model 1 (Ricker) and Model 2 (Beverton-Holt S-R) of the "base case" model are similar, although the absolute levels differ (see Figure 3). Both exhibit severe depletion during the late 1960's and early 1970's, followed by a subsequent slow but steady recovery. The estimated unexploited biomass obtained from the "base case" model assuming a Ricker stock-recruitment relationship is less than that obtained assuming a Beverton-Holt stock-recruitment relationship. This results in there being differences between the two variations of the "base case" models for the estimated level to which the biomass was depleted in 1990 (0.41K for Model 1 and 0.35K for Model 2), as well as for the "current" biomass level (1990) (see Table 7).

In both cases (Models 1 and 2) the estimates of current biomass (B_{90}) and biomass at MSY (B_{MSY}) assess the stock to be below the MSY level and therefore still biologically overexploited. The estimates for MSY and B_{MSY} obtained from Model 2 (Beverton-Holt) are very similar to the results obtained by Punt (1993) for his age-structured production model. This is not surprising as Punt (1993) used the same approach and a Beverton-Holt stock-recruitment relationship (see Tables 4 and 7). The estimate of B_{MSY} obtained from Model 1 (Ricker) is very similar to that obtained by Punt (1993) in his age-structured model, however the estimate of MSY is greater. The estimate of MSY from Model 1 (Ricker) is very close to estimate of MSY obtained for the surplus-production model method used by Punt (1993) (see Table 1 and 7). Of the quantities estimated, the MSY estimates are determined with the greatest precision (C.V.s <2%). Generally the results from the model which assumes a Beverton-Holt stock-recruitment relationship has lower C.V. values for all the estimated parameters.

As far as the sensitivity tests are concerned, a change in an estimate greater than 5 percent was assumed to be significant (see Table 8 for both variations of the "base case" model). As expected, the consequences for the assessment of changing the value used for natural mortality (M) is minimal, although significant decreases in the estimates of B_{MSY} were obtained when M was changed from 0.3 yr^{-1} to 0.5 yr^{-1}. The results obtained from assuming an age-specific mortality function are also very similar to the "base case" assessments. As far as the selectivity function is concerned significant increases in the estimates of B_{MSY} and B^{E}_{90} were obtained in both models when the age-at-50%-selectivity was made equal to 1year instead of 2year. The model which is based on the Beverton-Holt stock-recruitment relationship was significantly sensitive (in terms of increases in B_{MSY} and $B^E{}_{90}$) to the age of maturity (especially when age of maturity was 5 yrs instead of 4 yrs).

Model estimates of catch-at-age (see Table 9) can be compared to the observed catch-at-age data (see Table 3). Even though the total model catch in one year is forced to be close to total observed catch, the model does reproduce some of the observed catch-at-age trends *i.e.*, the highest numbers caught are in age class 2 with progressively less individuals being caught in the older age classes. However, the model does not seem to capture the large decreases in observed numbers of individuals caught as one moves towards older age classes (as shown by the catch-at-age data in Table 3). As mentioned previously, a conflict exists between the observed catch-at-age and the CPUE (or production model based on CPUE) and this is the main reason for exploring the possibility of decreasing selectivity at older age classes in the study, as it may explain the reason for the low numbers of fish in the older age classes.

The incorporation of catch-at-age information

As mentioned above, the VPA and surplus production currently applied to data for the Cape hake stocks off South Africa provide different estimates of the status and productivity of these stocks. The two estimation procedures are essentially different in that the one is a production model-based assessment techniques which utilizes CPUE data, and the other is a catch-at-age-based assessment technique. In this assessment both CPUE data and catch-at-age data were incorporated into the age-structured production model and the weighting factor was varied. Table 10 presents the estimates of MSY, $B_{MSY,}$ $B^E{}_{90}$ and $B^E{}_{90}/K^E$ for each of these applications. The results are presented for the two variations of the model considered - the Ricker and Beverton-Holt stock-recruitment relationships. As the weight assigned to the catch-at-age data is increased from $\phi=0.001$ to $\phi=2$ or 4, the quality of the model fit to the CPUE data deteriorates (see Figure 5, for $\phi=1.0$) as expected. Correspondingly, there is a reduction in the catch-at-age residuals as the weight assigned to the catch-at-age data is increased from $\phi=0.001$

to ø=2 or 4 (see Table 12). The model catch-at-age data shown in Table 11, (for ø=1.0) should be compared with the observed catch-at-age data in Table 3.

It is clear from Table 10 that it is possible for the estimator to select either of the " production model" or "VPA" scenarios depending on the weight placed on the catch-at-age data (Punt 1993). The biomass trajectories for all these applications are quite similar over the pre-1970 period, but diverge thereafter (see Figure 4). These results are similar to the results obtained by Punt (1993), who concludes that there is a basic conflict between the catch-at-age and the CPUE data and that the estimation methods themselves are not necessarily flawed. Punt (1993) believes that further research be directed at refining the available data and checking the validity of the assumptions made in the assessments. Punt (1993) suggests that it is possible that one of the data types used in the assessments may not be indexing the population trends in the way assumed. Punt and Payne (1992) have suggested that there should be a re-evaluation of vessels power factors used to calculate CPUE. This analysis is currently being undertaken. Punt (1993) also suggests they may be problems with the catch-at-age data, citing ageing errors, and otolith sampling errors. However in this report, the possibility of resolving some of the conflicts between the catch-at-age data and the surplus production estimates, by considering that selectivity decreases with age at older age classes is examined in detail.

The estimation of selectivity-at-age

The possibility of an age-specific selectivity function whose slope is negative for older age classes was examined by making selectivity-at-age a fitted parameter in the regression. The resultant selectivity-at-age estimates are shown in Figure 7 (selectivity-at-age for age classes 2 to 7 was estimated). Beyond age 2 or 3 (Beverton-Holt of Ricker forms, respectively), the results indicate that selectivity-at-age for older age classes decreases, *i.e.* older fish are not being caught by the trawl fishery. In both cases (Ricker and Beverton-Holt) the estimates of B_{90} and K are far larger than the estimates of B^E_{90} and K^E (see Table 13). This is clearly shown in the biomass trajectories of exploitable biomass and absolute biomass of the resource in Figure 6. The exploitable biomass is the biomass which is available to the fishery under the selectivity pattern of the fishery and is comparable to the estimates of biomass from the surplus production methods. One of the S_a must be fixed, otherwise the product S_aF_y is not uniquely determined. The model included a condition that did allow the F_y values to get unrealistically high, so the resulting S values still range between 0 and 1, even though one of the S_a was not set. There may therefore be some error in the estimates of exploitable biomass and they should not be taken as exact. The important point is that some of the results indicate that there may be a larger absolute biomass of fish. This may have implications in terms of the risk of the spawning biomass dropping below certain threshold levels, although this would require a detailed numerical study. This larger absolute biomass of fish may sustain the recruitment to the trawl fishery during periods when the exploitable biomass is low. In the recently banned longline fishery the selectivity of the fishery resulted in the capture of large hake and concern was expressed that the removal of the previously unexploited spawning stock of large fish was likely to have a detrimental impact on recruitment to both the trawl and longline fisheries (Anon 1993).

The selectivity estimates obtained in this analysis are qualitatively similar to selectivity-at-age estimates for the trawl fishery reported by Armstrong and Japp (1992). In their analysis the selectivity-at-age was computed by comparing commercial catch-at-age data with survey estimates of the numbers-at-age. The ratio between these estimates are the estimates of the fishing mortality-at-age in each year. A selectivity curve can then be obtained by expressing each value of fishing mortality-at-age as a fraction of the maximum value (see Figure 15). Their results indicated that the hake become most vulnerable to trawling at about 3-5 years, which is different to the 2-3 year range suggested in this study. However, both studies the function for selectivity-at-age is domed-shaped. Armstrong and Japp (1992) postulate that the decrease in selectivity at older age classes is probably caused by the movement of large hake out of the commercial fishing grounds.

There are actually a few possible reasons why the older fish are not been captured by the fishery: i) the larger fish may be migrating offshore and not be available to the fishery or the larger fish may also be moving on to "rough ground" which may be a more favourable habitat (these areas may be optimal habitats for hake in general, with the larger, older fish taking the prime niche and excluding the smaller individuals), and/or ii) the fishery may be targeting particular size classes (*e.g.* for market reasons) by fishing at certain depths, and/or iii) there may be net avoidance. The survey catches are assumed to be more representative of the stock than the commercial data, because the surveys are conducted in a random pattern over the entire range of the resource. Therefore it is possible that ii) is the most likely reason for the discrepancies between the data. However i) and iii) remain a distinct possibility. In order to consider the above hypotheses it is important to consider the theory behind fishing selectivity in more detail and the evidence that exists.

Fishing selectivity

In the widest sense, selectivity can be considered as any factor that causes the size composition of the catch to be different from the population (Pope *et al.* 1975). Such differences can arise from differences in the area or time fished, differences in the probability of fish of different sizes encountering the net, and differences in the probability of fish of different sizes being retained by the gear, once they have encountered it. So it is important at this point when considering selectivity-at-age to distinguish between vulnerability and availability (Parrish 1957, quoted in Fujiishi 1980).

a) Vulnerability

Vulnerability relates to the selectivity of the net. Mesh selectivity experiments have been important as, for example, on both sides of the North Atlantic the main method of conservation of fish stocks has been by regulation of the mesh size of trawls (Gulland 1964). Various mesh selection experiments have been performed on hake species (*e.g.* Gulland 1955; Jensen and Hennemuth 1966; Cardador and Borges 1991), including experiments on the Cape hake. Extensive experiments were undertaken during the late 1960s and early 1970s to determine the optimal mesh size to regulate the Cape hake fishery (see van Eck *et al.* 1968; Bohl *et al.* 1971). Research was also conducted on the changes in yield with changes in mesh size (*e.g.* Ikeda, 1974, Newman 1974, Andrew and Butterworth 1988). At that time it was thought that the mesh size being used would lead to overexploitation and the mesh size was subsequently increased to 110mm. It is often assumed that as the length of fish increases, the selectivity increases until, above a certain size, retention is "complete" (van Eck *et al.* 1968). However, net avoidance or escapement by larger, older fish is important in certain species. Larger fish may be more wary or more active and thus be more likely to move out of the path of the trawl before it reaches them. Thus avoidance of the net by large fish will tend to make older fish less vulnerable and therefore cause a decrease in the selectivity of fish at older age classes, therefore retention will not necessarily be "complete" for large fish. The possibility of escapement of large fish has been considered, however most of the studies have focused on the ogive in the region of younger age classes, since it is the escapement of smaller, younger fish which is the reason for having mesh size regulation and conducting mesh size experiments in the first place (MacLennan, 1992). Interestingly, the viability of mesh regulation as a management tool in the hake fishery is open to conjecture owing to apparently low survival rates of hake passing through the meshes of trawl nets (R. Leslie, pers comm., quoted in Andrew 1984).

b) Availability

When considering selectivity in terms of availability, one needs to consider that the older fish may not be available to be selected by the fishing gear because they may, for example, be migrating offshore, or there is the possibility that the fishery is targeting particular size classes (*e.g.* for market reasons) by fishing at certain depths where these size classes occur. If the older fish are going into deeper water, there is an effective emigration of older animals to water beyond the fishing area. One of the assumptions made in the stock assessments is that fishing effort and/or the stock is homogeneously distributed across the range of the resource. It is important to consider the implications of these two factors in terms of the effects on fishing selectivity.

i) Distribution of fishing effort

It is known that fishing effort for hake is definitely not homogeneously distributed across the range. The effort is focused on certain areas (Figure 16). The trawlers cannot operate on "rough ground" because of the potential damage to and loss of trawl gear. Even within the trawl grounds commercial vessels do not sample the area randomly; instead they use acoustic techniques to locate hake aggregations. Trawling is done by bottom gear (otter trawls mostly) and, because of the nature of the gear, trawlers are restricted to soft substrata. Large areas of the South African coast are inaccessible to the trawl fleet, especially on the shelf margins and in areas where coral is prevalent on the South and East coasts. Although bobbins are not outlawed, they are seldom used as good skippers can target on hard grounds by flying gear over very rough patches or by fishing lightly (Anon 1993). Trawling is done mostly in daylight with three to four trawls per day of between 2-4 hours each. Fishing is weather dependent and is also determined by species-abundance and size category market requirements. Bottom trawling is not selective, although skippers can target to a certain extent on a particular size category of hake (Anon 1993). Another factor which may also not be randomly distributed (as is commonly assumed) is the distribution of the fish stock.

ii) *The distribution of the fish stock*

The stock is also not homogeneously distributed across its range - differences occur between the two species and within the species - the larger fish tending to be found in deeper water in the case of both species (MacPherson and Duarte 1991). The distribution of each species is depth-dependent; *M. paradoxus* occurs in deep water while *M. capensis* is a shallow water species. The distribution areas of the two species overlap in intermediate waters where small *M. paradoxus* occur together with medium to large *M. capensis* individuals (Botha 1973). Gordoa and Duarte (1991) showed that hake abundance data collected along the Namibian coast showed strongly aggregated (non-random) spatial distributions. Average fish size was shown to increase with depth. They also suggested that the formation of hake aggregations is size dependent. Gordoa and Durate (1991) postulated that this will have implications in terms of fishing mortality - fishing pressure targeting aggregates of small hake (*i.e.* shallow shoals) will have a disproportionate effect on fishing mortality and recruitment compared with similar fishing pressure targeting aggregates off larger hake (*i.e.* deep shoals). Therefore by fishing at a particular depth (maybe because the catch rates are highest or they are targeting particular size classes for market reasons) the fishery is selecting for a particular size of fish and species. Botha (1980) found that on the west coast the major fishing effort is centered on the juvenile *M. paradoxus* population inducing a substantial fishing mortality on it.

The distribution of *M. paradoxus* extends offshore to depths of at least 800m, although little commercial activity takes place deeper than 500m (Payne 1989). Botha (1985) collected data that showed that between 1955 and 1974 more than 80 per cent of the commercial catches were made in the depth range 230-549m. Most of the fish which have been caught in deeper water measured 50-70 cm long and were virtually all female, mostly in post-spawning stages. It also appears that the *M. paradoxus* stock extends substantially deeper than do survey biomass cruises (Payne *et al.* 1988). Payne *et al.* (1988) postulated from this information that there is a "pool" of hake able to spawn seaward of the commercial fishing grounds, this they believe, is a reason for confidence in the fishery's future. Therefore the commercial effort is concentrated in areas where CPUE is the greatest (normally in 200-300m of water) and the catch size structure is dictated by depth related size patterns (where predominately small *M. paradoxus* and large *M. capensis* can be found). However, not only is the average distribution of the fish stock important, but so are possible movements of the stock could have an effect on fishing selectivity in terms of availability.

Effects of possible horizontal and observed vertical hake migrations on fishing selectivity

Although, Roux (1949) was convinced that there was some form of annual horizontal hake migration, such conclusions were drawn on the basis of the incorrect premise that only one species existed. There is a tendency for hake to move offshore into deeper water as they grow older (Payne *et al.* 1989), but apart from that, there is no firm proof of extensive horizontal migration (Botha 1973). Botha (1973) however only sampled along a single line of stations. There is some evidence of seasonal offshore-onshore migration, especially for *M. paradoxus* (Dave Japp, pers comm.)

Not only is horizontal distribution by depth important but there may be some vertical structure to the stock. Hake are known to rise in the water column to spawn (Botha 1980) and this will only involve the older mature fish. The commercial trawl nets only sample an area 2 to 3 metres off the bottom. It is possible therefore that there are larger fish which are spawning in midwater which are not being captured by the fishery, as suggested by the fact that both survey and commercial gear catch very few spawning fish.

Model specification

Although no quantitative analysis was performed, the conflict between the CPUE and the catch-at-age data can be basically resolved. If selectivity is assumed to decrease at older age classes the model is able to fit the model CPUE reasonably well (see Figure 8) and still produce model catch-at-age data which are closer to the observed than those of the "base case" assessments (compare Tables 14 and 3 and the residuals in Table 15).

Selectivity-at-age was also estimated for age classes 1 to 7 (see Figure 10) (previously age class 1 was set at 0.02). For age classes greater than 2 to 3 years the estimated selectivity-at-age decreases for older ages. As for the previous analysis, in the estimates of B_{90} and K are larger than the estimates of B^E_{90} and K^E, (see Table 16 or Figure 9). The model is also able to fit the model CPUE reasonably well (see Figure 11) and still produce model catch-at-age data which are closer to the observed than those of the "base case" assessments (compare Tables 17 and 3 and the residuals in Table 18). Again, the conflict between the CPUE and catch-at-age data is also partly resolved in this case.

An attempt was also made to consider the sensitivity of the estimated selectivity-at-age values to the value of natural mortality and the weighting factor. In all the above assessments, $M=0.3\ yr^{-1}$ and $\o=1.0$. The model chosen to test the sensitivity of the assessment to these assumptions was the Ricker form where the selectivity-at-age was estimated for age classes 1 to 7. In the first trial the assumption was made that $M=0.5\ yr^{-1}$ and in the second trial M was still assumed to be equal to $0.5\ yr^{-1}$ but the weighting factor was varied. Figure 12 and 13 show the estimated selectivity-at-age values for the two trials, respectively. As M is increased from M=0.3 yr^{-1} to M=0.5 yr^{-1} the selectivity at older ages increases, as was expected. The estimated values are more sensitive to M than the weighting factor.

Temporal changes in fishing selectivity

Interpretations are rendered more complex by the possibility of a change in the age-specific selectivity pattern over recent years, with selectivity increasing for younger fish. The selectivity function is assumed in this study to be time invariant. It is possible that this function has changed over time, but no other options are practical because paucity of data on the selectivity of trawl gear changes over time, precludes the estimation of the extra parameters that would be required to reflect changes over time. Butterworth *et al.* (1986a) found that there had been an increase in the number of young fish caught for the most recent years. They attributed this to the possibility of increased recruitment and/or the possibility that a change in the fishing strategy had occurred over time. They postulated that the trawlers were operating in shallower waters recently (which younger hake inhabit) and that if younger fish were easier to catch the changes observed in CPUE may be unrelated to changes in stock abundance. The CPUE would then prove to be an unreliable index of stock abundance changes (if younger fish are more available the net result would be an effective increase in the catchability coefficient) (Butterworth *et al.* 1986a). Hence the increasing trends in CPUE observed would reflect increasing catchability rather than increasing stock sizes. This would explain why the CPUE and catch-at-age data show contradictory trends. Butterworth *et al.* (1986a) included a time dependent selectivity function into their VPA assessments of the Cape hake stock. For Division 1.6 their fitting procedure allocates unrealistically large fishing mortality values to the older age classes in the most recent year. Their selectivity function is time-dependent, but assumes that at older age classes selectivity has a slope of zero (they do not allow for a dome-shaped selectivity function). The results presented by Butterworth *et al.* (1986a) are probably an indication that their selectivity-at-age model is too simple for adequate representation of the data set and that a more appropriate model is needed. The results in this study indicate that a model assuming decreasing selectivity-at-age for older age classes may be the appropriate model.

It is possible that there has been a change in fishing strategy leading to increasing selectivity's for younger (and more readily-available) hake. This would have resulted in an effective increase in catchability, so that CPUE trends overestimate changes in resource biomass. However, there is an absence of independent information to quantify such hypothetical changes.

Model complexity

The more complex a model, that is the larger the number of parameters that have to be estimated, the more accurate the estimates will be (lower bias). However, the estimates will have lower precision (high variance). This higher variance is evident when one considers the C.V. estimates of the estimated selectivity-at-age values (see Table 19). The results for the trials where selectivity is being fitted should be interpreted with caution as more than three parameters are being fitted. The sensitivity of the model parameters to the starting values provided for the model-fitting process have not been adequately assessed (it is possible that the sum of squares surface is multi-modal in these cases and this could lead to imprecision). This method required the estimation of more than 6 parameters, one for each estimate of selectivity-at-age. Experience has shown that it becomes difficult to estimate more than three parameters reliably (Hilborn 1990). In most assessment techniques three parameters are estimated. The amount of contrast in the data determines how many parameters can be estimated (Hilborn 1979). The contrast is increased if the resource has been fished very hard at some times, and very little at times; and also if the spawning biomass has been low at some times and high at others (Hilborn 1990). The data contrast has in a sense been provided by the reversal of trends in the catch rates in the late 1970s. This would narrow the confidence limits in any assessment provided (e.g. see Andrew and Butterworth 1987). Instead of estimating selectivity-at-age by fitting each as a parameter to be estimated by the regression, the model could have been simplified by assuming that selectivity could be described by a known function involving only a small number of estimated parameters like the relationship described by Thompson and Bakkala (1990).

Further considerations

Because of the problems mentioned above with model complexity and the estimation of more than three parameters, a further assessment of the effect of decreasing selectivity-at-age was performed by including selectivity-at-age as an input function rather than estimating selectivity-at-age using the model (see Appendix II, Equation A.2.3)(Figure 14, Function 2). The new function however, assumes that selectivity-at-age decreases for older age classes. The results of this assessment are provided in Table 20. The aim was to see whether the results differ from those shown in Table 10 where the selectivity-at-age relationship has a slope of zero at older age classes (see Figure 14, Function 1). In both different weights are assigned to the catch-at-age data. The results in Table 20 differ depending on which assumed stock-recruitment relationship is used. For the case of the model where the assumed stock-recruitment relationship is the Ricker curve, the estimates do not show the same trend as in Table 10 where as more weight is assigned to the catch-at-age data the estimates of the current depletion decrease (the "VPA" scenario). As for the model which assumes a Beverton-Holt stock-recruitment relationship the results are similar to those in Table 10. It is still clear from Table 20 in the case of the assumed Beverton-Holt stock-recruitment relationship, that it is possible for the estimator to select either of the "production model" or "VPA" scenarios depending on the weight placed on the catch-at-age data. However, in the case of the model which assumes a Ricker stock-recruitment relationship this is not the case anymore.

These results indicate that the conflict between the catch-at-age information and the CPUE data can be partly resolved by making new assumptions about the selectivity-at-age, especially for the older age classes where selectivity was assumed to decrease. The conflict may be further resolved by additional research into methods which can obtain more reliable estimates for the CPUE and catch-at-age data. The CPUE data need to be revised by re-evaluating the vessels power factors. Only a crude analysis of power factors has ever been carried out. A revision of the CPUE is currently being undertaken and as soon as results are obtained a re-assessment of the status and productivity of the Cape hake stocks should be undertaken using the surplus production model assessment technique and the age-structured production model which utilizes

CPUE and catch-at-age data. However, the discrepancies will not be resolved if one of the data types (*e.g.* catch-at-age or survey biomass) used in the assessments is not indexing the population trends in the way that has been assumed in the assessment procedure. It is therefore imperative that the validity of the assumptions made in the assessments are substantiated. Even if more reliable estimates of CPUE and catch-at-age data are obtained it is not certain that the conflict will be resolved. However, the results in this study indicate that the conflict between the observed trends in the catch-at-age data and the estimates from the production model can be partly resolved by assuming that for older age classes selectivity-at-age decreases.

CONCLUSIONS

* Applications of an age-structured model in which both CPUE and catch-at-age data are included and which assumes selectivity increases with age, provides similar results to the surplus production model if more weight is given to the CPUE data than the catch-at-age data and, similar results to the *ad hoc* tuned VPA if more weight is given to the catch-at-age data rather than the CPUE data. This led Punt (1993) to conclude that the discrepancies between the various sets of results obtained from production model-based assessment techniques which utilize CPUE data and the catch-at-age-based assessment techniques are a consequence of a conflict between the catch-at-age information and the CPUE data and that they are not primarily a result of differences in the two methods themselves.

* The approaches above are based on certain assumptions regarding recruitment, natural mortality and selectivity patterns/behaviours. The approaches assume that selectivity at older age classes has a slope of zero. Therefore an attempt was made to obtain estimates of selectivity-at-age from the age-structured model which takes CPUE and catch-at-age information into account. Selectivity-at-age was found to decrease with age at older age classes.

* The results obtained indicate that the conflict between the catch-at-age data and the CPUE data can be basically resolved by making new assumptions about the selectivity-at-age *i.e.* by assuming that for the older age classes selectivity-at-age decreases.

* Punt (1993) believes that the discrepancy between the results from the two current assessment methods (VPA and surplus production model) will be further resolved by additional research into methods which can obtain more reliable estimates for the CPUE and catch-at-age data. However, the discrepancies will not be resolved if one of the data types (*e.g.* CPUE or survey biomass) used in the assessments is not indexing the population trends in the way assumed in the assessment procedure. It is therefore imperative that the validity of the assumptions made in the assessments are substantiated. Even if more reliable estimates of CPUE and catch-at-age data are obtained it is not certain that the conflict will be resolved. However, the results in this study indicate that the conflict between the observed trends in the catch-at-age data and the estimates from the production model can be partly resolved by assuming that for older age classes selectivity-at-age decreases.

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REFERENCES

Andrew, P.A. 1986. Dynamic catch-effort models for the southern African Hake populations. *Rep. Benguela Ecol. Progm. S. Afr.* 10: 248 pp.

Andrew, P.A. and Butterworth, D.S. 1987. Is $f_{0.1}$ an appropriate harvesting strategy for the Cape hakes? In: *The Benguela and Comparable Ecosystems.* Payne, A.I.L., Gulland, J.A. and K.H. Brink (Eds). *S. Afr. J. mar. Sci.* 5: 925-935.

Andrew, P.A. and Buterworth, D.S. 1988. An examination of the effect of changes in mesh size on the catchability coefficient (q) and the sustainable yield of the southern African Hake stocks. *Colln Scient. Pap. int. Commn SE. Atl. Fish.,* 15(1): 23-45.

Andrew, P.A., Butterworth, D.S.and Punt, A.E. 1989. Analysis of the Cape hake stock in Division 1.6 using an extension of the Butterworth-Andrew estimation procedure which takes biomass surveys into account. *Colln Scient. Pap. int. Commn SE. Atl. Fish.,* 16(1): 15-30.

Anon, 1993. Historical overview and scientific perspective on longlining in South Africa prepared by the Sea Fisheries Research Institute for the subcommittee of the SFAC on longlining for hake. Sea Fisheries Research Institute WG/02/93/D: H: 8.

Armstrong, M.A. and Japp, D.W. 1992. Longlining vs Otter trawling in the Hake fishery. Sea Fisheries Research Institute, WG/01/92/D:H:3, 11pp.

Beverton, R.J.H. and Holt, S.J. 1957. On the dynamics of exploited fish populations. *U.K. Min. Agric. Fish Invest. (Ser. 2)* 19: 533pp.

Bohl, H. Botha, L. and Van Eck, T.H. 1971. Selection of Cape hake (*Merluccius merluccius capensis* Cast and *Merluccius merluccius paradoxus* Franca) by bottom trawl codends. *J. Cons. perm. int. Explor. Mer.* 33(3): 438-470.

Botha, L. 1973. Migrations and spawning behaviour of the Cape hakes. *S. Afr. Shipp. News Fish. Ind. Rev.* 28(4): 62, 63, 65, 67.

Botha, L. 1980. The biology of the Cape Hakes *Merluccius capensis* Cast and *M. paradoxus* Franca in the Cape of Good Hope area. Ph.D. thesis, University of Stellenbosch: 182pp.

Botha, L. 1985. Occurence and distribution of Cape hakes *Merluccius capensis* Cast and *M. paradoxus* Franca in the Cape of Good Hope area. *S. Afr. J. mar. Sci.* 3: 179-190.

Botha, L. 1986. Reproduction, sex ratio and rate of natural mortality of Cape hakes *Merluccius capensis* Cast and *M. paradoxus* Franca in the Cape of Good Hope area. *S. Afr. J. mar. Sci.* 4: 23-35.

Butterworth, D.S. and Andrew, P.A. 1984. Dynamic catch-effort models for the hake stocks in ICSEAF divisions 1.3- 2.2. *Colln Scient. Pap. int Commn SE. Atl. Fish.,* 11(1): 29-58.

Butterworth, D.S. and Andrew, P.A. 1987. On the appropriateness of approaches used at ICSEAF to obtain TAC estimates from catch-effort data for the hake. *Colln Scient. Pap. int Commn SE Atl Fish.,* 14(1): 161-191.

Butterworth, D.S and Punt, A. E. 1992. A review of some aspects of the assessment of the western North Atlantic Bluefin tuna. *Colln Vol. Sci. Pap. ICCAT,* 39: 731-757.

Butterworth, D.S., Bergh, M.O., Andrew, P.A. 1986a. A Comparison of dynamic catch-effort model and VPA assessments for the hake stocks in ICSEAF divisions 1.3- 1.6. *ICSEAF, 1986, Colln Scient. Pap. int . Commn SE Atl. Fish.,* pages 131-165.

Butterworth, D.S., Bergh, M.O., Andrew, P.A. and Punt, A.E. 1986b. Some aspects of the management strategies for and the assessment of the hake stocks off southern Africa. *Colln Scient. Pap. int . Commn SE Atl. Fish.* 13(1): 167-193.

Butterworth, D.S., Hughes, G.S, and Strumpfer, F.S. 1990. VPA with *ad hoc* tuning: implementation for disaggregated fleet data, variance estimation, and application to the horse mackeral stock in ICSEAF Divisions 1.3 + 1.4 + 1.5. *S. Afr. J. mar. Sci.* 9: 327-357.

Butterworth, D.S., Punt, A.E., Bergh, M.O., and Borchers, D.L. 1992. Assessments and Management of South African marine resources during the period of the Benguela Ecology Programme: key lessons and future directions. In: *Benguela Trophic Functioning*. Payne, A.I.L.. Brink, K.H. Mann, K.H. and Hilborn, R. (Eds) . *S. Afr. J. mar. Sci.* 12: 989-1004.

Cardador, F and Borges, F. 1991. Bottom trawl mesh selection of Hake (*Merluccius merluccius* L.) and Horse Mackeral (*Trachurus trachurus* L.) in the Portuguese coast. *Bol. Inst. Nac. Invest. Pescas, Lisboa,* 16: 73-84.

Chalmers, D.S. 1976. Weight conversion factors, length/ weight relationships, and annual landings of the South Afircan trawl-caught fish. *Fish. Bull. S. Afr.* 8: 1-4.

Crawford, R.J.M., Shannon, L.V. and Pollock, D.E. 1987. The Benguela ecosystem 4. The major fish stocks and invertebrate resources. In: *Oceanography and Marine Biology. An Annual Review* 25. Barnes, M. (Ed.). Aberdeen; University Press: 353-505.

Deriso, R.B., Quinn II, T.J. and Neal, P.R. 1985. Catch-Age Analysis with Auxillary Information. *Can. J. Fish aquat. Sci.* 42: 815-824.

Efron, B. 1981. Non-parametric estimates of the standard error: The jacknife, the bootstrap and other methods. *Biometrika,* 68: 589-599.

Efron, B. 1982. *The Jacknife, the Bootstrap and Other Resampling Plans.* Society for Industrial and Applied Mathematics, Philadelphia. 92pp.

Fujiishi, A. 1980. Theoretical approaches to mesh selectivity of the trawl nets. *J. Shimonoseki U. Fish.,* 29(1): 1-90.

Gavaris, S. 1988. An adaptive framework for the estimation of population size. *Can. Alt. Fish. Sci. Adv. Fish Sci Adv. Comm. (CAFSAC). Res. Doc.* 88/29. 12pp.

Gordoa, A. and Duarte, C.M. 1991. Size-dependent spatial distribution of Hake *(merluccius capensis and Merluccius paradoxus)* in Namibian waters. *Can. J. fish. Aquat. Sci.,* 48: 2095-2099.

Gulland, J.A. 1955. On the selection of Hake and Whiting by the mesh of trawls. *J. cons perm. int. Explor. Mer.,* 21: 296-309.

Gulland, J.A. 1964. Variations in selection factors, and mesh differentials. *J. cons CIEM* 29(2): 158-165.

Hilborn, R. 1979. Comparison of fisheries control systems that utilize catch and effort data. *J. Fish. Res. Board Can.* 36: 1477-1489.

Hilborn, R. 1990. Estimating the parameters of full age-structured models from catch and abundance data. *Bull. Int. North Pac. Fish. Comm.,* 50: 207-213.

ICES 1988. Report of the workshop on methods of fish stock assessment, Reykjavik 6-12 July 1988. *ICES Document C.M. 1988/Assess: 26.* 117pp.

Ikeda, I. 1974. An effect of mesh size regulation on the catch of Cape Hake. *Colln Scient. Pap. int. Commn SE. Atl. Fish.,* 1: 200-208.

Jensen, A.C. and Hennemuth R.C. 1966. Size selection and retainment of Silver and Red Hake in the Nylon Codends of Trawl nets. *Res. Bull. int. Commn N.W. Allant. Fish.,* 3: 86-101.

Jones, B.W. and Van Eck, T.H. 1967. The Cape Hake: its biology and the fishery. *S. Afr. Shipp. News Fish. Ind. Rev.,* 22(11): 90-97.

Leslie, R.W. 1985. Hake assessments in Divisions 1.6 and 2.1+ 2.2. *Colln Scient. Pap. int Commn SE. Atl. Fish.,* 12(1): 107-117.

Lewy, P. 1988. Integrated Stochastic virtual population analysis estimates and their precision of the fishing mortalities and stock sizes for the North Sea Whiting stock. *J. Cons int. Explor. Mer.,* 44: 217-228.

MacLennan, D.N. 1992. Fishing gear selectivity: an overview. *Fisheries Research,* 13: 201-204.

MacPherson, E. and Duarte, C.M. 1991. Bathymetric trends in demersal fish size: is there a general relationship? *Mar. Ecol. Prog. Ser.,* 71: 103-112.

Newman, G. 1974. Changes in hake yield with increased mesh size. *Colln Scient. Pap. int Commn SE. Atl. Fish.,* 1: 212-219.

Payne, A.I.L. 1989. Cape Hakes. In: *Oceans of Life off Southern Africa.* Vlaeberg, Cape Town. pages 136-147, Payne, A.I.L. and R.J.M. Crawford (Eds).

Payne, A.I.L. and Punt, A.E. 1992. The biology, fishery and management of the Cape hakes *Merluccius capensis* and *M. paradoxus* off South Africa. In: *Hake: Fisheries, Products and Markets.* Alheit, J. and T. Pitcher (Eds).

Payne, A.I.L. Rose, B. and Leslie, R.W. 1987. Feeding of hake and a first attempt at determining their role trophic role in the South African west coast marine environment. In: *The Benguela and Comparable Ecosystems.* Payne, A.I.L., Gulland, J.A. and K.H. Brink (Eds). *S. Afr. J. mar. Sci.* 5: 471-501.

Payne, A.I.L., Leslie, R.W. and Augustyn, C.J. 1988. Revised Biomass indices for Cape hake and other demersal fish species in Division 1.6 and the result of the surveys made in 1987. *Colln Scient. Pap. int Commn SE. Atl. Fish.,* 15(2): 175-196.

Payne, A.I.L., Badenhorst, A., Augustyn, C.J. and Leslie, R.W. 1989. Biomass indices for Cape hake and other demersal fish species in South African waters in 1988 and earlier. *Colln Scient. Pap. int. Commn SE. Atl. Fish.,* 16(2): 25-62.

Pope, J.G. and Shepherd, J.G. 1985. A Comparison of the performance of various methods of tuning VPAs using effort data. *J. Con. int. Explor. Mer.,* 42: 129-151.

Pope, J.A., Margetts, A.R., Hamley, J.M. and Akyuz, E.F. 1975. Manual of methods for fish stock assessment. Part 3. Selectivity of fishing gear. *FAO Fish. Tech. Pap.* (41)Rev.1:46p.

Punt, A.E. 1988. Model Selection for the Dynamics of South African Hake Resources. M.Sc. Thesis. University of Cape Town, South Africa. *Rep. Benguela Ecol. Progm. S.Afr.* 15:[vii] + 395 pp.

Punt, A.E. 1990. Is $B_1 = K$ an appropriate assumption when applying an observation error production model estimator to catch-effort data. *S. Afr. J. mar. Sci.* 9: 249-259.

Punt, A.E. 1991. Management procedure for Cape Hake and Baleen Whale resources. Ph.D.. Thesis. University of Cape Town, South Africa. *Rep. Benguela Ecol. Progm. S.Afr.* 23:[viii] + 689 pp.

Punt. A.E. 1992. Selecting management methodologies for marine resources, with an illustration for southern African hake. In: *Benguela Trophic-Functioning.* Payne, A.I.L., Brink, K.H. Mann, K.H., and R. Hilborn (Eds). *S. Afr. J. mar. Sci.,* 12: 943-958.

Punt, A.E. 1993. Assessments of the stocks of Cape hake (*Merluccius* spp.) of South Africa. *S. Afri. J. mar Sci.* 13 (submitted).

Punt, A.E. and Butterworth, D.S. 1989. Application of an *ad hoc* tuned VPA assessment procedure to the Cape hake stocks in the ICSEAF Convention area. *Int. Comm. SE. Atl. Fish.* SAC/89/S.P./23: 24pp.

Punt, A.E. and Butterworth, D.S. 1991. On an approach for comparing the implications of alternative fish stock assessments, with implications to the stock of Cape Hake, *Merluccius* spp. off northern Namibia. *S. Afri. J. mar. Sci.* 10: 219-240.

Punt, A.E. and Leslie, R.W. 1991. Estimates of some biological parameters for the Cape hakes off the South African west coast. *S. Afri. J. mar. Sci.* 10: 271-284.

Ricker, W.E. 1954. Stock and recruitment. *J. Fish. Res. Board Can.* 11: 559-623.

Roux, E.R. 1949. Migrations of the Cape hake or stockfish (*Merluccius capensis* Cast) on the west coast of South Africa. *Trans. R. Soc. S. Afri.* 32(2): 217-231.

Stuttaford, M. (Ed.) 1993. *South African Fishing Industry Handbook and buyers guide.* 21st Edition. Marine Information Services (Pty) Ltd.

Thompson, G.G and Bakkala, R.G. 1990. Assessment of the Eastern Bearing Sea Pacific cod stock using a catch-at-age model and trawl survey data. *Bull. Int. North Pac. Fish. Comm.,* 50: 215-235.

Van Eck, T.H. 1969. The South African hake '*Merluccius capensis* ' or '*Merluccius paradoxus*'. *S. Afr. Shipp. News Fishg Ind. Rev.* 24(5): 95-97.

Van Eck, T.H., Botha, L. Von Brandt, A. and Bohl, H. 1968. The selectivity of synthetic fibre codends for the capture of South African hake. *S. Afr. Shipp. News Fishg Ind. Rev.* 23(1): 124-135.

APPENDICES

APPENDIX I : THE AGE-STRUCTURED PRODUCTION-MODEL

The resource dynamics are modelled by the following Equation:

$$N_{y+1,a+1} = N_{y,a}\, e^{-(M_a + S_a F_y)} \qquad (A.1.1)$$

where $N_{y,a}$ is the number of fish of age a at the start of year y,

M_a is the rate of natural mortality on the fish of age class a,

S_a is the age-specific selectivity function,

F_y is the year effect for the fishing mortality in year y.

The maximum number of age classes considered was 10. Age class a=1 are all the fish from age 0 to 1. So for example for fish four years old, a = 5.

In order to reduce the number of model parameters which need to be estimated from the data the following assumptions are made:

a) For the "base case" models selectivity-at-age (S_a) is input instead of being estimated.

b) The resource was at the deterministic equilibrium that corresponds to an absence of harvesting at the start of 1917.

c) The strength of the 1-year-class is deterministically related to spawner stock biomass by either the Ricker (A) or Beverton-Holt (B) stock-recruitment relationship.

A: Model 1 The Ricker stock-recruitment relationship:

$$N_{y,1} = \alpha \ SB_y e^{-\beta \ SB_y} \qquad \text{(A.1.2)}$$

$$SB_y = \sum_{a=m}^{Max} W_a N_{y,a} \qquad \text{(A.1.3)}$$

where	SB_y	is the spawning biomass at the beginning of the year,
	W_a	is the mass-at-age for a fish aged exactly a-1
	α, β	are the stock-recruitment relationship parameters.
	m	is the age at sexual maturity. In this model all fish greater than four years old are sexually mature.

B: Model 2 The Beverton-Holt stock-recruitment relationship:

$$N_{y,1} = (\alpha \ SB_y) \ / \ (\beta + SB_y) \qquad \text{(A.1.4)}$$

$$SB_y = \sum_{a=m}^{Max} W_a N_{y,a} \qquad \text{(A.1.5)}$$

where	SB_y	is the spawning biomass at the beginning of the year y,
	W_a	is the mass-at-age for a fish aged exactly a-1
	α, β	are the stock-recruitment relationship parameters.
	m	is the age at sexual maturity. In this model all fish greater than four years old are assumed to be fecund.

d) The annual harvest, C_y , is given by:

$$C_y = \sum_{a=1}^{Max} W_{a-0.5}\, S_a\, F_y\; N_{y,a}\, (1- e^{-(M_a + S_a F_y)}) / (M_a + S_a F_y) \qquad (A.1.6)$$

where C_y is the catch-by-mass in year y and

$W_{a-0.5}$ is the mass-at-age for a fish of age a-0.5

The objective function which is minimized to estimate the model parameters is:

$$SS = \sum_{y=1955}^{1990} [\ln(C/E_y(mod)) - \ln(C/E_y(obs))]^2 \qquad (A.1.7)$$

where $C/E_y(obs)$ is the observed CPUE for year y and,

$C/E_y(mod)$ is the model predicted CPUE for year y, and

$$C/E_y(mod) = qB^E{}_y \qquad (A.1.8)$$

where q is the catchability coefficient and is estimated by the model along with α and β - the parameters in the stock-recruitment relationship and,

$B^E{}_y$ is the exploitable biomass for year y:

$$B^E{}_y = \sum_{a=1}^{Max} N_{y,a}\, W_{a-0.5}\, S_a e^{-((M_a + S_a F_y)/2)} \qquad (A.1.9)$$

for the "base case" models, and the function minimized to estimate the model parameters is:

$$SS = \sum_{y=1955}^{1990} [\ln(C/E_y(mod)) - \ln(C/E_y(obs))]^2 + \phi \sum_{y=1978}^{1990} \sum_{a=2}^{7} [\ln(C_{y,a}(obs)/C_{y,a}(mod))]^2 \quad (A.1.10)$$

for the models where catch-at-age data are included in the objective function,

where $C_{y,a}(obs)$ is the observed catch-at-age for age class a and year y,

$C_{y,a}(mod)$ is the model predicted catch-at-age for age class a and year y, computed using Equation (A.1.6) above.

APPENDIX II : INPUT FUNCTIONS AND PARAMETER ESTIMATION

(i) Selectivity-at-age

The selectivity function used in the "base case" model is a logistic curve which is assumed to be time invariant. Paucity of data on the selectivity of trawl gear changes over time preclude estimation of the extra parameters that would be required to reflect changes over time. The model used is:

$$S_a = 1/(1+ e^{((-a - A_c)/\delta)}) \qquad \text{(A.2.1)}$$

where S_a is the selectivity of the trawl gear on fish of age a,

A_c is the age-at-50%-selectivity,

δ is a "steepness" parameter for the selectivity curve.

The values A_c = 2yr and δ = 0.5 yr^{-1} used for the "base case" model are based on an analysis by Punt (1991)(see Figure 14, Function 1). However to investigate the effect of decreasing selectivity-at-age for older fish the selectivity function was used

$$S_a = 1/(1+ e^{((-a - A_c)/\delta)}) \qquad \text{for } a<a_m$$

$$S_a = e^{(-\psi(a-a_m))} \qquad \text{for } a>\text{or} = a_m \qquad \text{(A.2.2)}$$

where a_m is the age at which selectivity reaches its maximum value - after this age selectivity-at-age decreases and,

ψ is the exponentially decreasing selectivity coefficient at older ages.

The values for the parameters ψ and a_m were chosen to be 0.1 and 5yr, respectively (see Figure 14, Function 2)

(ii) Mass-at-age

The relationship between mass and age is calculated from the following function:

$$W_a = A\,(Ly(1-e^{-KP(a-TN)}))^{b} \qquad \text{(A.2.3)}$$

(*i.e.* a Von Bertalanffy age-length relationship imbedded in a standard mass-length relationship)

where W_a is the mass-at-age for a fish aged exactly a-1,

Ly is the asymptotic length of fish in cm,

KP is the rate at which length approaches Ly (the growth rate parameter and,

TN is the age at zero growth

A = 0.0055
Ly = 230.3
b = 3.084
KP = 0.046
TN = -0.825

The values for the parameters related to growth and mass-at-length were selected on the basis of the results of Punt and Leslie (1991). Punt and Leslie (1991) found that the difference between the two species for both maturation and growth is not particularly marked and that it is justifiable to use one set of growth/maturity parameter values when performing assessments.

(iii) Mortality-at-age

For most estimation procedures mortality is assumed to be constant, either M= 0.3 yr^{-1} or M= 0.5yr^{-1} . In order to be consistent with previous assessments of the resource (eg. Andrew 1986), a value of M= 0.3 yr^{-1} was chosen for the "base case" assessments. However, in the sensitivity tests values of M= 0.4 yr^{-1} and M= 0.5 yr^{-1} are used. Botha (1986) calculated an unweighted mean value of $M= 0.4\ yr^{-1}$ for the Cape hake off the west coast from age-at-maturity data.

There is no reason to assume that any other relationship exists. In reality, the assumption that M is constant with respect to age and time does not hold. M is dependent on the age of the fish, being higher for smaller fish younger fish (which are available to a broader range of predators). Therefore, in a sensitivity test the following relationship between mortality and age was used:

$$M_{a-0.5} = 0.3 + 0.5e^{(-0.3(a) - 0.5)} \qquad \text{(A.2.4)}$$

where $M_{a-0.5}$ is the mortality at age a-0.5.

This function defines a relationship where mortality decreases exponentially with age.

APPENDIX III : THE BOOTSTRAP METHOD OF VARIANCE ESTIMATION

This method, developed by Efron (1981), assumes independent identical sampling from an unkown distribution F. It is a non-parametric method for estimating the variance of a statistic $\widehat{P}$ where $\widehat{P}$ is based on a number of random bootstrap samples drawn with replacement from the empirical distribution $\widehat{F}$. If the unknown distribution F is taken to be equal to the observed distribution $\widehat{F}$, the bootstrap variance estimate will simply be the variance of the quantity of interest, namely P. The quantity P is based on the observed data set $\underline{X} = (X_1, \ldots X_n)$ from the empirical distribution $\widehat{F}$, while $\widehat{P}^*$ is based on a random sample $\underline{R} = (R_1, \ldots R_n)$ from the unknown distribution F.

If we let $\widehat{P}^* = \widehat{P}(R_1, \ldots R_n)$ where $(R_1, \ldots R_n)$ is the random "bootstrap sample" of size *n* drawn from F, the bootstrap estimate of the variance of $\widehat{P}^*$ is defined as:

$$\widehat{S}^2 = 1/(N-1)\sum_{i=1}^{N} (\widehat{P}^*_i - P(.))^2 \qquad \text{(A.3.1)}$$

where N is the number of bootstrap samples,
$\widehat{P}^*_i$ is the estimate of $\widehat{P}^*$ from the i th bootstrap sample, and
$P(.)$ is the mean of the $\widehat{P}^*_i$'s, *i.e.*

$$P(.) = (1/N)\sum_{i=1}^{N} \widehat{P}^*_i \qquad \text{(A.3.2)}$$

The variance thus obtained, $\widehat{S}^2$, is considered the non-parametric maximum likelihoood estimate (MLE) of the true variance S^2 of the model parameter P (Efron, 1982). Also we have

$$\lim_{N > .} \widehat{S}^2 = S^2 \qquad \text{(A.3.3)}$$

Usually the choice of N seems not to be crucial, past N = 50 or 100 (Efron 1981). Since values of N greater than 50 were found to produce only a slightly better performance, this value was presumed to be sufficiently accurate for the present variance estimates.

The bootstrap estimate of the standard deviation of P is simply given by:

$$\hat{S} = \sqrt{\hat{S}^2} \qquad \text{(A.3.4)}$$

Table 1: Management variable estimates, their estimated C.V.s (expressed as percentages) and their percentile method 95% confidence intervals obtained from the production model approach based on a Butterworth-Andrew ($B_1 = K$; Schaefer from) observation error estimator. Results are for the west coast and biomass units are in '000 tons (from Punt 1993).

Parameter	Estimate	C.V.	95% confidence interval
MSY	138.3	2.1	132.1 ; 143.6
B_{MSY}	680.5	-	- -
B_{90}	623.4	8.0	533.0 ; 724.2
B_{90} /K	0.458	6.7	0.399 ; 0.520

Table 2: Management variable estimates, their estimated C.V.'s (expressed as percentages) and their percentile method 95% confidence intervals obtained from the *ad hoc* VPA method based on a Laurec-Shepherd tuning algorithm. Results are for the west coast and biomass units are in '000 tons. (from Punt 1993).

Parameter	Estimate	C.V.	95% confidence interval
MSY	101.9	14.0	78.0 ; 134.5
B_{MSY}	225.3	-	- -
B_{90}	139.7	9.2	119.4 ; 171.6
B_{90}/K	0.18	15.4	0.14 ; 0.25

Table 3. Catch-at-age ($C_{y,a}$) data aggregated over the participating fleets for the Cape hake fishery. Units are millions (Source: R.W. Leslie, SFRI pers comm (after Punt 1993).

Age	1	2	3	4	5	6	7
Year							
1978	31.06	307.97	65.16	16.65	6.8	2.11	0.39
1979	34	163.1	64.34	18.97	13.86	3.92	0.99
1980	14.9	126.21	77.2	29.93	12.73	4.52	1.44
1981	86.17	171.65	59.97	28.16	10	4.35	1.41
1982	141.15	187.25	44.33	15.94	8.93	3.58	1.05
1983	25.58	105.33	54.13	18.04	9.24	3.37	1.26
1984	22.42	113.88	64.4	25.67	10.77	4.06	1.34
1985	13.21	126.8	73.75	23.99	12.8	6.01	2.05
1986	5.87	84.48	89.9	29.83	15.01	6.62	2.37
1987	7.15	123.23	84.77	31.03	14.19	3.37	1.22
1988	11.13	164.61	65.17	14.82	10.56	5.58	1.23
1989	0.95	49.86	77.95	25.22	11.52	5.09	1.69
1990	0.41	58.78	93.1	25.71	6.31	2.52	0.85

Table 4: Management variable estimates, their estimated C.V.'s (expressed as percentages) and their percentile method 95% confidence intervals obtained from the application of the age-structured production-model (in Punt 1993). Results are for the west coast and biomass units are in '000 tons. (from Punt 1993).

Parameter	Estimate	C.V.	95% confidence interval
MSY	122.0	1.1	120.7 ; 125.7
B_{MSY}	808.1	-	- -
B_{90}	793.6	4.4	720.0 ; 851.2
B_{90}/K	0.340	4.1	0.313 ; 0.370

Table 5: Total catch and CPUE data for the Cape hake stocks off the west coast. Units are catch ('000 t) and CPUE ('000t/ std day). The definition of std day may be found in Andrew (1986)(after Punt 1993). Sources: 1917-1954- Chalmers (1976), catches multiplied by 39% to correct for discarding of small hake (Andrew 1986). 1955-1990-R.W. Leslie, SFRI pers comm. (after Punt 1993).

Year	Total Catch	Year	Total Catch	CPUE
1917	1	1955	115.4	17.31
1918	1.1	1956	118.2	15.64
1919	1.9	1957	126.4	16.47
1920		1958	130.7	16.26
1921	1.3	1959	146	16.26
1922	1	1960	159.9	17.31
1923	2.5	1961	148.7	12.09
1924	1.5	1962	147.6	14.18
1925	1.9	1963	169.5	13.97
1926	1.4	1964	162.3	14.6
1927	0.8	1965	203	10.84
1928	2.6	1966	195	10.63
1929	3.8	1967	176.7	10.01
1930	4.4	1968	143.6	10.01
1931	2.8	1969	165.1	8.62
1932	14.3	1970	142.5	7.23
1933	11.1	1971	202	7.09
1934	13.8	1972	243.933	4.9
1935	15	1973	157.782	4.97
1936	17.7	1974	123	4.65
1937	20.2	1975	89.617	4.66
1938	21.1	1976	143.894	5.35
1939	20	1977	102.328	4.84
1940	28.6	1978	101.14	5.9
1941	30.6	1979	92.704	6.13
1942	34.5	1980	101.538	5.48
1943	37.9	1981	100.678	5.81
1944	34.1	1982	85.97	5.87
1945	29.2	1983	77.677	6.49
1946	40.4	1984	88.41	6.67
1947	41.4	1985	99.59	7.29
1948	58.8	1986	109.091	6.93
1949	57.4	1987	104.01	6.46
1950	72	1988	90.131	6.88
1951	89.5	1989	84.896	7.18
1952	88.8	1990	78.724	7.29
1953	93.5			
1954	105.4			

Table 6: Specification of the "base case" age-structured production model assessments, and the associated sensitivity tests. All applications assume the same mass-at-age relationship (see Appendix II). The parameters A_c and ∂ refer to the age-specific selectivity function, MAT refers to the age at maturity and MAX to the maximum number of age classes considered.

a) Ricker stock-recruitment relationship

Acronym	Natural Mortality M (yr^{-1})	A_c	∂	MAT	MAX
"base case"	0.3	2	0.5	4	10
$M= 0.4yr^{-1}$	0.4	2	0.5	4	10
$M= 0.5yr^{-1}$	0.5	2	0.5	4	10
$^*Ma=0.3+0.5e^{(-0.3a-0.5)}$	$Ma=0.3+0.5e^{(-0.3a-0.5)}$	2	0.5	4	10
$A_c=1$	0.3	1	0.5	4	10
$A_c=3$	0.3	3	0.5	4	10
$\partial=0.25$	0.3	3	0.25	4	10
$\partial=1$	0.3	3	1	4	10
MAT =3	0.3	3	0.5	3	10
MAT=5	0.3	3	0.5	5	10
MAX=9	0.3	3	0.5	4	9
MAX=11	0.3	3	0.5	4	11

b) Beverton-Holt stock-recruitment relationship

Acronym	Natural Mortality M (yr^{-1})	A_c	∂	MAT	MAX
"base case"	0.3	2	0.5	4	10
$M= 0.4yr^{-1}$	0.4	2	0.5	4	10
$M= 0.5yr^{-1}$	0.5	2	0.5	4	10
$^*Ma=0.3+0.5e^{(-0.3a-0.5)}$	$Ma=0.3+0.5e^{(-0.3a-0.5)}$	2	0.5	4	10
$A_c=1$	0.3	1	0.5	4	10
$A_c=3$	0.3	3	0.5	4	10
$\partial=0.25$	0.3	3	0.25	4	10
$\partial=1$	0.3	3	1	4	10
MAT =3	0.3	3	0.5	3	10
MAT=5	0.3	3	0.5	5	10
MAX=9	0.3	3	0.5	4	9
MAX=11	0.3	3	0.5	4	11

* mortality is age-specific

Table 7: Management variable estimates and their estimated C.V.'s (expressed in percentages) obtained from the "base case" application of the age-structured production-model assuming either a Ricker or a Beverton-Holt stock-recruitment relationship. Biomass units are in '000 tons. The values of the estimated parameters α, β and q and their associated C.V.'s are also shown.

Parameter	Ricker		Beverton-Holt	
	Estimate	C.V.	Estimate	C.V.
MSY	137.6	2.0	124.1	0.9
B_{MSY}	830.1	4.6	829.6	2.2
B^E_{90}	591.5	7.1	697.1	5.0
K^E	1609.7	4.9	2043.0	1.4
B^E_{90}/K^E	0.367	5.9	0.341	5.0
B_{90}	648.9	6.7	756.4	4.8
K	1677.7	4.9	2129.2	1.4
B_{90}/K	0.407	5.8	0.355	4.9
α	2.33×10^{-3}	10.3	1.01×10^{9}	2.7
β	1.12×10^{-12}	11.6	3.21×10^{11}	9.8
q	1.36×10^{-11}	7.5	1.15×10^{-11}	3.7

Table 8: Sensitivity of the estimates of MSY, B_{MSY}, B^E_{90} and B^E_{90}/K^E to the assumptions of the age-structured production model assessment method. Biomass units are '000t.

a) Ricker stock-recruitment relationship

Acronym	MSY	B_{MSY}	B^E_{90}	B^E_{90}/K^E
"base case"	137.6	830.1	591.5	0.367
M= $0.4yr^{-1}$	137.8	799.8	538.1	0.373
M= $0.5yr^{-1}$	138.1	776.6	488.0	0.378
$Ma=0.3+0.5e^{(-0.3a-0.5)}$	138.0	816.6	532.0	0.372
A_c =1	138.7	889.4	679.4	0.379
A_c =3	136.1	780.21	497.5	0.351
∂ =0.25	138.1	814.7	585.8	0.367
∂ =1	137.2	849.6	588.4	0.367
MAT =3	135.3	831.9	605.7	0.361
MAT=5	139.9	831.6	575.6	0.374
MAX=10	137.4	803.1	573.6	0.369
MAX=12	138.6	839.7	597.6	0.366

b) Beverton-Holt stock-recruitment relationship

Acronym	MSY	B_{MSY}	B^E_{90}	B^E_{90}/K^E
"base case"	124.1	829.6	697.1	0.341
M= $0.4yr^{-1}$	124.8	798.3	631.8	0.341
M= $0.5yr^{-1}$	125.5	773.1	570.6	0.342
$Ma=0.3+0.5e^{(-0.3a-0.5)}$	124.6	813.6	628.2	0.339
A_c =1	124.4	896.6	812.0	0.349
A_c =3	121.7	800.6	583.7	0.325
∂ =0.25	123.9	823.7	696.4	0.340
∂ =1	129.3	751.6	668.8	0.356
MAT =3	119.6	897.2	726.6	0.334
MAT=5	113.9	1032.3	783.5	0.330
MAX=10	124.8	803.5	666.9	0.342
MAX=12	123.5	848.4	723.4	0.340

Table 9: Model-predicted catch-at-age ($C_{y,a}$ (mod)) data obtained from the "base case" assessments of the age-structured production model. Units are millions.

a) Ricker

AGE	1	2	3	4	5	6	7
YEAR							
1978	21.67	40.26	29.05	16.98	10.36	6.49	3.51
1979	19.47	34.86	28.41	15.83	8.87	5.38	3.37
1980	20.93	37.36	29.48	18.61	9.94	5.54	3.35
1981	21.17	36.75	28.81	17.57	10.63	5.64	3.14
1982	17.87	31.98	24.5	14.86	8.69	5.22	2.77
1983	15.42	28.15	22.53	13.43	7.82	4.54	2.73
1984	16.98	30.45	25.01	15.63	8.95	5.18	3.01
1985	19.22	33.57	26.96	17.26	10.35	5.89	3.41
1986	21.3	37.41	29.1	18.17	11.16	6.66	3.79
1987	20.33	36.31	28.34	17.12	10.25	6.26	3.73
1988	17.05	31.19	24.92	15.14	8.77	5.23	3.19
1989	15.36	28.15	23.28	14.54	8.48	4.89	2.91
1990	13.71	24.92	20.81	13.49	8.1	4.7	2.71

b) Beverton–Holt

AGE	1	2	3	4	5	6	7
YEAR							
1978	19.78	36.63	27.82	16.83	10.36	6.45	3.6
1979	17.77	32.11	26.4	15.56	9.03	5.52	3.44
1980	19.05	34.38	27.72	17.74	10.03	5.79	3.54
1981	18.94	33.69	27.07	16.96	10.41	5.86	3.38
1982	15.9	28.86	22.97	14.36	8.63	5.27	2.96
1983	13.75	25.37	20.84	12.97	7.79	4.66	2.84
1984	15.07	27.56	23.12	14.9	8.91	5.32	3.18
1985	16.79	30.24	25.05	16.46	10.19	6.06	3.61
1986	18.36	33.16	26.95	17.45	11.01	6.77	4.03
1987	17.45	31.82	25.87	16.41	10.2	6.4	3.94
1988	14.72	27.31	22.55	14.34	8.73	5.4	3.39
1989	13.34	24.87	21.06	13.65	8.34	5.05	3.12
1990	11.91	22.17	18.98	12.65	7.88	4.79	2.9

Table 10: The age-structured production-model estimates of MSY, B_{MSY}, B^E_{90} and B^E_{90}/K^E for a range of weight (ø) assigned to the catch-at-age data in the sum of squares function (see Equation E.22) for the Ricker and Beverton-Holt forms. Units for MSY, B_{MSY} and B^E_{90} are '000t.

a) Ricker stock-recruitment relationship

ø	MSY	B_{MSY}	B^E_{90}	B^E_{90}/K^E
0.001	138.4	820.0	585.1	0.368
0.01	145.3	727.1	519.1	0.372
0.1	161.9	508.6	344.3	0.368
1	161.8	509.0	258.0	0.275
2	161.8	509.2	226.5	0.242
4	161.8	509.2	209.3	0.223

b) Beverton-Holt stock-recruitment relationship

ø	MSY	B_{MSY}	B^E_{90}	B^E_{90}/K^E
0.001	117.0	958.2	751.6	0.332
0.01	117.3	950.1	733.4	0.326
0.1	135.0	618.8	504.1	0.292
1	137.0	569.8	312.0	0.187
2	135.1	607.1	210.2	0.120

Table 11: Model-predicted catch-at-age ($C_{y,a}$ (mod)) data obtained from assessments of the age-structured production model where the observed catch-at-age data (ages 2 to 7) are included in the sum of squares function (see Equation E.22)(note: the weighting factor, o = 1.0). Units are millions.

a) Ricker

AGE	1	2	3	4	5	6	7
YEAR							
1978	53.01	87.68	44.11	18.76	9.06	4.2	1.52
1979	46.04	73.63	47.39	17.5	7.07	3.39	1.57
1980	48.54	76.72	48.25	22.95	8.06	3.23	1.55
1981	52.76	75.26	46.04	21.25	9.6	3.35	1.34
1982	45.14	69.53	38.48	17.25	7.55	3.39	1.18
1983	36.91	60.7	37.43	15.38	6.56	2.85	1.28
1984	39.41	62.39	41.93	19.41	7.6	3.22	1.4
1985	46.75	67.98	43.56	21.89	9.66	3.76	1.59
1986	54.04	79.56	46.1	21.95	10.5	4.6	1.79
1987	51.96	79.99	46.39	19.85	8.99	4.27	1.87
1988	41.8	68.38	42.11	18.12	7.38	3.32	1.57
1989	35.76	58.7	39.67	18.38	7.55	3.05	1.37
1990	31.13	49.43	34.36	17.65	7.82	3.19	1.29

b) Beverton–Holt

AGE	1	2	3	4	5	6	7
YEAR							
1978	60.49	91.03	48.6	19.5	8.15	3.28	1.22
1979	54.86	82.05	46.95	18.22	6.93	2.87	1.16
1980	58.92	88	50.62	21.21	7.81	2.95	1.22
1981	60.16	87.33	49.41	20.66	8.21	3	1.13
1982	50.86	76.02	42.09	17.32	6.86	2.71	0.99
1983	41.87	65.73	38.97	15.95	6.24	2.46	0.97
1984	43.04	68.06	43.55	19.36	7.56	2.94	1.15
1985	46.12	71.76	46.13	22.12	9.37	3.63	1.41
1986	49.52	77	48.35	23.21	10.6	4.46	1.73
1987	46.45	73.09	45.7	21.37	9.77	4.43	1.86
1988	37.87	61.65	39.74	18.62	8.3	3.77	1.71
1989	31.94	53.72	36.94	18.09	8.1	3.59	1.63
1990	26.01	44.8	32.57	17.17	8.05	3.58	1.59

Table 12: The residuals obtained from the model -predicted and observed catch-at-age data for assessments of the age-structured production model where the observed catch-at-age data (ages 2 to 7) are included in the sum of squares function (see Equation E.22)(note: the weighting factor, ϕ = 1.0). Units are millions.

a) Ricker

AGE	2	3	4	5	6	7
YEAR						
1978	1.26	0.39	-0.12	-0.29	-0.69	-1.36
1979	0.8	0.31	0.08	0.67	0.15	-0.46
1980	0.5	0.47	0.27	0.46	0.33	-0.07
1981	0.82	0.26	0.28	0.04	0.26	0.05
1982	0.99	0.14	-0.08	0.17	0.06	-0.12
1983	0.55	0.37	0.16	0.34	0.17	-0.01
1984	0.6	0.43	0.28	0.35	0.23	-0.04
1985	0.62	0.53	0.09	0.28	0.47	0.25
1986	0.06	0.67	0.31	0.36	0.36	0.28
1987	0.43	0.6	0.45	0.46	-0.24	-0.43
1988	0.88	0.44	-0.2	0.36	0.52	-0.25
1989	-0.16	0.68	0.32	0.42	0.51	0.21
1990	0.17	1	0.38	-0.21	-0.24	-0.42

b) Beverton-Holt

AGE	2	3	4	5	6	7
YEAR						
1978	1.22	0.29	-0.16	-0.18	-0.44	-1.14
1979	0.69	0.32	0.04	0.69	0.31	-0.16
1980	0.36	0.42	0.34	0.49	0.43	0.16
1981	0.68	0.19	0.31	0.2	0.37	0.22
1982	0.9	0.05	-0.08	0.26	0.28	0.06
1983	0.47	0.33	0.12	0.39	0.32	0.26
1984	0.51	0.39	0.28	0.35	0.32	0.15
1985	0.57	0.47	0.08	0.31	0.5	0.37
1986	0.09	0.62	0.25	0.35	0.39	0.32
1987	0.52	0.62	0.37	0.37	-0.27	-0.42
1988	0.98	0.49	-0.23	0.24	0.39	-0.33
1989	-0.07	0.75	0.33	0.35	0.35	0.04
1990	0.27	1.05	0.4	-0.24	-0.35	-0.62

Table 13: Management variable estimates obtained from the application of the age- structured production-model either a Ricker or a Beverton-Holt stock-recruitment relationship where selectivity (ages 2 to 7) are estimated by the model. Biomass units are in '000 tons. The values of the estimated parameters α, β and q are also shown. (Ages 2 to 7 of the catch-at-age data are used and the weight (ø) assigned to the data in the sum of squares function is equal to 1).

Parameter	Ricker	Beverton-Holt
MSY	147.5	116.5
B_{MSY}	736.3	1577.2
B^E_{90}	400.1	704.2
K^E	838.6	1471.3
B^E_{90}/K^E	0.477	0.478
B_{90}	662.8	1770.3
K	1566.3	4032.9
B_{90}/K	0.423	0.438
α	4.99×10^{-3}	1.01×10^{9}
β	1.53×10^{-12}	3.21×10^{11}
q	2.36×10^{-11}	1.15×10^{-11}

Table 14: Model-predicted catch-at-age ($C_{y,a}$ (mod)) data obtained from assessments of the age-structured production model where the observed catch-at-age data (ages 2 to 7) are included in the sum of squares function (see Equation E.22) (note: the weighting factor, $\phi = 1.0$). Selectivity for ages 2 to 7 were estimated by the model. Units are millions.

a) Ricker

AGE	1	2	3	4	5	6	7
YEAR							
1978	84.2	94.04	45.03	17.11	9.77	4.44	1.23
1979	75.96	84.07	47.7	15.17	7.73	3.59	1.32
1980	79.43	90.92	51.62	19.57	8.3	3.44	1.29
1981	78.9	86.55	50.45	19.09	9.69	3.35	1.12
1982	66.98	74.44	41.78	16.1	8.14	3.34	0.93
1983	58.32	66.63	38.64	14.31	7.28	2.95	0.96
1984	64.44	73.37	44.29	17.04	8.26	3.37	1.08
1985	72.52	81.01	48.5	19.45	9.82	3.83	1.24
1986	80.24	89.13	52.06	20.72	10.95	4.45	1.38
1987	76.46	86.25	49.94	19.31	10.14	4.31	1.39
1988	63.88	74.8	44.41	16.93	8.59	3.61	1.21
1989	56.43	68.02	42.59	16.64	8.23	3.32	1.09
1990	49.61	59.85	38.98	16.02	8.07	3.16	0.99

b) Beverton–Holt

AGE	1	2	3	4	5	6	7
YEAR							
1978	72.79	92.04	46.99	18.05	9.82	4.2	1.25
1979	67.32	85.1	45	16.24	8.35	3.7	1.25
1980	72.43	93.74	49.8	18.62	8.98	3.76	1.32
1981	70.5	91.47	49.59	18.64	9.33	3.66	1.21
1982	59.52	77.26	41.96	16.02	8.04	3.27	1.01
1983	53.36	69.33	37.88	14.42	7.31	2.97	0.95
1984	60.45	78.36	43.07	16.51	8.32	3.42	1.09
1985	68.21	87.93	48.11	18.61	9.48	3.88	1.26
1986	75.19	96.46	52.34	20.22	10.42	4.32	1.4
1987	72.04	92.69	49.87	19.1	9.85	4.13	1.35
1988	61.96	80.88	43.66	16.51	8.42	3.53	1.17
1989	57.2	75.7	41.66	15.76	7.9	3.26	1.08
1990	52.19	69.16	38.66	14.87	7.43	3.01	0.98

Table 15: The residuals obtained from the model -predicted and observed catch-at-age data for assessments of the age-structured production model where the observed catch-at-age data (ages 2 to 7) are included in the sum of squares function (see Equation E.22) (note: the weighting factor, ϕ = 1.0). Selectivity for ages 2 to 7 were estimated by the model. Units are millions.

a) Ricker

AGE	2	3	4	5	6	7
YEAR						
1978	1.19	0.37	-0.03	-0.36	-0.74	-1.15
1979	0.66	0.3	0.22	0.58	0.09	-0.29
1980	0.33	0.4	0.43	0.43	0.27	0.11
1981	0.68	0.17	0.39	0.03	0.26	0.23
1982	0.92	0.06	-0.01	0.09	0.07	0.12
1983	0.46	0.34	0.23	0.24	0.13	0.27
1984	0.44	0.37	0.41	0.27	0.19	0.22
1985	0.45	0.42	0.21	0.27	0.45	0.51
1986	-0.05	0.55	0.36	0.32	0.4	0.54
1987	0.36	0.53	0.47	0.34	-0.25	-0.13
1988	0.79	0.38	-0.13	0.21	0.44	0.02
1989	-0.31	0.6	0.42	0.34	0.43	0.44
1990	-0.02	0.87	0.47	-0.25	-0.23	-0.15

b) Beverton-Holt

AGE	2	3	4	5	6	7
YEAR						
1978	1.21	0.33	-0.08	-0.37	-0.69	-1.17
1979	0.65	0.36	0.16	0.51	0.06	-0.23
1980	0.3	0.44	0.47	0.35	0.19	0.09
1981	0.63	0.19	0.41	0.07	0.17	0.15
1982	0.89	0.05	-0.01	0.1	0.09	0.03
1983	0.42	0.36	0.22	0.23	0.13	0.28
1984	0.37	0.4	0.44	0.26	0.17	0.2
1985	0.37	0.43	0.25	0.3	0.44	0.49
1986	-0.13	0.54	0.39	0.36	0.43	0.53
1987	0.28	0.53	0.49	0.37	-0.2	-0.1
1988	0.71	0.4	-0.11	0.23	0.46	0.05
1989	-0.42	0.63	0.47	0.38	0.44	0.45
1990	-0.16	0.88	0.55	-0.16	-0.18	-0.14

Table 16: Management variable estimates obtained from the application of the age- structured production-model assuming either a Ricker or a Beverton-Holt stock-recruitment relationship where selectivity (ages 1 to 7) are estimated by the model. Biomass units are in '000 tons. The values of the estimated parameters α, β and q are also shown. (Ages 1 to 7 of the catch-at-age data are used and the weight (ϕ) assigned to the data in the sum of squares function is equal to 1).

Parameter	Ricker	Beverton-Holt
MSY	138.6	104.4
B_{MSY}	898.6	1423.6
B^E_{90}	473.0	600.7
K^E	835.8	1877.5
B^E_{90}/K^E	0.566	0.319
B_{90}	985.1	1037.4
K	1948.	3520.81
B_{90}/K	0.505	0.1706
α	3.53×10^{-3}	4.037×10^{9}
β	9.88×10^{-13}	2.01×10^{11}
q	2.11×10^{-11}	1.025×10^{-11}

Table 17: Model-predicted catch-at-age ($C_{y,a}$ (mod)) data obtained from assessments of the age-structured production model where the observed catch-at-age data (ages 1 to 7) are included in the sum of squares function (see Equation E.22)(note: the weighting factor, $\phi = 1.0$). Selectivity for ages 1 to 7 were estimated by the model. Units are millions.

a) Ricker

AGE	1	2	3	4	5	6	7
YEAR							
1978	15.74	107.58	49.15	16.79	9.9	4.56	1.31
1979	14.1	98.74	48.88	16.65	7.45	3.65	1.33
1980	14.74	104.71	54.14	20.01	8.87	3.29	1.27
1981	14.25	100.41	52.23	20.14	9.71	3.57	1.05
1982	11.97	84.47	43.76	16.84	8.43	3.35	0.97
1983	10.65	74.91	39.94	15.2	7.5	3.08	0.95
1984	11.92	83.59	45.27	17.74	8.61	3.48	1.11
1985	13.39	93.38	50.09	20	10.03	3.99	1.26
1986	14.67	102.6	54.31	21.53	11.03	4.55	1.41
1987	13.86	98.63	51.99	20.29	10.34	4.35	1.4
1988	11.62	84.93	45.96	17.74	8.85	3.69	1.2
1989	10.43	77.14	43.77	17.27	8.45	3.43	1.1
1990	9.3	68.81	39.94	16.45	8.18	3.25	1.01

b) Beverton-Holt

AGE	1	2	3	4	5	6	7
YEAR							
1978	14.22	76.96	45	27.89	9.79	4.32	1.42
1979	12.95	70.96	43.21	26.5	8.07	3.67	1.29
1980	13.65	76.34	47.39	30.26	9.15	3.6	1.31
1981	13.37	73.72	46.41	30.22	9.51	3.73	1.17
1982	11.39	62.68	38.93	25.71	8.2	3.34	1.04
1983	10.35	56.36	35.32	23.01	7.42	3.03	0.98
1984	11.81	64.07	40.05	26.32	8.4	3.47	1.13
1985	13.47	72.59	44.88	29.42	9.51	3.91	1.29
1986	15	80.8	49.16	31.86	10.32	4.33	1.42
1987	14.39	78.42	47.28	30.17	9.65	4.07	1.37
1988	12.26	68.06	41.61	26.32	8.24	3.42	1.15
1989	11.23	62.64	39.47	25.31	7.84	3.16	1.04
1990	10.28	56.7	36.06	23.83	7.46	2.96	0.95

Table 18: The residuals obtained from the model -predicted and observed catch-at-age data for assessments of the age-structured production model where the observed catch-at-age data (ages 1 to 7) are included in the sum of squares function (see Equation E.22)(note: the weighting factor, $\phi = 1.0$). Selectivity for ages 1 to 7 were estimated by the model. Units are millions.

a) Ricker

AGE	1	2	3	4	5	6	7
YEAR							
1978	0.68	1.05	0.28	-0.01	-0.38	-0.77	-1.21
1979	0.88	0.5	0.27	0.13	0.62	0.07	-0.29
1980	0.01	0.19	0.35	0.4	0.36	0.32	0.12
1981	1.8	0.54	0.14	0.34	0.03	0.2	0.3
1982	2.47	0.8	0.01	-0.05	0.06	0.07	0.08
1983	0.88	0.34	0.3	0.17	0.21	0.09	0.28
1984	0.63	0.31	0.35	0.37	0.22	0.15	0.19
1985	-0.01	0.31	0.39	0.18	0.24	0.41	0.49
1986	-0.92	-0.19	0.5	0.33	0.31	0.38	0.52
1987	-0.66	0.22	0.49	0.43	0.32	-0.26	-0.14
1988	-0.04	0.66	0.35	-0.18	0.18	0.41	0.02
1989	-2.4	-0.44	0.58	0.38	0.31	0.4	0.43
1990	-3.12	-0.16	0.85	0.45	-0.26	-0.25	-0.17

b) Beverton-Holt

AGE	1	2	3	4	5	6	7
YEAR							
1978	0.78	1.39	0.37	-0.52	-0.36	-0.72	-1.29
1979	0.97	0.83	0.4	-0.33	0.54	0.07	-0.27
1980	0.09	0.5	0.49	-0.01	0.33	0.23	0.1
1981	1.86	0.85	0.26	-0.07	0.05	0.16	0.19
1982	2.52	1.09	0.13	-0.48	0.09	0.07	0.01
1983	0.91	0.63	0.43	-0.24	0.22	0.1	0.25
1984	0.64	0.58	0.47	-0.03	0.25	0.16	0.17
1985	-0.02	0.56	0.5	-0.2	0.3	0.43	0.47
1986	-0.94	0.04	0.6	-0.07	0.37	0.43	0.51
1987	-0.7	0.45	0.58	0.03	0.39	-0.19	-0.11
1988	-0.1	0.88	0.45	-0.57	0.25	0.49	0.06
1989	-2.47	-0.23	0.68	0	0.39	0.48	0.48
1990	-3.22	0.04	0.95	0.08	-0.17	-0.16	-0.11

Table 19: Selectivity-at-age estimates and their estimated C.V.'s (expressed in percentages) obtained from the application of the age-structured production-model (assuming a Beverton-Holt stock-recruitment relationship) where selectivity (ages 1 to 7) are estimated by the model. (Ages 2 to 7 of the catch-at-age data are used and the weight (ø) assigned to the data in the sum of squares function is equal to 1).

Age	Selectivity	C.V.
1	0.12	26.3
2	0.99	13.4
3	0.97	14.3
4	0.99	33.9
5	0.48	44.8
6	0.28	64.1
7	0.13	104.2

Table 20: The age-structured production-model management variable estimates for a range of weight (ø) assigned to the catch-at-age data in the sum of squares function (see Equation E1.9) for the Ricker and Beverton-Holt forms. The selectivity-at-age function used is given in Appendix II (Equation A.2.2) and is shown as Function 2 in Figure 14. Units for MSY, B_{MSY}, B^E_{90}, B_{90}, K^E and K are '000t.

a) Ricker stock-recruitment relationship

ø	MSY	B_{MSY}	B^E_{90}	K^E	B^E_{90}/K^E	B_{90}	K	B_{90}/K
0.001	140.1	857.4	470.8	1224.3	0.384	649.4	1778.1	0.365
0.01	145.7	771.5	430.0	1096.2	0.392	590.4	1592.0	0.370
0.1	159.9	554.7	319.7	764.8	0.418	436.4	1110.7	0.392
1	161.9	538.9	297.6	793.8	0.402	407.0	1074.4	0.378
2	159.9	555.1	280.5	765.4	0.366	384.2	1111.7	0.345

b) Beverton-Holt stock-recruitment relationship

ø	MSY	B_{MSY}	B^E_{90}	K^E	B^E_{90}/K^E	B_{90}	K	B_{90}/K
0.001	111.3	1173.6	664.5	1995.0	0.333	933.4	2897.3	0.322
0.01	114.1	1107.5	632.3	1911.1	0.330	886.0	2775.4	0.319
0.1	111.0	1149.1	590.7	1959.7	0.301	828.0	2846.0	0.290
1	137.0	599.9	346.6	1344.8	0.257	470.0	1953.0	0.240
2	109.3	1082.2	223.8	1860.5	0.120	311.5	2893.2	0.107

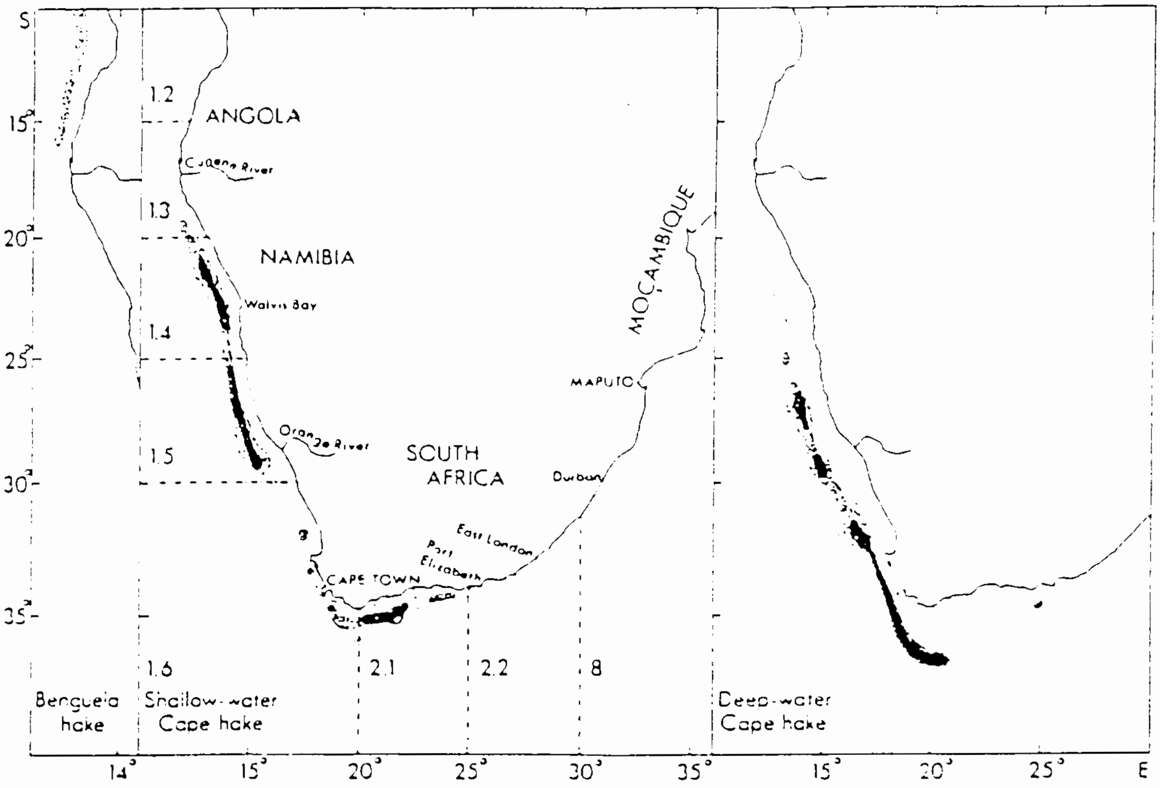
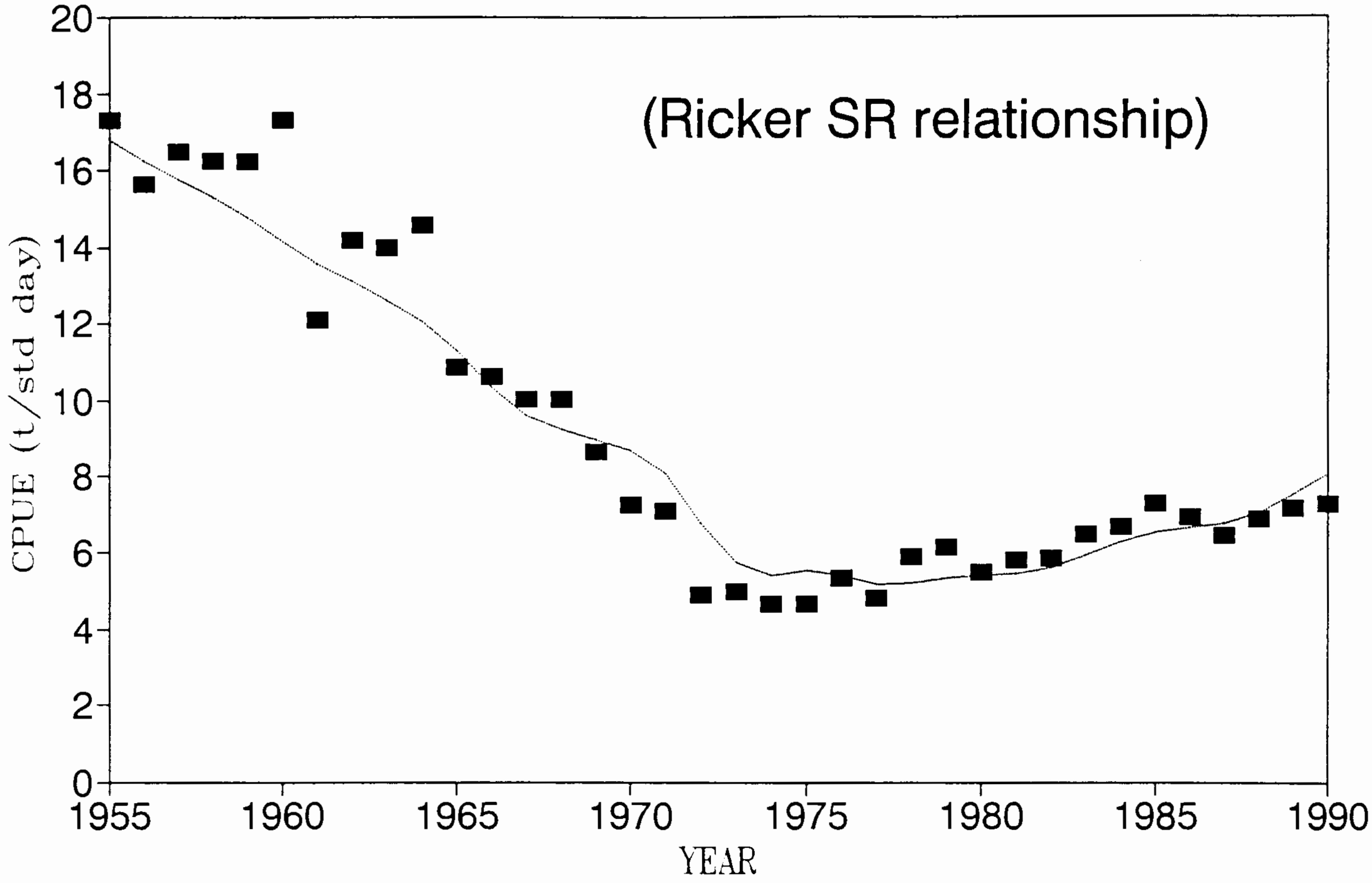


Figure 1: Map of South Africa showing the partition of the ocean into management regions. The distribution patterns of the two species (*Merluccius capensis* (shallow-water species) and *M. paradoxus* (deep-water species)) are also indicated (after Payne 1989).



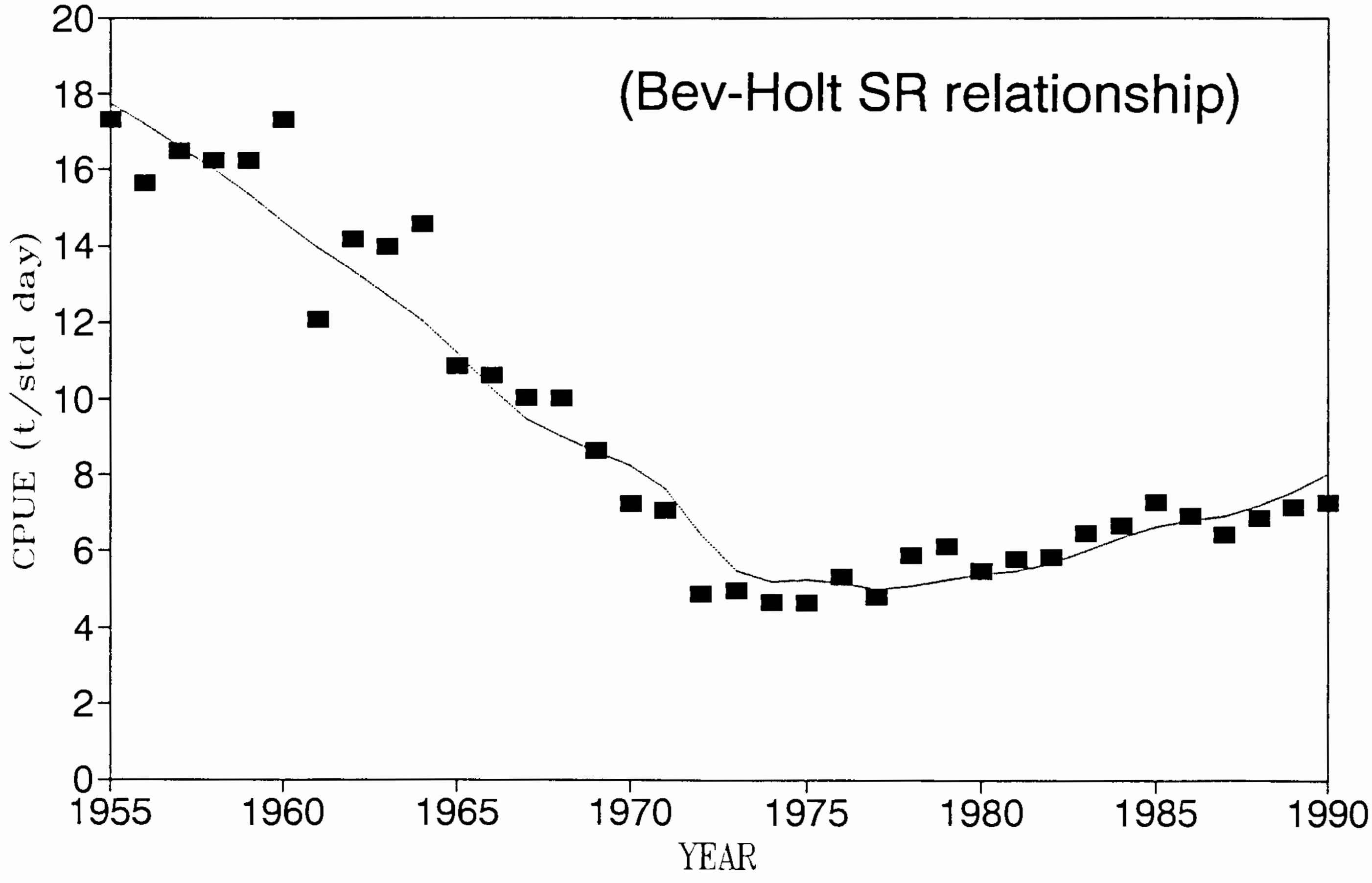


Figure 2: Actual (solid squares) and age-structured model-predicted (dotted line) CPUE series for the West Coast assuming (a) Ricker and (b) Beverton-Holt stock-recruitment relationships.

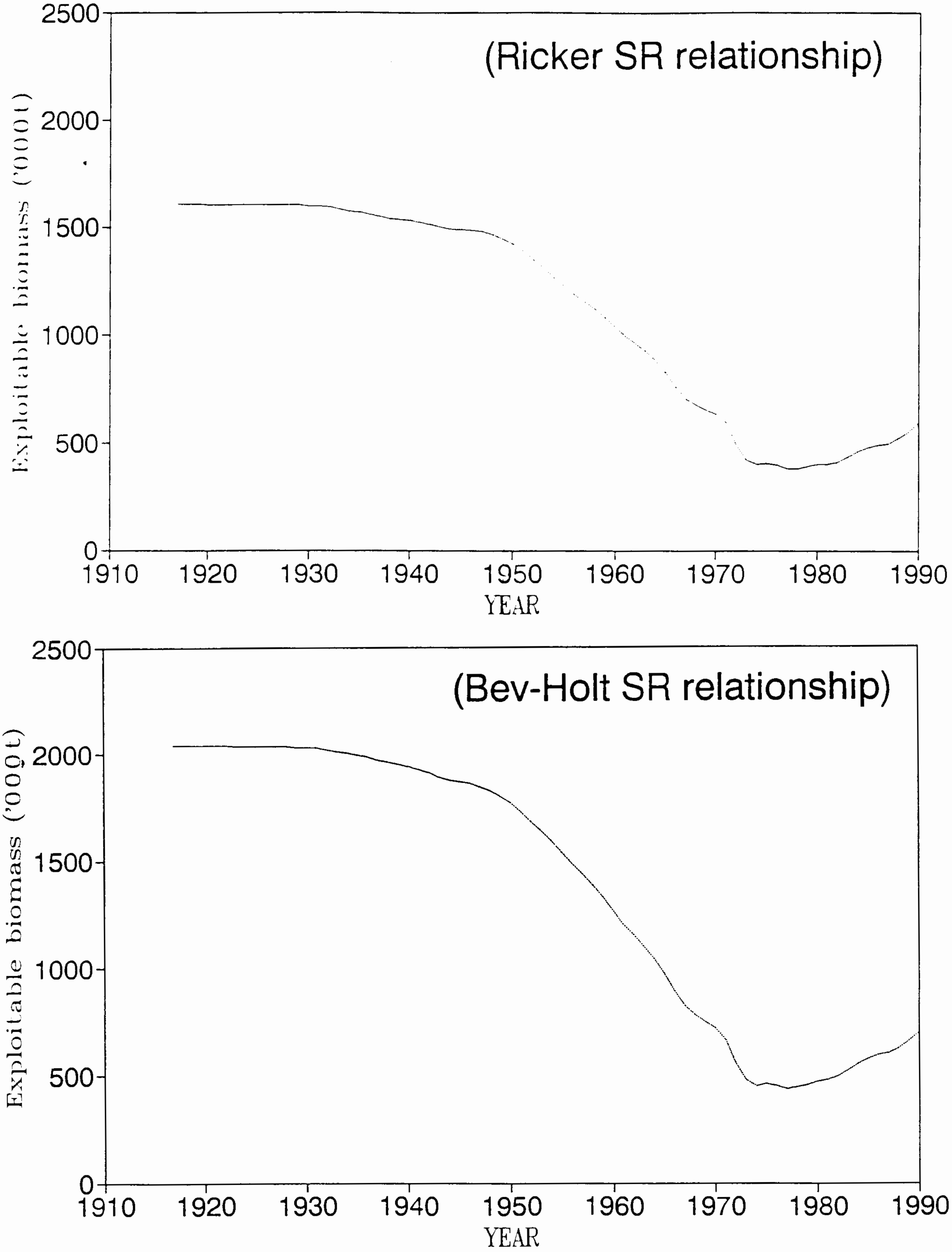


Figure 3. Exploitable biomass trajectories for the West Coast Cape hake stock from the age-structured production model assuming (a) Ricker and (b) Beverton-Holt stock-recruitment relationships.

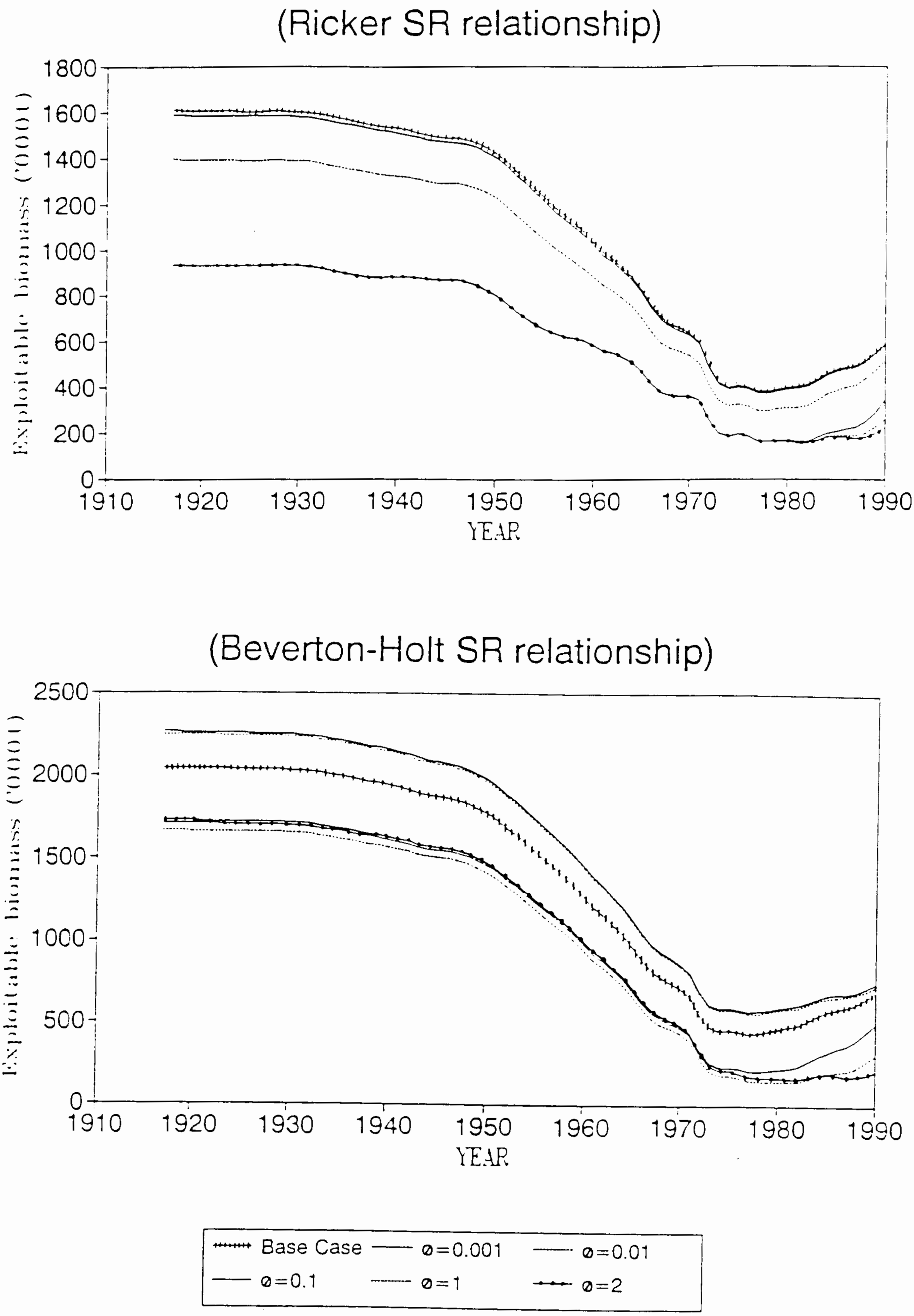


Figure 4: Exploitable biomass trajectories for the West Coast Cape hake stock from the age-structured production model assuming (a) Ricker and (b) Beverton-Holt stock-recruitment relationships. Results are shown for the base case and variants which utilize catch-at-age data when estimating the model parameters.

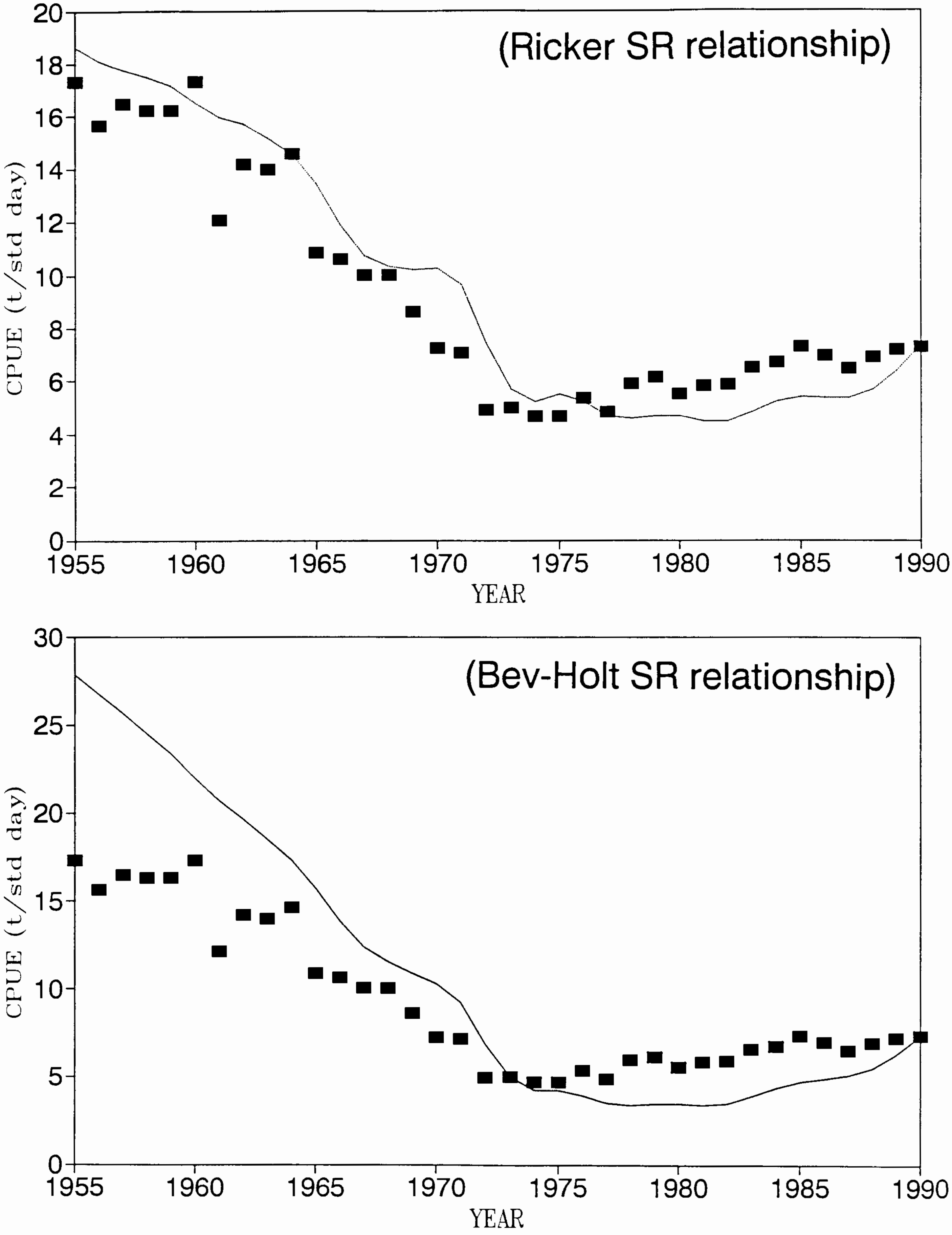


Figure 5: Actual (solid squares) and age-structured model-predicted (dotted line) CPUE series for the West Coast assuming (a) Ricker and (b) Beverton-Holt stock-recruitment relationships. Catch-at-age data (ages 2 to 7) are incorporated into the sum of squares function.

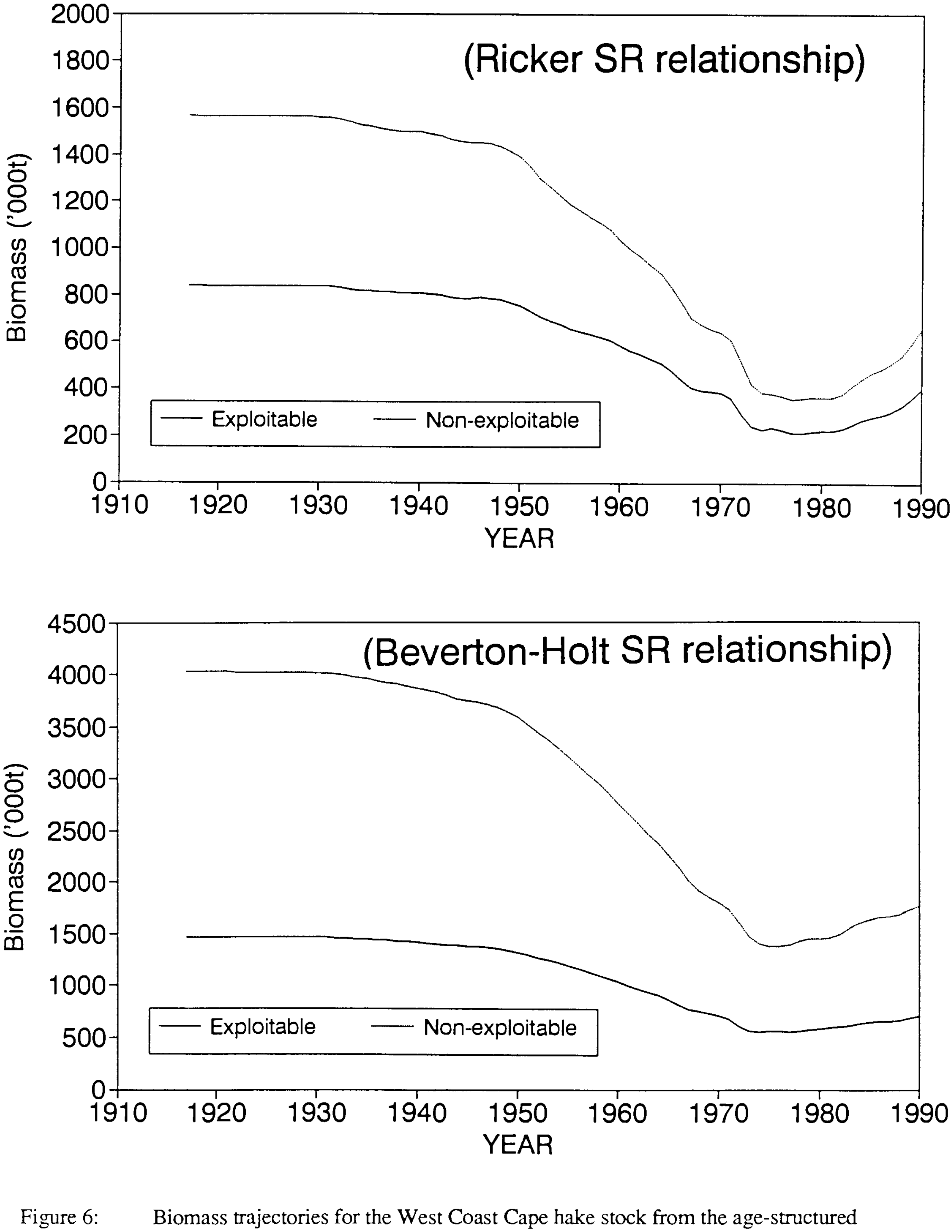


Figure 6: Biomass trajectories for the West Coast Cape hake stock from the age-structured production model assuming (a) Ricker and (b) Beverton-Holt stock-recruitment relationships. Catch-at-age data (ages 2 to 7) are incorporated into the sum of squares function and selectivity-at-age (mid-year for ages 2 to 7) is estimated by the model.

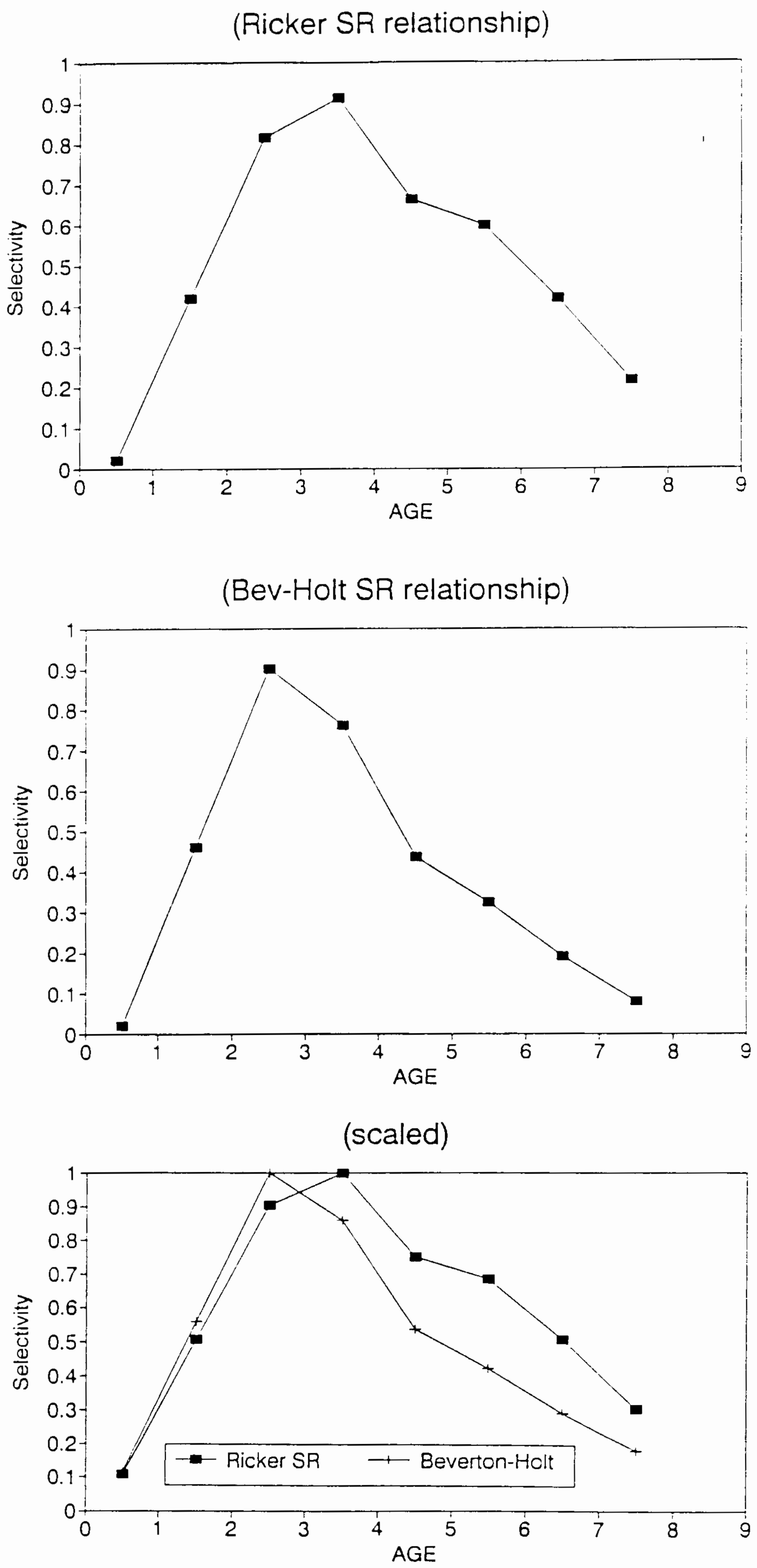


Figure 7: Estimated selectivity-at-age (mid-year for age) from the age-structured production model assuming (a) Ricker and (b) Beverton-Holt stock-recruitment relationships. Catch-at-age data (ages 2 to 7) are incorporated into the sum of squares function and selectivity-at-age (mid-year for ages 2 to 7) is estimated by the model. A comparison can be made in (c) where the selectivity-at-age estimates have been equally scaled.

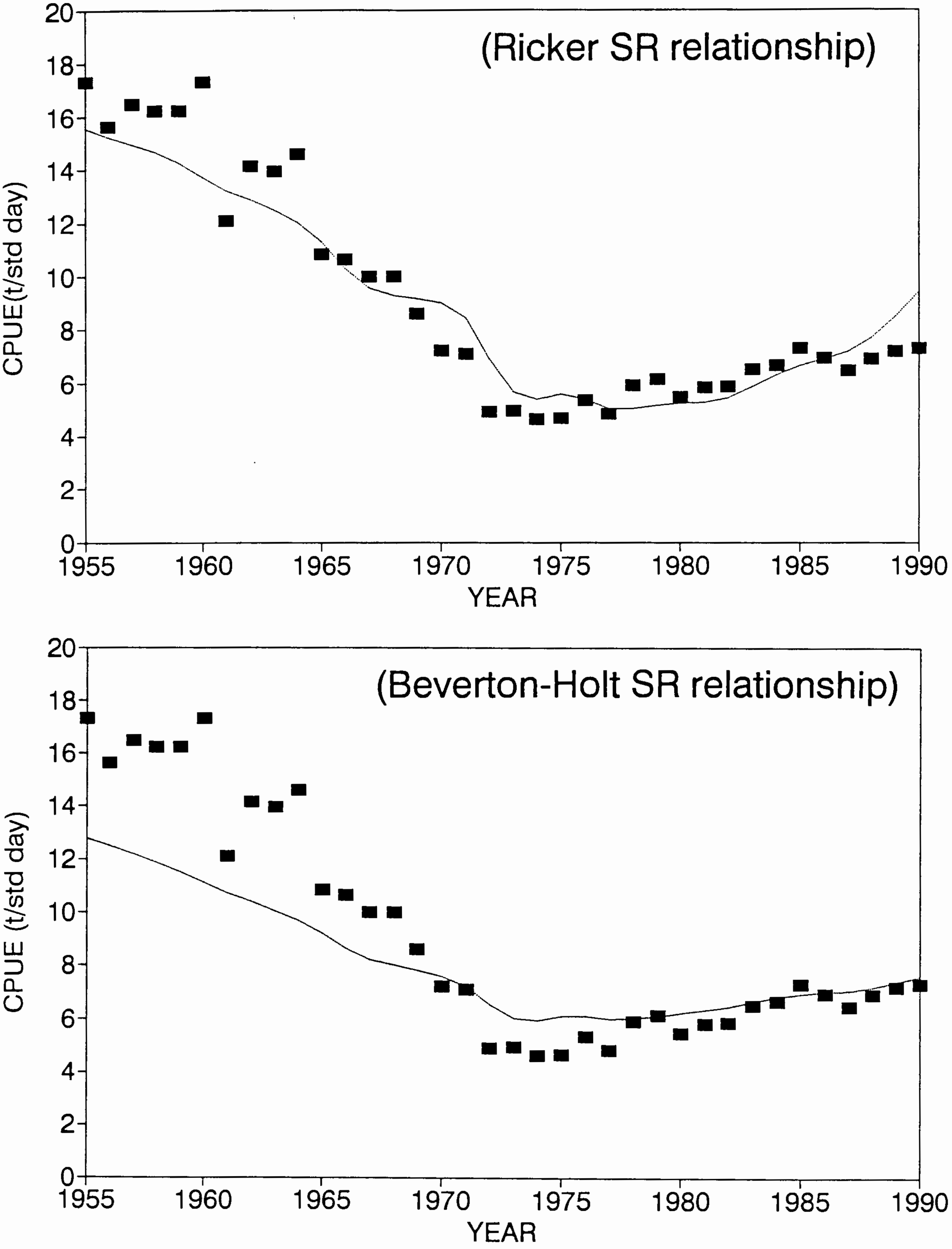
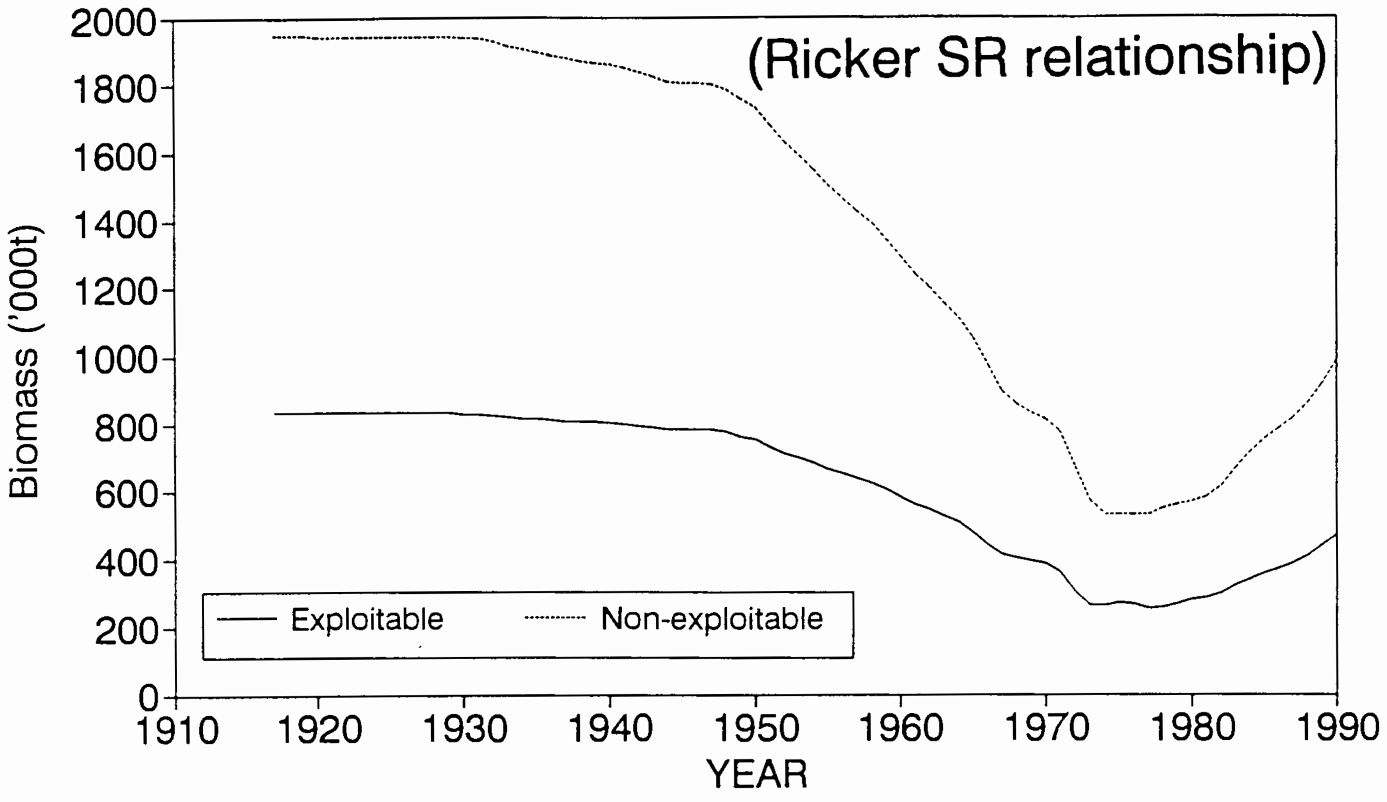


Figure 8: Actual (solid squares) and age-structured model-predicted (dotted line) CPUE series for the West Coast assuming (a) Ricker and (b) Beverton-Holt stock-recruitment relationships. Catch-at-age data (ages 2 to 7) are incorporated into the sum of squares function and selectivity-at-age (mid-year for ages 2 to 7) is estimated by the model.



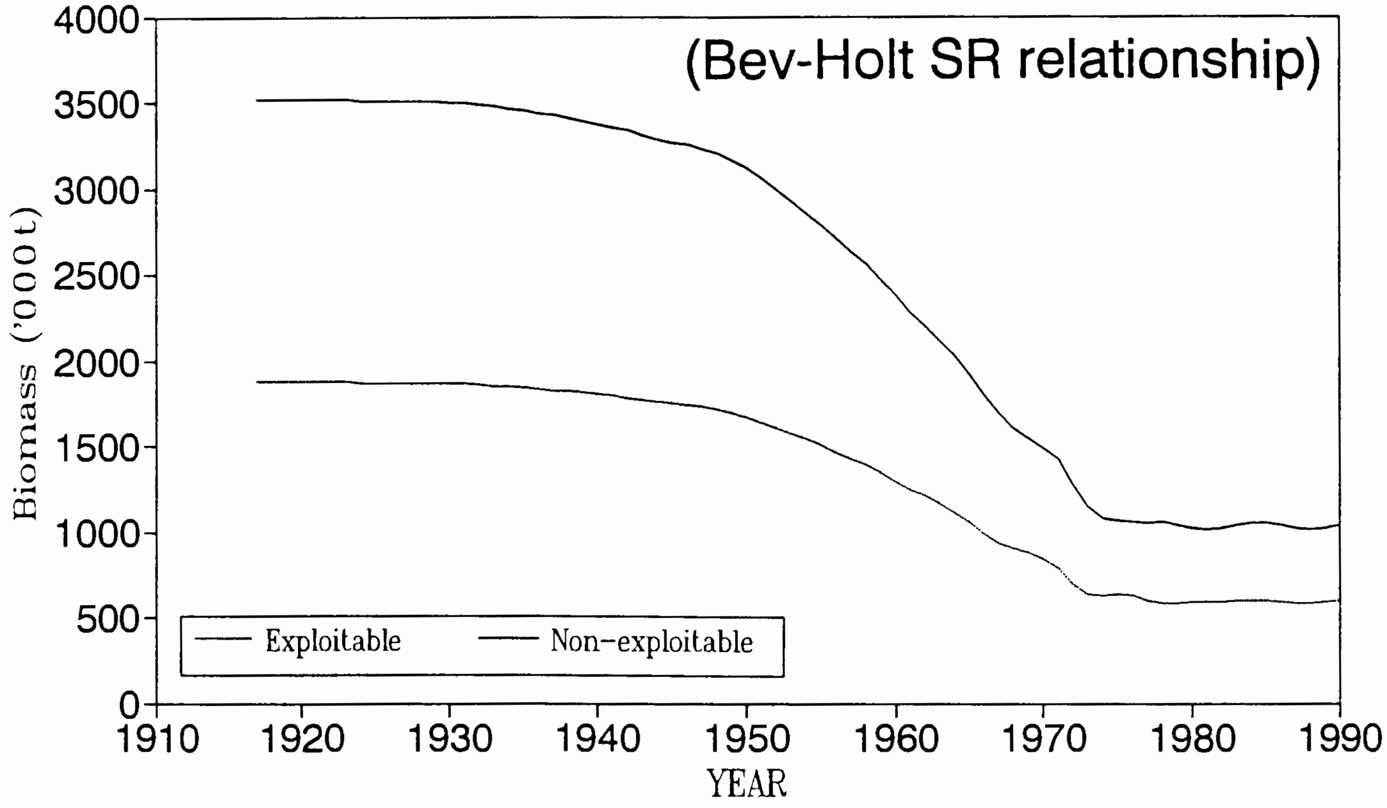


Figure 9: Biomass trajectories for the West Coast Cape hake stock form the age-structured production model assuming (a) Ricker and (b) Beverton-Holt stock-recruitment relationships. Catch-at-age data (ages 1 to 7) are incorporated into the sum of squares function and selectivity-at-age (mid-year for ages 1 to 7) is estimated by the model.

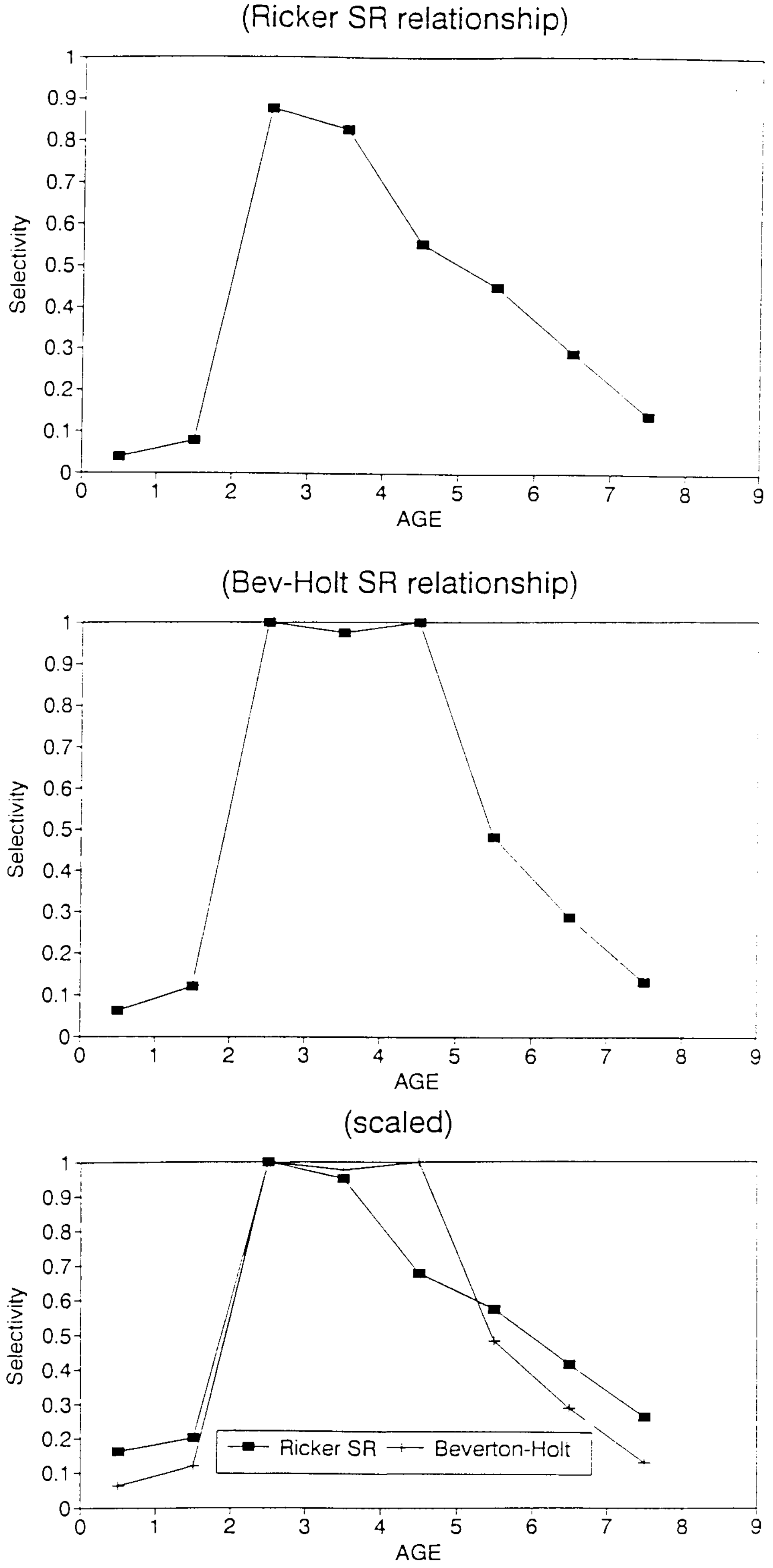


Figure 10: Estimated selectivity-at-age (mid-year for age) from the age-structured production model assuming (a) Ricker and (b) Beverton-Holt stock-recruitment relationships. Catch-at-age data (ages 1 to 7) are incorporated into the sum of squares function and selectivity-at-age (mid-year for ages 1 to 7) is estimated by the model. A comparison can be made in (c) where the selectivity-at-age estimates have been equally scaled.

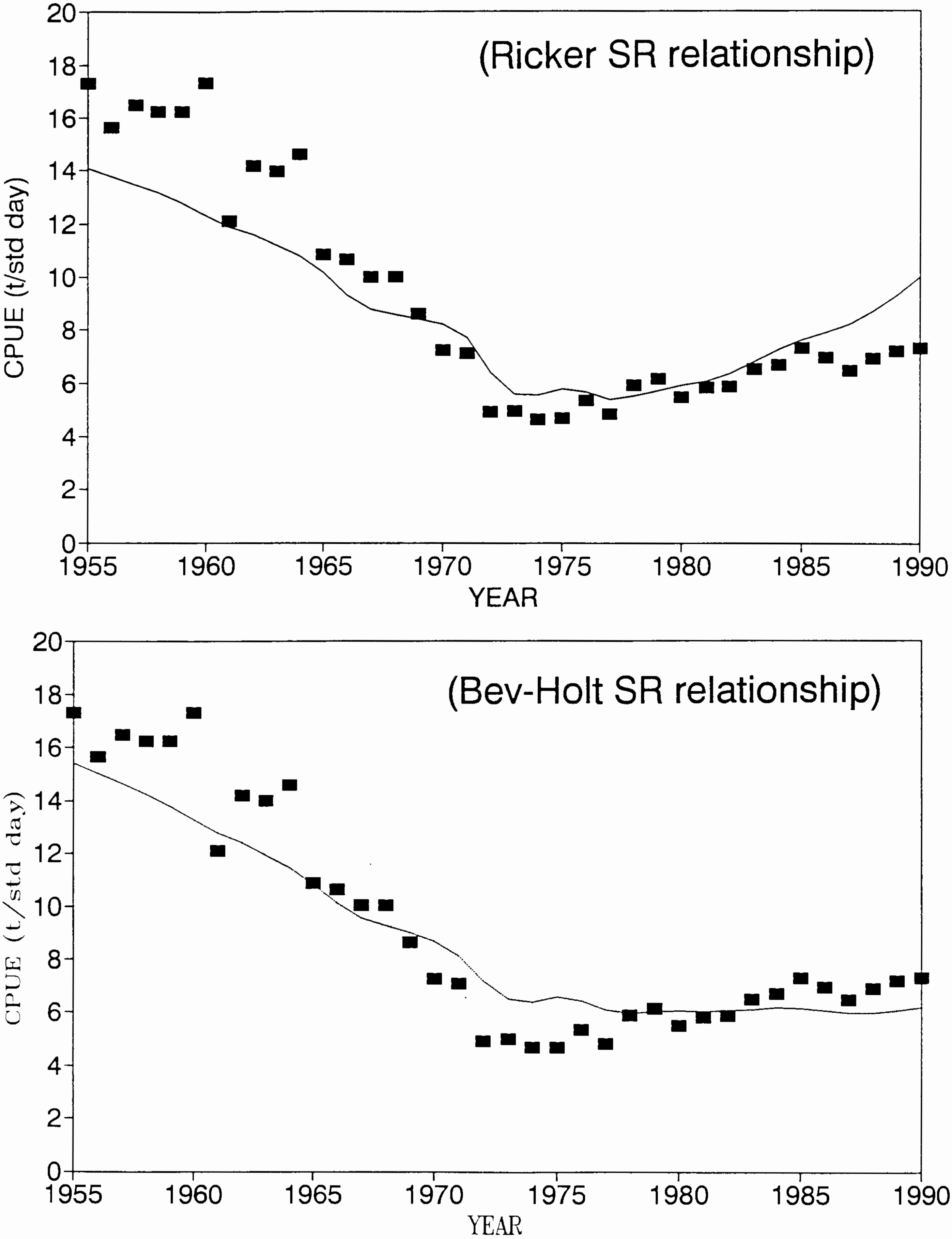


Figure 11: Actual (solid squares) and age-structured model-predicted (dotted line) CPUE series for the West Coast assuming (a) Ricker and (b) Beverton-Holt stock-recruitment relationships. Catch-at-age data (ages 1 to 7) are incorporated into the sum of squares function and selectivity-at-age (mid-year for ages 1 to 7) is estimated by the model.

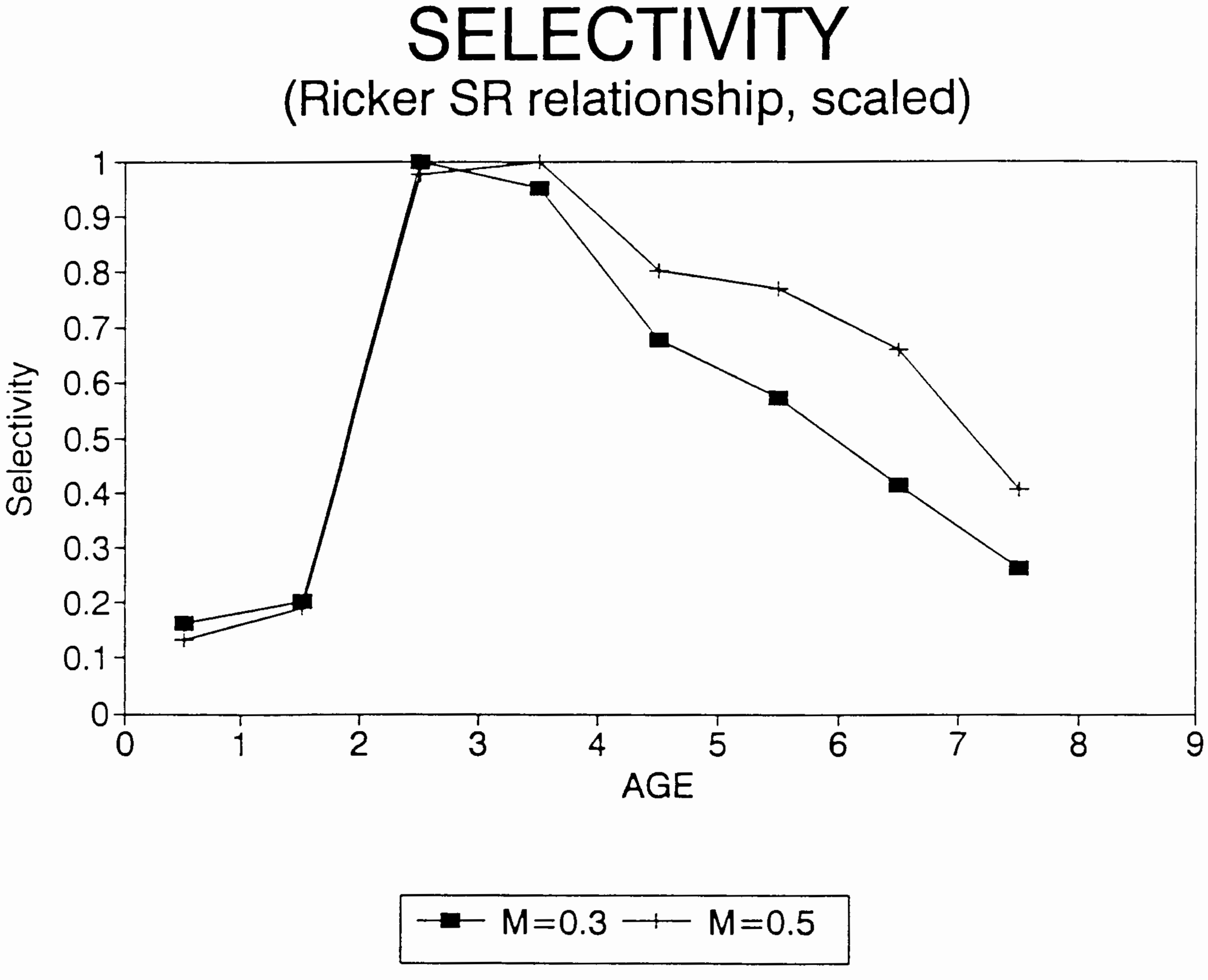


Figure 12: Estimated selectivity-at-age (mid-year for age), for different values of M (natural mortality), from the age-structured production model assuming a Ricker stock-recruitment relationship. Catch-at-age data (ages 1 to 7) are incorporated into the sum of squares function and selectivity-at-age (mid-year for ages 1 to 7) is estimated by the model. A comparison can be made as the selectivity-at-age estimates have been equally scaled.

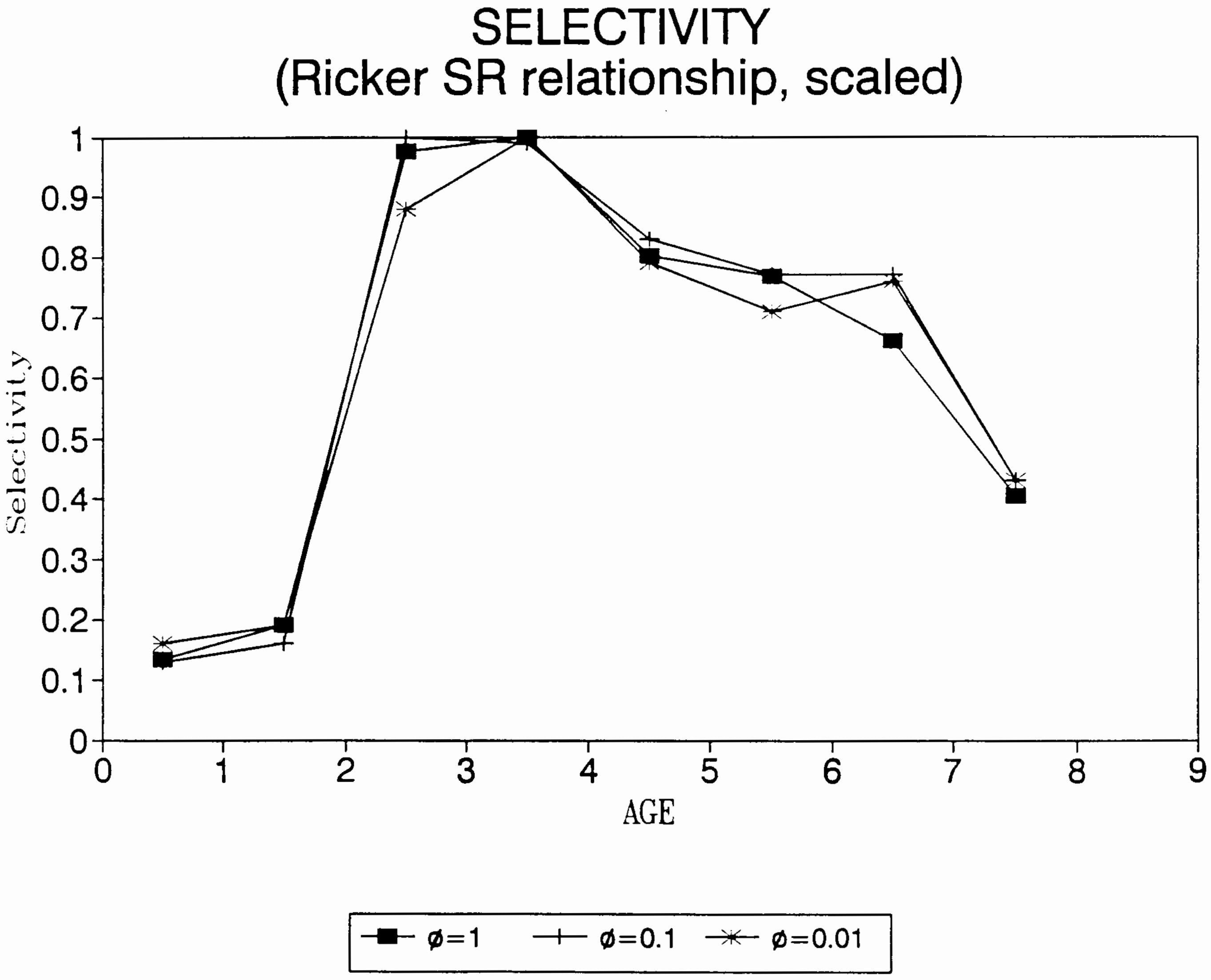


Figure 13: Estimated selectivity-at-age (mid-year for age), for different values of ø (weighting factor), from the age-structured production model assuming a Ricker stock-recruitment relationship. Catch-at-age data (ages 1 to 7) are incorporated into the sum of squares function and selectivity-at-age (mid-year for ages 1 to 7) is estimated by the model. The value of M was held constant at 0.5 yr^{-1} . A comparison can be made as the selectivity-at-age estimates have been equally scaled.

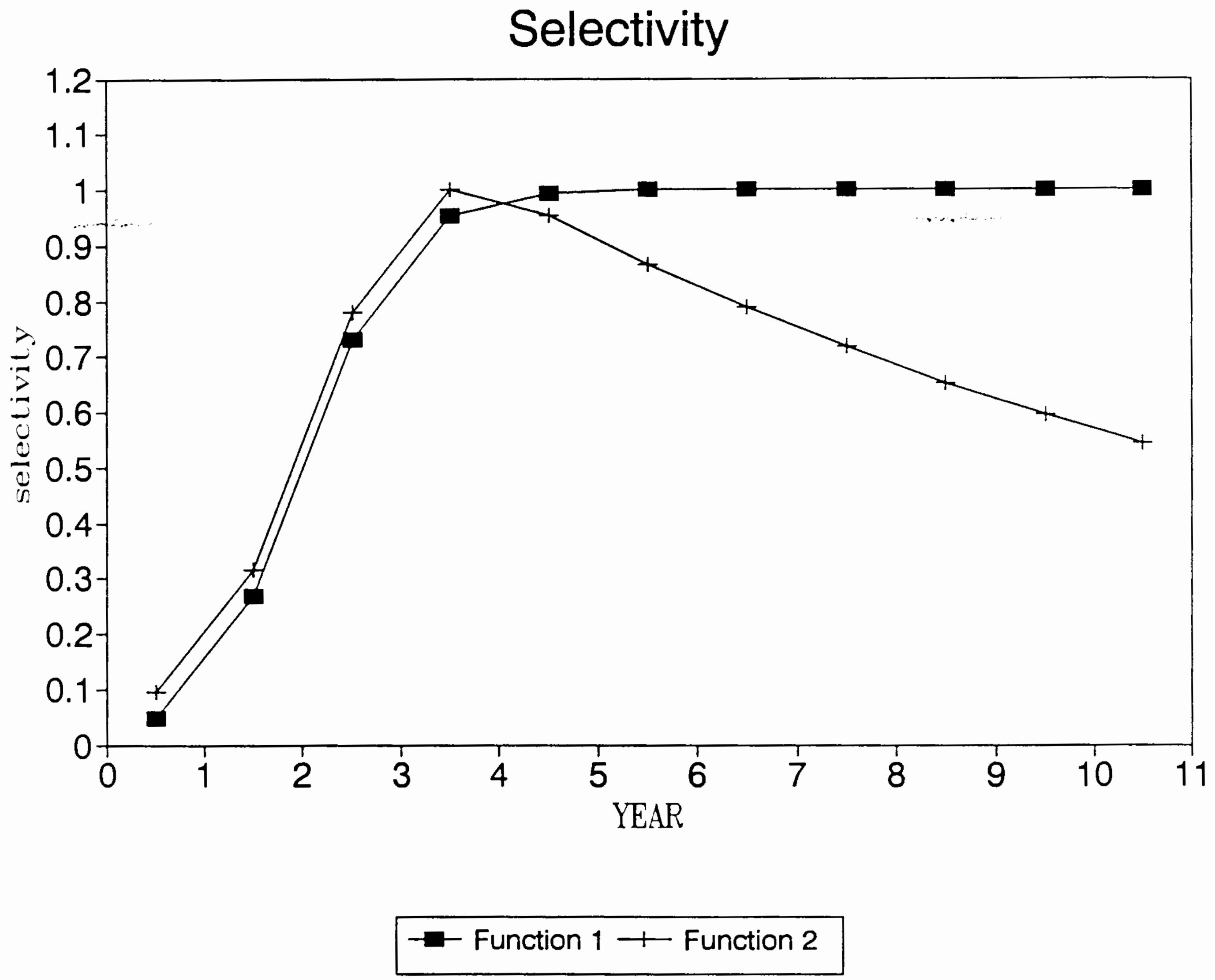


Figure 14: The selectivity-at-age values used in the age-structured production model, when selectivity-at-age was not been estimated. The "base case" models use the values defined by Function 1 and Function 2 was used in the assessment where selectivity-at-age was assumed to decrease at older age classes.

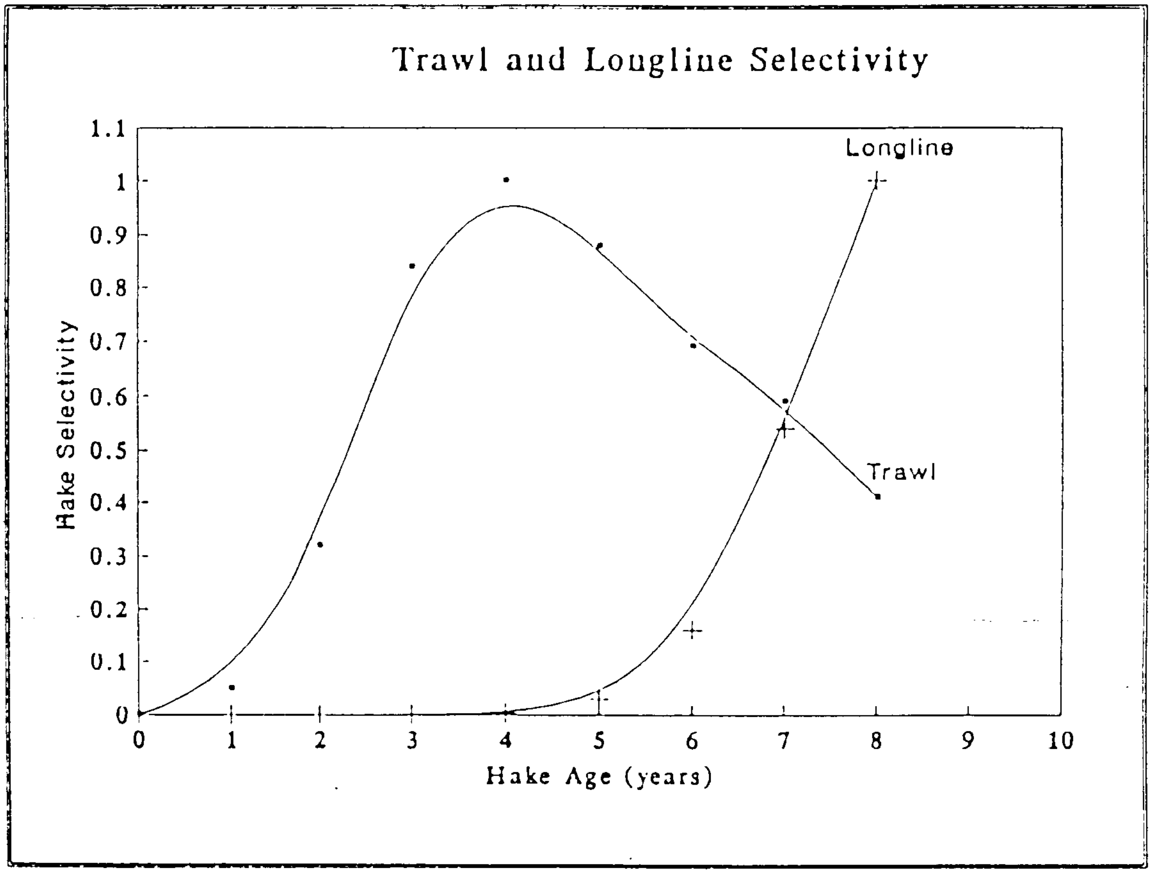


Figure 15: The selectivity values for the trawl and longline fisheries (Fig. 2. from Armstrong and Japp 1991).

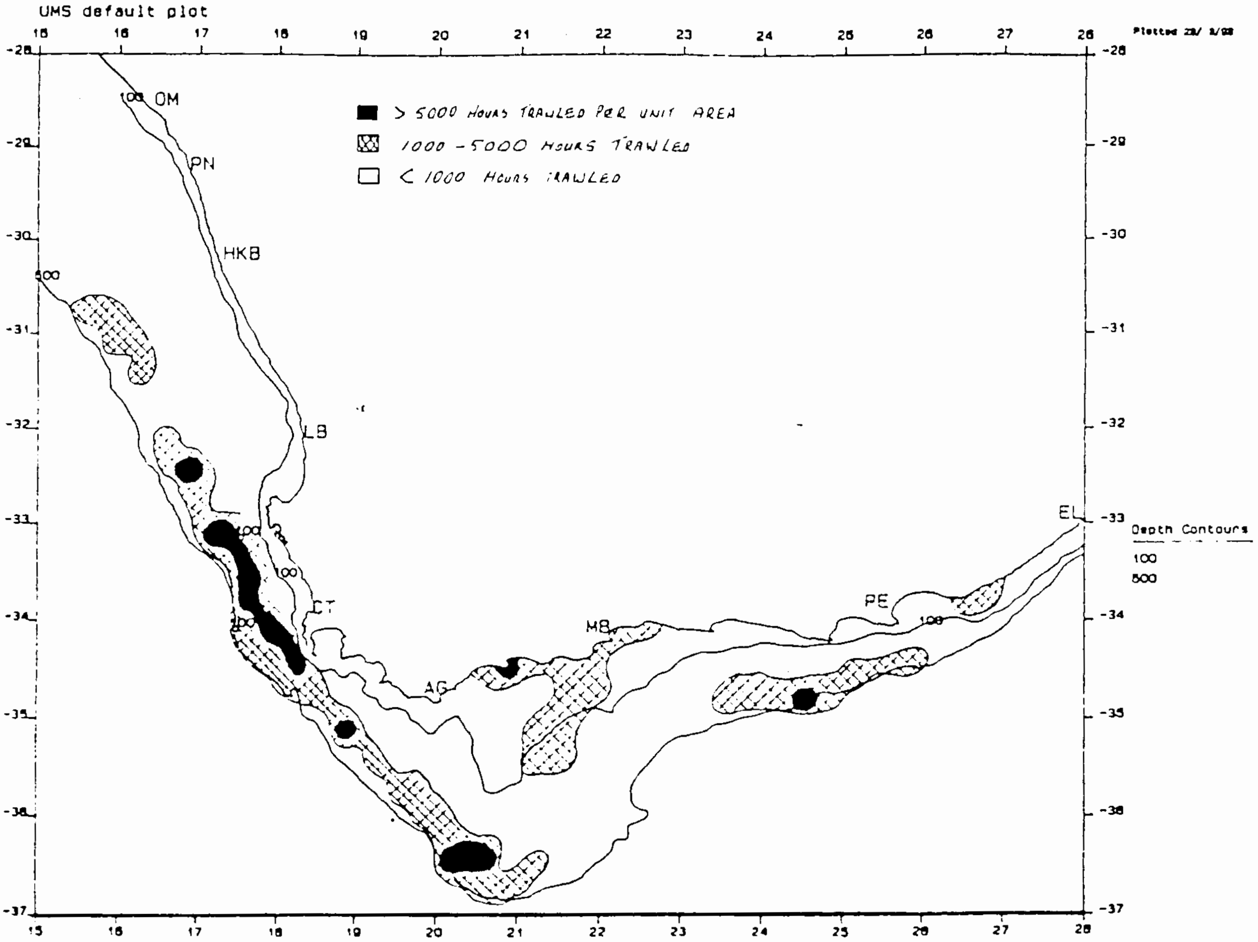


Figure 16: The distribution of effort for the hake fishery off the South African coast uring 1991. (the units of effort (uncorrected) are: hours trawled per unit area, unpublished data - SFRI, Dave Japp pers comm.).