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ABUNDANCE INDICES AND STOCK ASSESSMENT OF SOUTH ATLANTIC ALBACORE (*THUNNUS ALALUNGA*)

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ABSTRACT

An index of abundance for south Atlantic albacore is derived from catch and effort data for the South African baitboat fishery using multi-linear modelling techniques. Unfortunately, the abundance index is unreliable because of difficulties in identifying albacore-directed effort, and because some of the days on which albacore are targeted, but not caught, are not recorded as effort. Monte Carlo simulations show that fixing B_I *(the biomass at the start of the catch series) equal to K (the average pre-exploitation equilibrium level), rather than estimating it, is likely to provide more reliable results. The impact of the abundance index for South African baitboats together with revised indices for the Taiwanese and Japanese longline fisheries is examined using an age-structured production-model estimation method. The resource is estimated to be depleted to between 24% and 37% of its pre-exploitation equilibrium level, although the biomass is estimated to be currently larger than that at which MSY is achieved* (B_{MSY})*. This is a consequence of an estimate of* B_{MSY} *which is a small fraction of the pre-exploitation equilibrium level. Catches have been larger than replacement yields since 1986, and this has led to a reduction in biomass. This analysis suggests that annual catches need to be reduced to levels approaching the estimate of MSY if further reductions in population size are to be avoided.*

RESUME

Un indice de l'abondance en germon sud-atlantique est élaboré à partir de données de capture et d'effort de la pêcheries sud-africaine de canneurs au moyen de techniques de modélisation multilinéaire. Malheureusement, l'indice d'abondance est peu fiable du fait des difficultés d'identification de l'effort visant le germon, et parce que certains jours où le germon est visé, mais non capturé, sont enregistrés en tant qu'effort. Les simulations Monte-Carlo montrent qu'en attribuant à B_I *(la biomasse au début de chaque série de capture) une valeur égale à K (le niveau moyen équilibré non exploité), plutôt qu'en l'estimant, il est probable d'obtenir des résultats plus fiables. L'impact de l'indice d'abondance des canneurs sud-africains et les indices révisés des palangriers taïwanais et japonais sont examinés par une méthode d'estimation du modèle de production structuré par âge. La ressource est estimée avoir baissé à 24 % à 37 % de son niveau équilibré non exploité. bien que la biomasse soit estimée être actuellement plus forte que celle qui permet d'atteindre la PME* (B_{PME})*. Ceci vient du fait que l'estimation de* B_{PME} *est une petite fraction du niveau équilibré non exploité. Les prises ont été plus importantes que la production de remplacement depuis 1986, et ceci a entraîné une réduction de la biomasse. Cette analyse suggère qu'il faut réduire la prise annuelle à un niveau proche de l'estimation de la PME si l'on veut éviter d'autres réductions de la magnitude de la population.*

RESUMEN

De los datos de captura y esfuerzo de la pesquería de barcos de cebo de Sudáfrica, se obtiene un índice de abundancia para el atún blanco del Atlántico sur, usando técnicas multi-lineales de modelación. Desafortunadamente, el índice de abundancia no resulta fiable debido a dificultades para identificar el esfuerzo dirigido al atún blanco, y porque algunos de los días pasados en busca del atún blanco, sin capturarlo, no se han registrado como esfuerzo. Las simulaciones Montecarlo muestran que fijando el valor de B_I *(la biomasa al inicio de la serie de captura) como igual a K (el nivel medio de equilibrio sin explotar), en lugar de estimarlo, los resultados serán probablemente más fiables. Por medio de un método de estimación basado en un modelo de producción estructurado por edad, se examina el impacto del índice de abundancia para los barcos de cebo*

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de Sudáfrica, junto con los índices revisados para las pesquerías palangreras de Japón y Taiwan. Se estima que el recurso ha mermado entre un 24 y un 37% de su nivel de equilibrio sin explotar, si bien se estima que la biomasa es actualmente mayor a la necesaria para obtener el RMS (B_{RMS}). Esto es una consecuencia de que la estimación del B_{RMS} sea una pequeña fracción del nivel de equilibrio sin explotar. Desde 1986, las capturas han sido superiores a los rendimientos de reemplazo, lo que ha producido una reducción de la biomasa, las capturas anuales deben reducirse a niveles cercanos a la estimación del RMS.

1. INTRODUCTION

Albacore (*Thunnus alalunga*) are caught by longline and surface fisheries in the south Atlantic. In recent years, the bulk of the catch from this stock has been taken by the Taiwanese longline fleet, although the catches by the South African baitboat fishery (Penney *et al.* 1992) are becoming notable. Prior to 1992, assessments of this resource were conducted using the generalized production-model (Yeh *et al.* 1991, 1992). These assessments suggested that the resource was "fully exploited" and that *MSY* was roughly 28,000t. Punt (1993) showed, by means of Monte Carlo simulation, that this method provides positively biased estimates of *MSY* when the abundance index declines over the history of the fishery, as is the case for this stock. Punt *et al.* (1992) introduced the age-structured production-model technique. This method overcomes some of the problems associated with the generalized production-model. The results of this technique suggest that, in 1990, the resource was virtually at the level at which *MSY* is achieved, and that *MSY* was 23,000t. Punt *et al.* (1992) noted that current catches exceeded both the estimate of *MSY* and that of the 1991 replacement yield, and recommended that a *TAC* certainly not exceeding 25,000t was needed if further depletion was to be avoided.

Punt *et al.* (1994) updated the age-structured production-model assessments of Punt *et al.* (1992) using the then most recent data, and estimated *MSY* to be slightly in excess of 20,000t. Based on risk analyses, they suggested that catches needed to be reduced to 20,000t at least.

At the 1993 SCRS meeting (ICCAT 1994) it was noted that no *CPUE* index is available for south Atlantic albacore from the South African baitboat fishery. In this paper, we apply generalized linear modelling techniques to catch and effort data for the South African baitboat fishery to provide such an index. This modelling exercise considers areal, seasonal, and vessel power factors in the standardization process.

At its 1993 meeting, the SCRS (ICCAT 1994) considered applications of ASPIC (Prager 1992) in which the biomass at the start of the catch series (B_I) was not set equal to the average pre-exploitation equilibrium size (K). The results of these applications were not given much weight when assessing the state of the stocks and determining the value of the Maximum Sustainable Yield (*MSY*). However, the issue of whether it is more defensible to estimate, rather than fix, B_I is one which has to be examined. This is because, intuitively, fixing the value of B_I may lead to additional bias, but estimating it from data is likely to lead to increased variance. It is not clear which of these effects dominates for south Atlantic albacore and hence whether when conducting assessments of this resource, it is better to fix rather than estimate B_I. This paper examines this issue by comparing the performance of these two alternatives by means of Monte Carlo simulation.

Some of the data have been revised since the calculations of Punt *et al.* (1994) were conducted. This paper therefore conducts age-structured production-model assessments of the south Atlantic albacore resource using the most recent data.

2. CORRECTION OF SOUTH AFRICAN CATCH-AT-SIZE DATA

Examination of the size-frequency data for catches of albacore in the south Atlantic shows a number of apparent errors or discrepancies. Unrealistically large or small fish are reported in catches sampled by Taiwan and South Africa, and catch totals raised from the estimated total catch-at-size disagrees with the reported total catches in some cases. Data reported by Korea and a number of South American countries are sparse, and contain several fish which are indicated to be much larger than the known maximum size for this species.

Available south Atlantic albacore size data were reviewed by the Albacore Working Group during the 1993 meeting of the SCRS (ICCAT 1994). The problems referred to above were highlighted, and the data referred back to the countries of origin for correction in preparation for the development of a corrected catch-at-size database for south

Atlantic albacore. Correct, raised size-frequency data for South African south Atlantic albacore catches from 1985 to 1992 were presented by Penney (1994) for the three main fishing areas off the southern African west coast. Data for earlier years, as reviewed by the Albacore Working Group in 1993, were carefully examined during this study, and various errors corrected or the data in question removed.

The most obvious errors in the South African data were the existence of fish recorded as less than 40 cm or longer than 140 cm fork length. Original data records for samples measured prior to 1985 no longer exist, so it is not possible to check these against original measurements. However, it is clear from recent measures, during which unusually large and small albacore have been reliably recorded, that the South African surface fishery never lands albacore smaller than 40 cm or larger than 120 cm fork length. From investigation of Taiwanese longline catch records, it appears that albacore may occasionally exceed 120 cm fork length, but it is considered most unlikely that fish larger than 140 cm have been caught. It was therefore decided to delete fish smaller than 40 cm or larger than 140 cm from the South African historical data. Measurement errors may have resulted from incorrect use of total length, mis-identification of bigeye tuna as albacore, or simple data recording errors. Unfortunately, the lack of original historic sample records made it impossible to estimate the extent to which measurement errors may have occurred within the 40 cm to 140 cm range.

Other errors are the incorrect identification of catch method for a number of earlier samples. A few samples designated as originating from purse-seine catches refer to longline catches during the earliest years of the South African tuna fishery. A few of the then existing longline vessels obtained experimental purse-seine permits in an attempt to catch yellowfin tuna, and measures from these vessels were classified as originating from "purse-seine vessels". However, no catches of albacore were made with purse-seine nets, and the performance of these permits on yellowfin tuna was so poor that they lapsed after a few years. Following development of the surface baitboat fishery after 1980, a number of baitboat measures were incorrectly identified as originating from "sport" vessels, as a result of mis-interpretation of the ICCAT gear classification system. No code exists for poles, as used by the South African vessels, so the nearest code to a rod and line, the "sport" code, was used. These samples should therefore refer to baitboat catches.

3. DEVELOPMENT OF CPUE INDEX FOR THE SOUTH AFRICAN SURFACE FISHERY

Collection of vessel-specific catch and effort returns from South African tuna vessels started in 1985, with the introduction of the National Marine Linefish System (NMLS), a national computerized catch and effort database system for the capture and analysis of all South African commercial and recreational linefish catch and effort data (Penney 1993). The NMLS was developed in 1985 principally to capture monthly logbook returns, which became compulsory for all registered commercial line fishermen in that year. At that time, there were no specific vessels dedicated to the catching of tuna, with vessels being diverted from other fisheries at times when albacore or yellowfin tuna (*Thunnus albacares*) were particularly abundant in inshore waters. To a large extent, this is still the case, and the vessels comprising the current tuna fleet are also active participants in the squid (*Loligo vulgaris reynaudii*) jigging, snoek (*Thyrsites atun*) handline and inshore reef fisheries. This shift in targeting generally follows the seasons of maximum availability of the species concerned, but vessels frequently change from one species or area to another on a weekly or daily basis. As a consequence of this multi-species nature of South Africa's line fisheries, the data on the NMLS cannot distinguish between dedicated "tuna" vessels and those used predominantly in other fisheries. This has important implications for the apportioning of fishing effort to tuna catches reported to the NMLS.

The total number of vessels reporting catches of tuna to the NMLS ranged from 200 to 300 between 1985 and 1993. However, many of these are incidental or "recreational" participants in the fishery and there are only 100 - 150 larger vessels that participate in the South African tuna fishery on a regular basis. These vessels form only part of the 2,800 registered linefishing vessels fishing for approximately 120 different line-caught fish species, and reporting data to the NMLS. It is not possible to distinguish the tuna vessels, apart from by their catches, and many of the vessels participating in the tuna fishery change from year to year. It would therefore be incorrect to allocate all fishing effort reported to the NMLS to albacore, as this would exaggerate tuna-directed effort.

Monthly logbook returns submitted to the NMLS give no indication of original target species on each fishing day. In order to proceed, the assumption was made that a catch of any south Atlantic tuna species on any fishing day indicated active targeting for albacore on that day by the vessel concerned. This is likely to be a reasonable assumption, as albacore contribute in excess of 90% of the annual South African catch of tuna species (Penney *et. al* 1992), and albacore is generally the initial target species of any vessel that sets out to catch tuna off the Atlantic coast. Catches of yellowfin or bigeye tuna are generally made as a by-catch to an initial albacore-targeted operation. It was therefore decided to allocate a full day's fishing effort to albacore directed fishing on any day when any catch of albacore, yellowfin, bigeye or skipjack tuna was reported. Any effort reported when none of these species was caught was ignored. This approach inevitably results in the discarding of some non-successful effort when there was searching for albacore, but no catch was made. This should lead to trends in abundance estimated using the *CPUE* index derived from these data being positively biased.

This underestimate of effort is likely to have been reduced by two characteristics of the fishery. Firstly, most larger vessels, which make the bulk of the tuna catch, tend to report the total duration of a fishing trip when targeting on albacore, without indicating actual days fished. The catch is then apportioned between these days, implicitly incorporating unsuccessful fishing days during the trip. Secondly, relatively few vessels undertake exploratory fishing at the beginning of each tuna season, and most vessels tend to wait until albacore have been located before shifting their effort to the tuna fishery. The amount of unsuccessful searching effort is therefore limited to that of a few vessels.

The raw *CPUE* data extracted from the NMLS for this study consisted of the reported albacore catch, together with all effort on any day when any of the Atlantic tuna species were caught. In addition to year, there are a number of factors which are considered when standardizing *CPUE* data.

3.1.1 Within-year variability

The South African albacore fishery is markedly seasonal (Penney *et al.* 1992), with the bulk of the catch being taken between November and May. Albacore availability within South African waters, particularly in the nearshore waters, also exhibits inter-annual variations that do not appear to result solely from the abundance of the albacore resource. To attempt to capture this source of variability, month and quarter were included as factors in the model.

3.1.2 Fishing area

South African tuna vessels generally fish in three broadly defined areas, as described in Penney *et al.* (1992) and shown in Figure 1. To the south, in the vicinity of Cape Point (the Southwest Cape), smaller vessels, including recreational and sports fishermen, target on albacore within 60 nautical miles of the coast, usually during daily fishing trips. Off the South African west coast (the West Cape), commercial ice and freezer vessels target on albacore up to 180 nautical miles offshore, particularly in the vicinity of South Bank (31°S, 16°W), during trips of one to two weeks duration. Further north (off Namibia), the largest vessels, including many freezer vessels, fish on the Tripp Sea Mount fishing grounds, also up to 180 nautical miles offshore. Catch rates of albacore in these three areas are expected to differ, as a result of three factors:

i) Local availability effects such as shoaling behaviour and differing densities.

ii) Fishing gear used - sports vessels, localized in the southwestern Cape, use rod and line whereas all commercial vessels use baited poles.

iii) Vessel capability - the larger ice and freezer vessels, generally equipped with efficient navigation and colour-sounder systems, have the range and endurance to access the more distant grounds, and to remain on located tuna shoals for longer periods.

One of the factors considered in the analysis was therefore area, as it should capture the consequences of these effects.

3.1.3 Vessel power

Vessels participating in the South African albacore fishery range in size from 5m skiboats, carrying as few as 3 crew, to 30m or longer freezer vessels, carrying up to 30 crew (see Table 1). There is, in fact, a close relationship between size of vessel and number of crew carried, as South African marine safety regulations limit the maximum permissible number of crew on any vessel to the length of the vessel in metres. On most smaller vessels, all crew participate in the fishing operation, so the number of poles or rods used is related to the number of crew. Even on larger vessels where not all crew fish directly, most participate in the fishing operation by dressing landed fish or transferring them to the ice or freezer holds.

Discussions with tuna fishermen indicate that the modes in crew numbers (Table 1) closely represent the types of vessels involved. Vessels with less than 11 crew are generally recreational skiboats, gamefishing vessels or small commercial vessels occasionally used for tuna fishing. Vessels with 11 - 20 crew are generally the ice boats, particularly the older vessels diverted into the tuna fishery from other linefishing activities. However, this category also includes newer, smaller vessels, some with freezer capabilities, but with limited duration at sea. The vessels carrying more than 20 crew are generally the largest vessels, equipped with freezer facilities, and with extensive range and duration capabilities. The number of crew therefore also provides an index of the vessel size and type, and hence of the equipment and capabilities of the vessel.

Three methods of including crew size (vessel power) in the analyses have been considered.

i) *CPUE* is defined as catch / (crew x effort) rather than catch /effort.
ii) Crew is included as a covariate in the model.
iii) A categorical variable ("vessel-type") is added to the model. This variable has three levels ("Skiboat" - less than 11 crew; "Pole boats" - 11 to 20 crew; "Freezers" - more than 20 crew).

This approach to modeling vessel power does not capture all the factors which affect vessel power. For example, the earliest participants in 1980 were vessels diverted from other fisheries, and so not specialised for tuna fishing. In the ensuing years, vessels have gradually been equipped with GPS navigation systems, colour echo-sounders, live-bait wells, water-sprayers and improved freezer facilities. In some cases, new vessels have been constructed, with improved speed and range. Equally importantly, there was almost no local knowledge of albacore occurrence patterns in 1980, whereas fishing skippers have now developed a substantial knowledge of albacore migration routes, seasonal occurrence patterns and shoaling behaviour. These factors must all have served to increase the efficiency of vessels, but it has not been possible to quantify this increase. In interpreting *CPUE* trends, it has to be assumed that these factors have served to increase effective effort so that it seems likely that the trend in *CPUE* will be positively biased.

3.2 Results

An initial examination of the fit of the multi-linear model to the *CPUE* data suggested that defining *CPUE* as catch / (crew x effort) leads to extremely poor fits (in terms of r^2), so that all of the remaining analyses define *CPUE* as catch / effort. The base-case analysis excludes the data for skiboats because changes in the catch rates for these vessels are driven more by variation in nearshore oceanography than changes in overall albacore abundance. The sensitivity of the results to including the data for these vessels and to weighting each data point by its effort (to allocate more weight to catch rates derived from longer trips) is examined. Table 2 lists, and Figure 2 illustrates, the estimates of the year-factors (after exponentiation) for the various models considered. Results are shown for these three cases for the model which incorporates a year-factor only:

$$\ln(C/E) = \alpha_y + \epsilon \tag{1}$$

where α_y is the factor for year y,

as well as that which incorporates factors for year, month, area and "vessel-type":

$$\ln(C/E) = \alpha_y + \beta_v + \delta_a + \Gamma_m + \varepsilon \tag{2}$$

where β_v is the factor for "vessel-type" v,

δ_a is the factor for area a, and

Γ_m is the factor for month m.

The r^2 for model (2) when the data for all vessel-types are included in the analysis is relatively high (0.45) although the year-factors explain only 3.7% of the overall variance. The abundance index derived from this data set depends on the particular form of the model (Table 2; Figure 2). The residuals of these fits are however bimodal which suggests that the fit is not very satisfactory. The r^2s of the fits to data sets which exclude data from skiboats are relatively low (0.08-0.12) and there is virtually no improvement in r^2 by adding factors for vessel-type, area and month. One consequence of this is that the abundance indices (Table 2; Figure 2) are almost identical to the geometric mean catch rates. The residuals about the base-case fit (the residuals for model 2 are shown in Figure 3) are not bimodal, but are slightly skewed to the left.

4. SHOULD THE BIOMASS AT THE START OF THE CATCH SERIES BE ESTIMATED OR SHOULD IT BE SET EQUAL TO K?

4.1 Methodology

The method most commonly applied to determine the properties of complex statistical estimation procedures is Monte Carlo simulation. For example, Punt (1993) compared the estimation ability of observation error estimators and effort averaging approaches. He found that the former were clearly superior to the latter, and recommended that the latter not be applied at ICCAT.

Monte Carlo simulation is used here to examine the consequences, in terms of the bias and variance of the estimates of various management-related quantities, of fixing B_1 equal to K (the $B_1=K$ variant) rather than estimating B_1 (the B_1-estimated variant). The management-related quantities considered are as follows:

MSY - the Maximum Sustainable Yield
B_{1993} - the biomass at the start of 1993
B_{1993}/K - the biomass at the start of 1993 as a fraction of the pre-exploitation equilibrium biomass
E_{MSY} - the effort level at which *MSY* is achieved
RY - the current (1993) replacement yield

The age-aggregated observation error production-model considered in this analysis is specified in Appendix A. The *CPUE* data considered in these simulations are those provided by Yeh *et al.* (1994) - see Table 3 (Taiwanese 1).

Each simulation trial considers the implications of applying the two methods of determining B_1 if B_1/K equals a pre-specified value, and involves the following steps.

a) The model of Appendix A is fitted to the actual *CPUE* data for the specified value of B_1/K (this involves minimizing equation A.4 by varying the values of r, q and K). By-products of this fit are the maximum-likelihood estimates for the catch rates from 1968 to 1992.

b) 100 artificial data sets are generated using the formula:

$$(C/E)^U_y = (\widehat{C/E})_y e^{\nu^U_y} \qquad \nu^U_y \sim N(0;\sigma^2) \tag{3}$$

where $(C/E)^U_y$ is the catch rate for year y in artificial data set U,

$(\widehat{C/E})_y$ is the estimate of the catch rate in year y obtained by fitting the model to the actual data, and

σ is the (assumed) observation error variance.

c) The two variants of the estimator ($B_1=K$ and B_1-estimated) are then fitted to each of these artificial data sets.

Notes : -In order to give the B_1-estimated variant as much advantage as possible, the initial values assumed by the minimization procedure when fitting this variant are taken to be the correct values.
-Artificial catch rates are generated only for those years for which actual catch rates are available (in this case 1968 to 1992).
-The estimators are assumed to "know" the correct model of the resource, so the only uncertainty lies in the values of the model parameters.

The results of the simulations are summarised by the medians of the absolute values of relative errors (acronym MARE - $| X - X^{true} | / X^{true}$) as a function of the true value of B_1/K for the two variants. This statistic was chosen as it captures both bias and variance and because it is less sensitive to the effects of outlying estimates (which make statistics such as the root mean square error unreliable). It has been in used in previous examinations of the performance of alternative estimation methods (e.g. Punt 1988, 1989).

The base-case results correspond to the Schaefer surplus production function and the choice $\sigma=0.2$. The latter selection was made because the fit of the model to the actual data provides an estimate of σ of roughly this magnitude for a wide range of values for B_I/K. The sensitivity of the results to the replacement of the Schaefer by the Fox form, and values for σ of 0.1 and 0.3, is also examined.

4.2 Results

For B_{1993} (Figure 4a), the B_I-estimated variant outperforms the $B_I=K$ variant when the true value of B_I/K is lower than 0.5 or larger than roughly 1.75, although the difference in MAREs is not substantial when B_I/K is larger than 1.75. When B_I/K lies between 0.5 and 1.75, there is very little to choose between the two variants. For this quantity, the improvement gained by using the B_I-estimated variant is most marked when σ is set to 0.2 or 0.3, and when the surplus-production function is assumed to be of the Schaefer form.

The size of the MARE depends on the extent of observation error. The average MARE (over different values for B_I/K) is roughly 25% when ($\sigma=0.1$; this increases to 40% when σ is increased to 0.2 and reaches 50% when σ is assumed to be 0.3. This result is not unexpected as the value of σ determines the information content of the data - had σ been set to 0, the B_I-estimated variant would have provided the true values in every simulation. This same result is evident for the other management-related quantities.

The results for B_{1993}/K (Figure 4b) are notably different from those for B_{1993}. In this case, the $B_I=K$ variant outperforms the B_I-estimated variant for all values of B_I/K larger than 0.5. The extent of difference in performance is a function of the extent of observation error (σ). This difference is smallest for the lowest value of σ considered (corresponding to the most precise indices of abundance). The MAREs for this statistic are smaller than those for B_{1993}, indicating that production-model estimators are able to determine the ratio of current to pre-exploitation equilibrium biomass more reliably than the size of the current biomass itself.

For E_{MSY} (Figure 4c), the $B_I=K$ variant outperforms the B_I-estimated variant when the true value of B_I/K lies between 0.75 and 1.5 ($\sigma=0.1$), 1.75 ($\sigma=0.2$), or 2.5 ($\sigma=0.3$) if the Schaefer form of the surplus-production model is assumed. For the Fox form of the surplus-production function, the $B_I=K$ variant outperforms the B_I-estimated variant for all values of B_I/K larger than 0.5. The results for *MSY* (Figure 4d) are qualitatively the same as those for B_{1993}, with the differences in performance not being marked for any values of B_I/K except those smaller than 0.5. The MAREs for *MSY* are smaller than those for any of the other quantities, indicating that this quantity is well determined by either variant.

The results for *RY* (Figure 4e) suggest that the $B_I=K$ variant is to be preferred if B_I/K lies between 0.5 and 1.25, but that the B_I-estimated variant is to be preferred if B_I/K lies outside this interval. The MAREs for this quantity are almost as small as those for *MSY*.

4.3 Discussion

The results in Figures 4a to 4e indicate that the choice between the $B_I=K$ and B_I-estimated variants depends largely on the true value of B_I/K. If B_I/K lies between (roughly) 0.5 and 1.5, the $B_I=K$ variant is to be preferred and *vice versa*. There are two reasons why the albacore resource may not have been at its pre-exploitation equilibrium level at the start 1957: catches and variation in recruitment. From Table 3, it seems unlikely that the catches prior to 1957 would have had a substantial impact on the resource biomass so this factor is unlikely to be important when deciding whether to estimate B_I or to set it equal to K. To examine the consequences of recruitment variation on the size of the biomass at the start of 1957 relative to the pre-exploitation equilibrium size, the model used when conducting the age-structured production-model assessments was run 1000 times with no catches, but with randomly fluctuating recruitment. The *CV* of the recruitment residuals was taken to be 0.6 (roughly the median of the estimates of this quantity observed for a number of fish stocks by Beddington and Cooke (1983)). 95% of the 1000 values of B_I/K obtained from this exercise lay between 0.71 and 1.42 suggesting that the $B_I=K$ variant should be preferred to the B_I-estimated variant for this resource.

Another reason for preferring the $B_I=K$ variant is that, when it is outperformed by the B_I-estimated variant, the extent of the difference in performance between the two is small (provided B_I/K exceeds 0.5). In contrast, the $B_I=K$ variant markedly outperforms the B_I-estimated variant for the quantity B_{1993}/K (Figure 4b).

The average size (over different values of B_I/K) of the MARE for the different statistics suggests that, of the five quantities considered, B_{1993} is least and *MSY* most reliably determined.

5. REVISED STOCK ASSESSMENT

5.1 Methodology

The age-structured production-model assessment technique has been applied to data for south Atlantic albacore by Punt *et al.* (1992, 1994). This approach does not require estimates of the age-composition of the catches. In contrast to standard surplus production modelling techniques (e.g. Schaefer 1954, 1957), the method used here takes direct account of the age-structure of the population. It replaces estimation of the parameters of the surplus production function (e.g. r and K of the Schaefer model) by estimation of the parameters of a stock-recruitment relationship. The procedure differs from *ad hoc* tuned VPA, Integrated Analysis and ADAPT in that recruitment is assumed to be functionally dependent on spawner stock size, and catch-at-age data need not be used in the model-fitting process. The model and its associated estimation procedure are detailed in Appendix B, and the approach used to estimate the standard errors of the estimated quantities is given in Appendix C.

5.1.1 The base-case specification of parameter values

The base-case values of the parameters of the model have been set using the values specified by ICCAT (1990) for the stock of albacore in the north Atlantic.

a) Natural mortality (M_a) has been assumed to be independent of age a and time and equal to 0.3yr^{-1}.

b) The mass in gm (w) of a fish of age a in years (length L in cm) has been specified using the growth curve of Lee and Yeh (1993) and the length-mass relationship of Penney (1994):

$$L_a = 142.28(1 - e^{-0.1454(a-0.672)}) \tag{4}$$

and

$$w = 1.3718\text{x}10^{-5}\, L^{3.0973} \tag{5}$$

c) The fecundity schedule is given by:

$$f_a = \begin{cases} 0 & \text{if } a<5 \\ 0.5 & \text{if } a=5 \\ 1 & \text{if } a>5 \end{cases} \tag{6}$$

d) All fish older than fourteen years are lumped into a plus-group (i.e. $m=15$ - see equation B.1).

A further assumption is that the selectivity of the entire fishery is the same as that of the Taiwanese fleet, and follows a logistic curve with a length-at-50%-selectivity (L_{50}) of 80cm, and a width parameter δ assumed to be 0.5yr, so that:

$$S_{y,a} = (S_a^c)^1 = \frac{1}{1+e^{-(a-3.5)/0.5}} \tag{7}$$

where the *CPUE* series index $i=1$ refers to the series for the Taiwanese fleet.

5.1.2 Data utilized

The catch-by-mass data for the entire fishery (all fleets and gears combined) for the period 1957-1992 are listed in Table 3 and are shown in Figure 5. Table 3 also lists the Taiwanese and Japanese catch rate data used in the model fitting process. Two catch rate time series are provided for the Taiwanese longline fleet. The second of these "(2)" is not used in the analyses as "(1)" is a more recent version. The sensitivity of the results to using each of the *CPUE* series in Table 3 separately (acronyms "Taiwanese only" and "Japanese Only") is examined.

5.1.3 Further sensitivity tests

Ten additional applications of the stock assessment technique have been carried out to assess the sensitivity of the results to uncertainty in some of the parameters (acronyms in parenthesis).

a) M=0.2yr^{-1} instead of 0.3yr^{-1} (M=0.2yr^{-1}).

b) M=0.4yr^{-1} instead of 0.3yr^{-1} (M=0.4yr^{-1}).

c) The age-at-50%-selectivity is 2.61 years (corresponding to a length-at-50%-selectivity of 70 cm instead of 80 cm) (a_c=2.61).

d) The age-at-50%-selectivity is 4.61 years (corresponding to a length-at-50%-selectivity of 90 cm instead of 80 cm) (a_c=4.61).

e) The age-at-50%-selectivity changes from 4.61 in 1957 to 2.61 in 1992 (Decrease a_c).

f) The age-at-50%-selectivity changes from 2.61 in 1957 to 4.61 in 1992 (Increase a_c).

g) The Beverton-Holt form of the stock-recruitment relationship is replaced by the Ricker form (Ricker).

h) The length-mass relationship of Penney (1994) is replaced by that of Beardsley (1971) (Alt Lm).

i) The growth curve of Lee and Yeh (1993) is replaced by that of Bard (1981) (Alt Gr(1)).

j) The growth curve of Lee and Yeh (1993) is replaced by that of Gonzalez-Garces and Farina-Perez (S.Y. Yeh pers commn. to A.J. Penney) (Alt Gr(2)).

The variance estimation procedure described in Appendix C (henceforth referred to as the "standard" variance estimation procedure) is based on the assumption that the age-specific selectivity pattern is known without error. To assess the sensitivity of the variance estimates to this assumption, an alternative method of variance estimation has been implemented for the base-case application. This alternative (acronym "With selectivity variance") involves generating noise about the assumed pattern as follows:

$$S_{y,a} = S_a e^{\Phi_{y,a}} \qquad\qquad \Phi_{y,a} \sim N(0, 0.2^2) \tag{8}$$

where $N(0,0.2^2)$ is a normal distribution with mean zero and standard deviation 0.2.

On each occasion that the model is fitted to a bootstrap replicate data set, the deterministic selectivity pattern is replaced by a stochastic realization provided by equation (8). The choice of 0.2 for the *CV* of the fluctuations about the assumed age-specific selectivity pattern is essentially arbitrary, and is based on the selection made by Punt (1992) for analyses involving Cape hake.

5.2 Results and discussion - base-case application

Table 4 contains the base-case estimates of six management-related quantities, their *CV*s and 90% confidence intervals (results are shown for the "standard" and "alternative" variance estimation procedures). These six quantities are:

a) *MSY*	the Maximum Sustainable Yield,
b) TAC_{sq}	the $F_{status\text{-}quo}$ harvesting strategy *TAC* for 1993,
c) *RY(93)*	the 1993 replacement yield,
d) B_{1992}	the (exploitable) biomass in the middle of 1992,
e) B_{1992}/K	the (exploitable) biomass in the middle of 1992 as a fraction of the corresponding pre-exploitation equilibrium biomass, and
f) B_{1992}/B_{MSY}	the (exploitable) biomass in the middle of 1992 as a fraction of the corresponding equilibrium biomass at which *MSY* is achieved.

Figure 6 plots the actual and model-predicted *CPUE* data and Figure 7 shows the exploitable biomass time series (in absolute terms and as a fraction of the corresponding pre-exploitation equilibrium level).

There are no obvious indications of model mis-specification in Figure 6 for the Taiwanese and for the most recent Japanese *CPUE* series. In contrast, the model is unable to capture the large declines in catch rate between 1959 and 1975 which are indicated by the earlier Japanese *CPUE* data.

The estimate of *MSY* (26,000t) is lower than all but one of the catches since 1984, and the model indicates that catches have consistently exceeded replacement yields since 1986, with the consequence that the biomass has been dropping over this period (Figure 7). The resource is estimated to be above the biomass at which *MSY* is achieved

(B_{1992} is 133% of B_{MSY}). The current replacement yield is estimated to be 25,300t. All of the management-related quantities except B_{1992} are estimated fairly precisely ("standard" and "alternative" method *CVs* of roughly 20% or less). This is not unexpected given the results obtained in the previous section regarding the relative reliability of estimates of current biomass. The "standard" method *CV* for the $F_{status\text{-}quo}$ strategy *TAC* for 1993 seems unrealistically low compared to the *CVs* for the other quantities. This is probably because temporal fluctuations in selectivity are ignored by the "standard" method - this *CV* increases from 1.0% to 6.4% when the later source of variability is considered.

5.3 Results and discussion - sensitivity tests

In general, the results are insensitive to the values of the parameters of the age-specific selectivity pattern, the form of the stock-recruitment relationship, the growth equation, the length-mass relationship, the value of natural mortality, and which of the catch rate series are used in the model fitting process (Table 5). The most optimistic appraisals (in terms of the B_{1992} / B_{MSY} ratio) are those in which a_c decreases over the period 1957 to 1992 and in which a_c is assumed to be 4.61. Note, however, that this is not a reflection of a much larger biomass estimate, but rather a consequence of lower values for B_{MSY} / K (0.19 and 0.21 respectively compared to 0.25 for the base-case). The least optimistic appraisal (i.e. that which indicates the greatest level of biological over-exploitation) is that in which the Beverton-Holt form of the stock-recruitment relationship is replaced by the Ricker form ("Ricker" in Table 5). In this case, the resource is assessed to be only slightly larger than 75% of B_{MSY}. This is a reflection of a difference between the value of B_{MSY} / K for the base-case and for the "Ricker" sensitivity test (B_{MSY} / K is 0.46 for this test). The range of point estimates of current depletion is fairly narrow (0.241 to 0.428).

The estimate of current replacement yield ranges from 22,100 (Decrease a_c) to 27,200t (a_c=4.61), and the *MSY* estimates range from 22,500 (Ricker) to 32,900t (Decrease a_c). The estimates of $F_{status\text{-}quo}$ strategy *TACs* are almost completely insensitive to changes to the specifications of the assessment and range from 27,400t to 28,200t.

The estimates of *CV* in Table 5 are not considered reliable because in some cases, the point estimate of the stock-recruitment relationship parameter, ß, is zero. As each bootstrap simulation takes the point estimates as starting values for the non-linear minimization search, this can lead to problems with convergence to local minima.

5.4 Comparison with other approaches

The sensitivity of the stock assessment results to the form of the model used has been examined by applying two forms of the dynamic production-model to the data in Table 3. This model has the form:

$$B^e_{y+1} = B^e_y + g(B^e_y) - C_y$$

$$(C/E) = q\frac{(B_{y+1} + B_y)}{2} \qquad (9)$$

where the surplus production function is one of:

$$g(B) = \begin{cases} rB(1-B/K) & \text{-- Schaefer form} \\ rB(1-lnB/lnK) & \text{-- Fox form} \end{cases}$$

and r is the intrinsic growth rate parameter,
K is the average pre-exploitation equilibrium size ("carrying capacity"), and
B^e_y is the exploitable biomass at the start of year y (these models assume $B^e_{1957} = K$).

The results of fits of the two forms of the dynamic production-model are contrasted with those for the base-case application of the age-structured production-model in Table 6. The results of the two assessments in Table 6 are more pessimistic than those in Tables 4 and 5. For example, both assessments suggest that the resource is currently biologically overexploited and that *MSY* is less than 25,000t. It should however be noted that these estimates are less precise than those for the base-case.

6. CONCLUSIONS / RECOMMENDATIONS

a) Age-structured production-model analyses suggest once again that current catches are exceeding the Maximum Sustainable Yield, and that the resource has been declining since 1986.

b) Although the resource is estimated to be currently larger than the level at which *MSY* is achieved, catch levels should be reduced to a level which is sustainable to lessen the probability of the resource becoming biologically overexploited.

c) Age-aggregated production-model approaches provide markedly more pessimistic appraisals of resource status and productivity - the results of these assessments should be borne in mind when management recommendations are considered.

d) As it appears that the stock is currently close to B_{MSY}, or lower than this level already, all participants in the fishery should take the responsibility for accurately monitoring catches and abundance, in order to detect further changes timeously.

e) The abundance index derived from South African baitboat catch and effort data is not very reliable because of difficulties in defining directed effort.

f) B_I (the biomass at the start of the catch series) should be fixed at K, rather than estimated along with the other model parameters when conducting assessments of this resource.

Table 1. Average number of vessels (1985-1989) in the South African baitboat fishery as a function of the number of crew.

Number of crew	<4	4-5	6-7	8-9	10-11	12-13	14-15	16-17	18-19	20-21	22-23	24+
Avg. No. of vessels	34.4	45.5	11.3	5.7	6.6	20.2	27.9	32.4	14.9	30.8	10.0	12.0

Table 2 **Indices of south Atlantic albacore abundance calculated from multi-linear model fits to the South African baitboat catch and effort data.**

Year	Base-case		Include skiboats		Effort weighting	
	Model (1)	Model (2)	Model (1)	Model (2)	Model (1)	Model (2)
1985	1.000	1.000	1.000	1.000	1.000	1.000
1986	1.137	1.047	0.454	0.819	1.240	1.228
1987	1.650	1.792	0.826	1.386	1.464	1.615
1988	1.108	1.080	0.702	0.959	1.138	1.155
1989	0.806	0.831	0.605	0.756	0.822	0.879
1990	0.575	0.618	0.456	0.622	0.612	0.648
1991	0.582	0.665	0.332	0.727	0.771	0.898
1992	1.178	1.289	0.650	1.084	1.061	1.240
1993	0.643	0.758	0.574	0.753	0.643	0.761

Table 3. **Catch and catch rate data for the albacore resource in the South Atlantic.**

Year	Catch ('000t)	Taiwanese CPUE (1)	(2)	Japanese CPUE		
1957	0.7					
1958	1.0					
1959	4.8			394.713		
1960	10.5			315.550		
1961	10.8			237.978		
1962	18.9			216.452		
1963	17.4			142.927		
1964	26.0			122.474		
1965	29.8			76.864		
1966	27.3			75.207		
1967	15.9			99.258		
1968	25.7		354.006	74.745		
1969	28.5		781.405	49.687	48.578	
1970	23.7		452.270		30.349	
1971	24.9		669.089		35.365	
1972	33.2		274.434		28.315	
1973	28.2		235.732		16.744	
1974	19.7		318.979		16.697	
1975	17.6	2.488	236.841		10.761	7.417
1976	19.5	2.338	283.981			10.122
1977	21.7	2.392	306.590			9.516
1978	23.2	2.067	369.335			9.023
1979	22.6	1.838	315.058			6.451
1980	22.9	1.862	331.011			6.017
1981	24.0	2.178	359.760			9.193
1982	29.7	2.323	270.216			8.848
1983	14.9	1.933	303.181			6.400
1984	13.9	2.040	280.978			6.498
1985	29.7	2.386	274.233			9.480
1986	36.3	2.488	320.977			9.428
1987	39.7	1.695	287.410			6.098
1988	29.0	1.602	207.925			4.252
1989	26.7	1.721	221.405			5.465
1990	29.7	1.749	205.661			5.453
1991	25.7	1.750	276.276			5.618
1992	28.8		191.820			4.704

Table 4 **Management variable estimates, their estimated *CVs* (expressed as percentages) and their 90% confidence intervals for the base-case analysis. Results are shown for the "standard" variance estimation procedure which makes no allowance for variability about the assumed age-specific selectivity function, and for an alternative procedure which does. Biomass and catch units are '000t. The number of bootstrap resamples, U_{max}, used for obtaining the estimates in this Table is 500.**

Quantity	Estimate	No selectivity variance		With selectivity variance	
		CV	90% C.I.	CV	90% C.I.
MSY	26.0	16.6	14.1; 29.7	16.5	16.9; 29.9
TAC_{sq}	28.0	1.0	27.3; 28.3	6.4	24.5; 31.5
$RY(93)$	25.3	9.9	17.8; 26.3	9.7	19.3; 26.5
B_{1992}	102.7	49.8	70.9; 259.9	44.8	73.7; 218.9
B_{1992}/K	0.332	15.5	0.251; 0.456	14.8	0.262; 0.472
B_{1992}/B_{MSY}	1.334	21.9	0.856; 1.924	22.4	0.858; 1.927

Table 5. **Management variable estimates and their *CVs* estimated by means of the "standard" procedure (and expressed as percentages) for the base-case analysis and the sensitivity tests. Biomass and catch units are '000t.**

Quantity	Acronym				
	Base-case	Japanese Only	Taiwanese Only	M=0.2yr^{-1}	M=0.4yr^{-1}
MSY	26.0 (16.6)	25.1 (4.3)	25.2 (40.9)	25.5 (5.3)	25.3 (17.3)
TAC_{sq}	28.0 (1.0)	27.4 (1.8)	28.2 (0.9)	27.9 (0.9)	27.9 (1.2)
$RY(93)$	25.3 (9.9)	24.6 (3.9)	24.7 (22.5)	23.9 (2.3)	25.3 (10.0)
B_{1992}	102.7 (49.8)	66.6 (25.3)	166.3 (125.5)	140.4 (19.6)	91.2 (56.8)
B_{1992}/K	0.332 (15.5)	0.241 (19.5)	0.428 (20.6)	0.338 (13.6)	0.351 (14.5)
B_{1992}/B_{MSY}	1.334 (21.9)	1.161 (19.6)	1.298 (37.4)	1.432 (13.6)	1.178 (26.8)

Quantity	Acronym				
	a_c=2.61	a_c=4.61	Increase a_c	Decrease a_c	Alt-lm
MSY	26.0 (4.9)	27.2 (31.9)	20.6 (8.2)	32.9 (21.6)	26.8 (5.1)
TAC_{sq}	27.9 (1.0)	28.1 (0.8)	-	-	28.0 (0.9)
$RY(93)$	24.9 (2.4)	26.0 (7.9)	25.0 (5.6)	22.1 (12.7)	25.5 (1.9)
B_{1992}	111.4 (19.7)	92.1 (53.8)	79.2 (45.9)	115.6 (63.9)	100.6 (20.1)
B_{1992}/K	0.329 (14.0)	0.338 (15.6)	0.272 (20.0)	0.367 (15.8)	0.327 (14.1)
B_{1992}/B_{MSY}	1.336 (14.1)	1.578 (22.6)	0.950 (16.5)	1.912 (22.8)	1.506 (14.2)

Quantity	Acronym		
	Alt-Gr(1)	Alt-Gr(2)	Ricker
MSY	26.0 (17.0)	26.5 (16.8)	22.5 (8.5)
TAC_{sq}	28.0 (1.4)	28.0 (1.1)	27.4 (1.8)
$RY(93)$	25.7 (9.5)	25.8 (9.4)	22.7 (1.8)
B_{1992}	78.8 (57.5)	87.1 (58.5)	100.8 (40.6)
B_{1992}/K	0.339 (14.7)	0.335 (15.2)	0.352 (15.9)
B_{1992}/B_{MSY}	1.261 (19.6)	1.378 (23.1)	0.773 (14.4)

Table 6 Comparison of the results of the base-case assessment, set out as in Table 5, with those of the Fox and Schaefer forms of the dynamic production model. Biomass and catch units are '000t.

Quantity		Acronym	
	Base-case	Schaefer	Fox
MSY	26.0 (16.6)	23.6 (23.8)	24.8 (22.8)
TAC_{sq}	28.0 (1.0)	-	-
$RY(93)$	25.3 (9.9)	20.4 (28.1)	24.1 (23.2)
B_{1992}	102.7 (49.8)	62.6 (201.9)	53.2 (200.9)
B_{1992}/K	0.332 (15.5)	0.315 (25.8)	0.286 (24.7)
B_{1992}/B_{MSY}	1.334 (21.9)	0.630 (25.8)	0.777 (24.7)

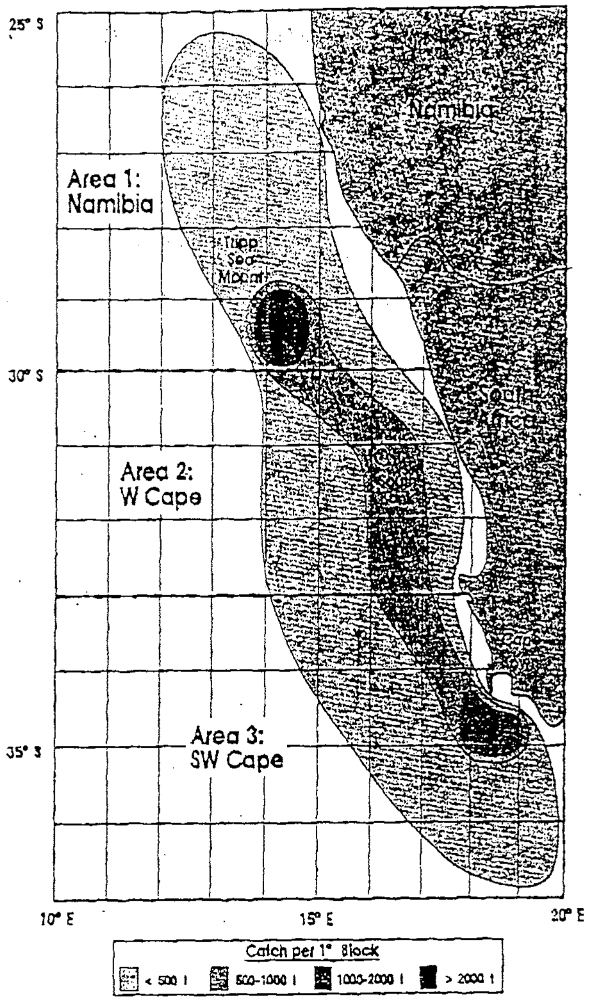


Fig. 1 Map of southern Africa showing the South African tuna fishing areas.

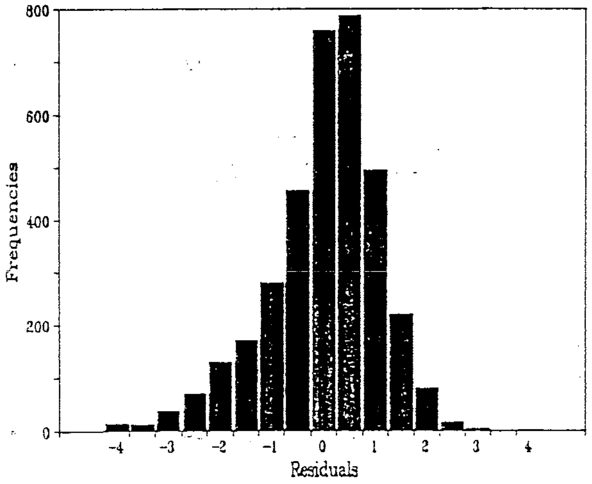


Fig. 3 Residuals about the base-case fit of the model of equation (2) to the catch rate data for the South African baitboat fishery.

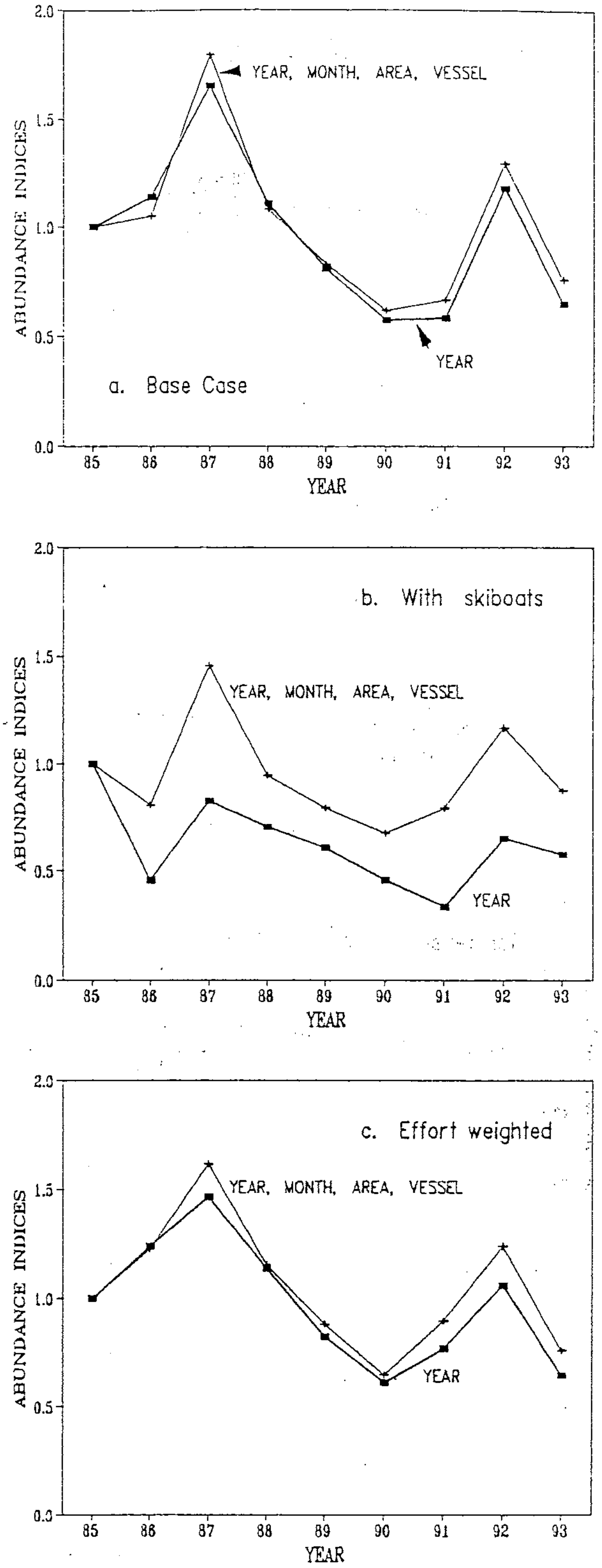
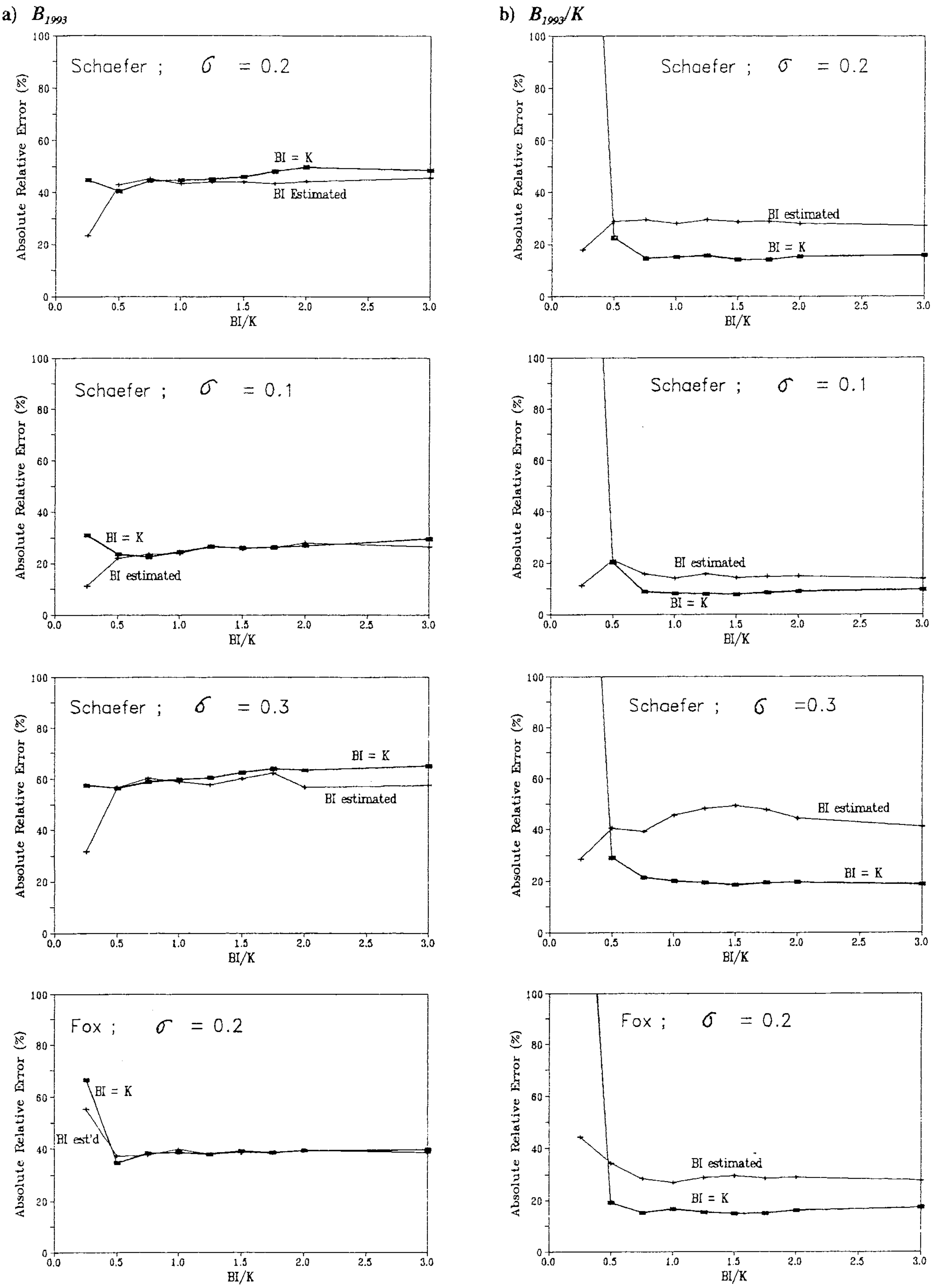


Fig. 2 Indices of south Atlantic albacore derived from analyses of the catch rate data for the South African baitboat fishery. Results are shown in (a) for the base-case analysis which excludes data from skiboats and weights each data point equally, in (b) for an analysis based on the complete data set, and in (c) for an analysis which weights each data point by its effort. These results are shown for the models of equation (1) and equation (2) of the main text.


a) B_{1993}

b) B_{1993}/K

Fig. 4 The median of the absolute values of relative errors as a function of the true value assumed for B_I/K. Results are shown in plots (a) to (e) for five management-related quantities. Each plot provides results for two variants of the Butterworth-Andrew observation error estimator ("B_I-fixed" and " B_I-estimated") and for four alternative paramerizations / observation error variance levels of the model used to generate the artificial data sets (see text for details).

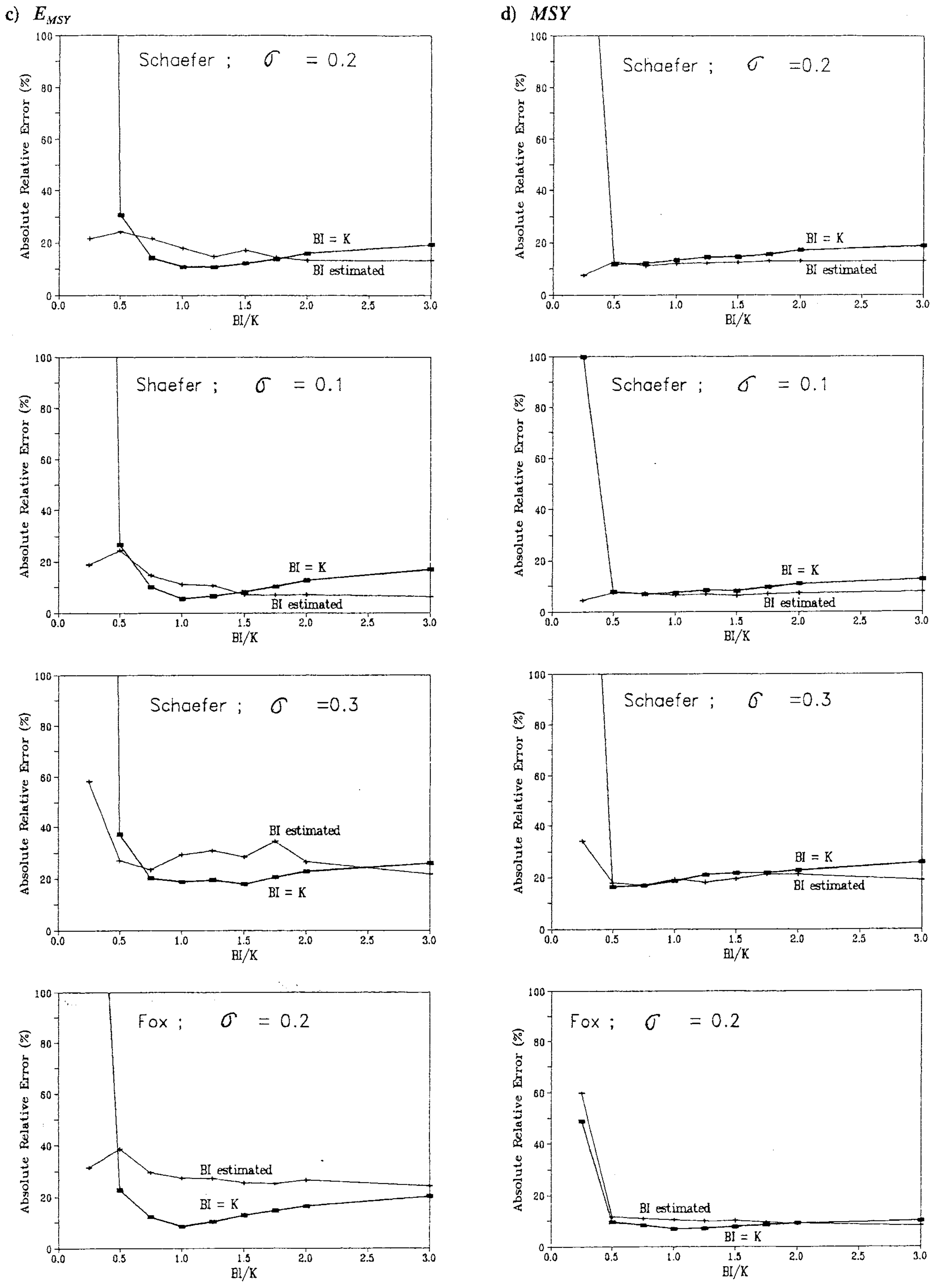

c) E_{MSY} d) MSY

Fig. 4. Continued.

e) ***RY***

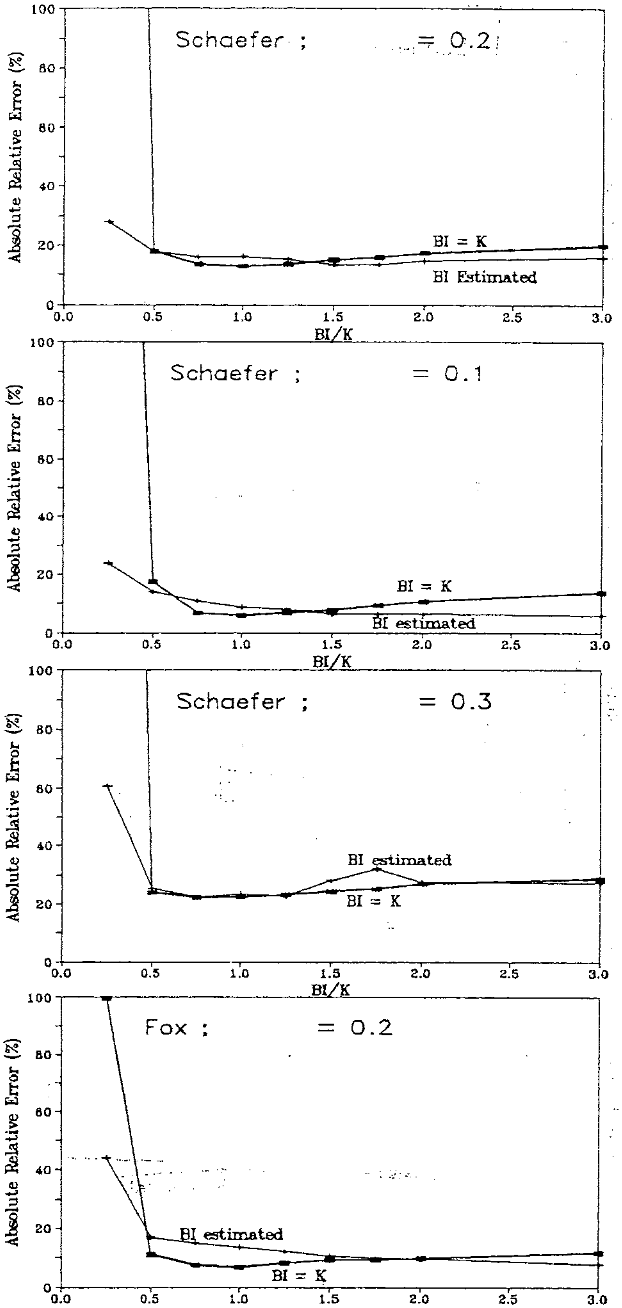


Fig. 4 Continued.

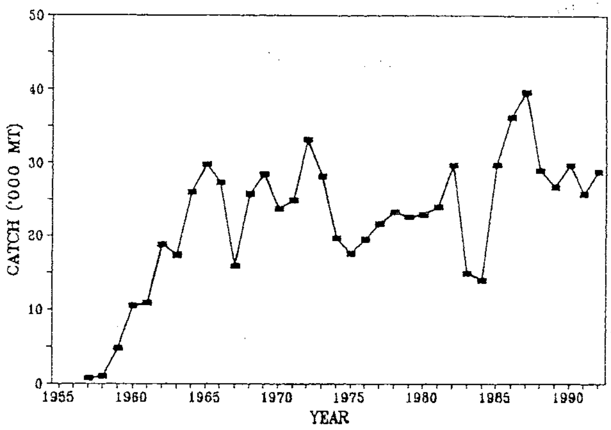


Fig. 5 Catch time series for the albacore population in the south Atlantic.

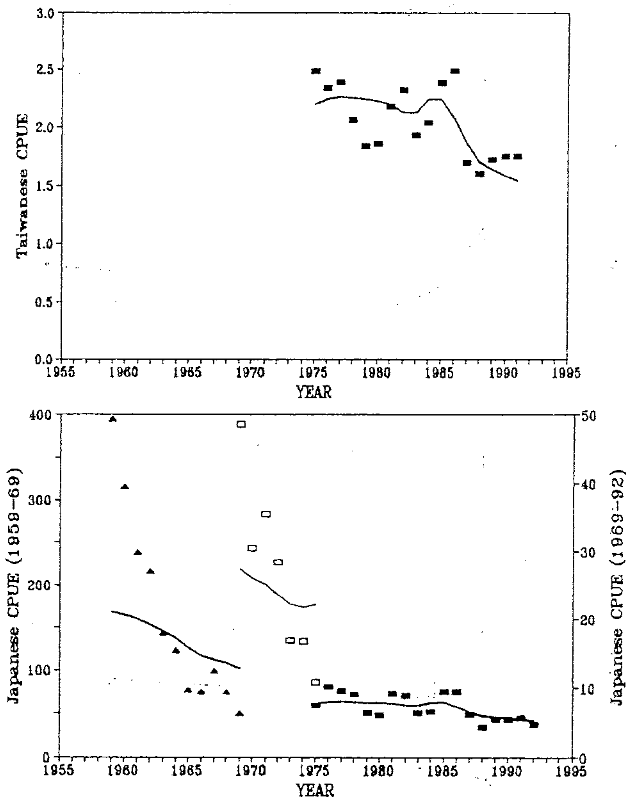


Fig. 6 Comparison of observed and base-case model-predicted *CPUE* series.

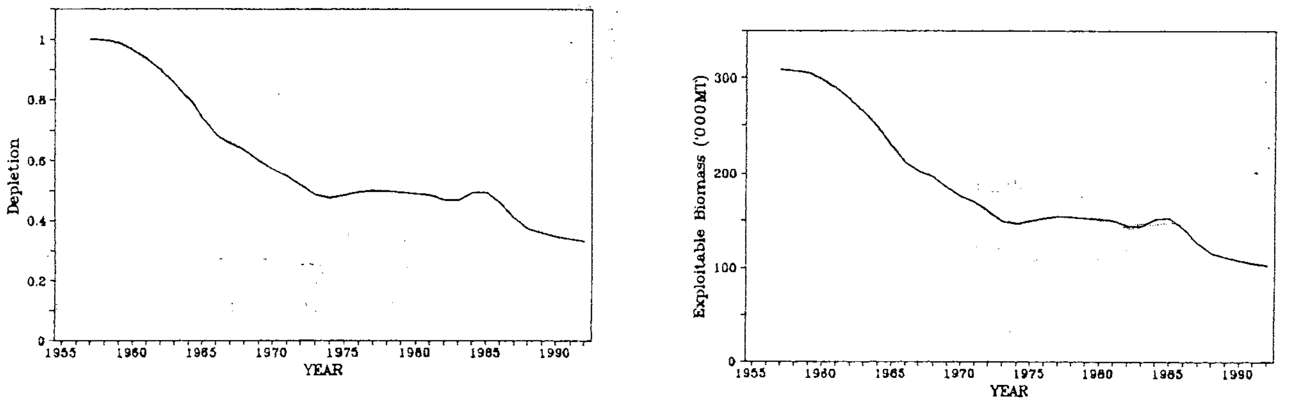


Fig. 7 Exploitable biomass trajectories for south Atlantic albacore obtained from the base-case application of the age-structured production-model. The biomass is shown as a fraction of its unexploited equilibrium level and in absolute terms.

APPENDIX A : THE BUTTERWORTH-ANDREW OBSERVATION ERROR ESTIMATOR

(Butterworth and Andrew 1984; Punt and Butterworth 1991; Punt 1994)

The fishery is modelled as follows:

$$B_{y+1} = B_y + g(B_y) - C_y \tag{A.1}$$

$$(C/E)_y = q\frac{B_y + B_{y+1}}{2}e^{v_y} \qquad v_y \textit{ from } N(0;\sigma_v^2) \tag{A.2}$$

where B_y is the biomass at the start of year y [the biomass at the start of the catch series (B_{1957}, termed B_I) is either set equal to K (acronym "$B_I = K$") or is estimated along with the other model parameters (acronym "B_I-estimated")],

$g(B)$ is surplus production as a function of biomass, either:

$$g(B) = rB(1-B/K) \qquad \text{- the Schaefer from}$$

or

$$g(B) = rB(1-\ln B/\ \ln K) \qquad \text{- the Fox form} \tag{A.3}$$

r is the intrinsic growth rate parameter,

K is the average biomass level prior to exploitation (carrying capacity),

C_y is the catch during year y,

$(C/E)_y$ is the *CPUE* for year y,

q is the catchability coefficient, and

σ_v^2 is the variance of the log of the (multiplicative) observation error.

Note that, since equation (A.1) is deterministic, zero process error is assumed, i.e. this model leads to an observation error estimator. Estimates of the parameter values are obtained by maximizing the appropriate likelihood function:

$$L = \left[\prod_y \exp\{-\hat{v}_y^2/(2\hat{\sigma}_v^2)\}/(\sqrt{2\pi}\,\hat{\sigma}_v)\right] \tag{A.4}$$

where the product is over all years (y) for which *CPUE* data are available,

$\hat{v}_y = \ln(C/E)_y - \ln(\widehat{C/E})_y$ and

$\hat{\sigma}_v^2 = \sum_y \hat{v}_y^2 / \sum_y 1$ [note that no attempt is made to adjust this estimate for bias].

APPENDIX B : THE AGE-STRUCTURED PRODUCTION MODEL

The resource dynamics are modelled by the equations:

$$N_{y+1,a} = \begin{cases} N_{y+1,0} & a = 0 \\ N_{y,a-1}\, e^{-(M_{a-1}+S_{y,a-1}F_y)} & a = 1,\ldots, m-1 \\ N_{y,m-1}\, e^{-(M_{m-1}+S_{y,m-1}F_y)} + N_{y,m}\, e^{-(M_m+S_{y,m}F_y)} & a = m \end{cases} \tag{B.1}$$

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 fish of age a,
$N_{y,0}$ is the number of 0-year-olds at the start of year y,
$S_{y,a}$ is the age-specific selectivity function (for all fleets and gears combined),
m is the maximum age considered (taken to be a plus-group), and
F_y is the (asymptotic) fishing mortality during year y.

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

a) Selectivity-at-age ($S_{y,a}$) is input instead of being estimated.

b) The strength of the 0-year-class is related deterministically to spawner stock size by the Beverton-Holt stock-recruitment relationship:

$$N_{y,0} = \frac{\alpha B^s_y}{\beta + B^s_y} \tag{B.2}$$

$$B^s_y = \sum_{a=1}^{m} f_a w_a N_{y,a} \tag{B.3}$$

where B^s_y is the spawner stock size at the start of year y,
w_a is the mass of a fish of age a at the start of the year,
f_a is the fecundity of a fish of age a, and
α, β are the stock-recruitment relationship parameters.

c) The resource was at the deterministic equilibrium that corresponds to an absence of harvesting at the start of 1957.

d) The catches-by-mass are assumed to be exact so that:

$$C_y = \sum_{a=0}^{m} w_{a+1/2} S_{y,a} F_y N_{y,a} \frac{1-\exp[-(M_a+S_{y,a}F_y)]}{M_a + S_{y,a}F_y} \tag{B.4}$$

where C_y is the catch-by-mass in year y, and
$w_{a+1/2}$ is the mass of a fish of age a in the middle of the year.

In order to estimate the parameters of this model (α, ß and the catchability coefficients - the values for the other parameters are input), it is assumed that *CPUE* is linearly proportional to a corresponding exploitable biomass. The quantity minimized (the negative of the log-likelihood function after removal of constants) to obtain the parameter estimates is:

$$-\ln L = \sum_i \left(\frac{1}{2(\sigma^i)^2} \sum_y \left(\ln(C/E)^i_y - \ln(q^i(B^e_y)^i)\right)^2 + n^i \ln \sigma^i \right) \tag{B.5}$$

where σ^i is the residual standard deviation for *CPUE* series i:

$$\hat{\sigma}^i = \sqrt{\frac{1}{n^i}\sum_y (\ln(C/E)^i_y - \ln(q^i(B^e_y)^i))^2} \tag{B.6}$$

$(C/E)^i_y$ is the *CPUE* for year y and *CPUE* series i,

n^i is the number of data points for *CPUE* series i,

$(B^e_y)^i$ is the exploitable biomass corresponding to the i'th *CPUE* series, for year y:

$$(B^e_y)^i = \sum_{a=0}^{m} w_{a+1/2}\,(S^e_a)^i N_{y,a}\, e^{-(M_a + S_{y,a}F_y)/2} \tag{B.7}$$

$(S^e_a)^i$ is the selectivity function corresponding to the i'th fleet (i.e. i'th *CPUE* series), and

q^i is the catchability coefficient for *CPUE* series i.

APPENDIX C : ESTIMATION OF STANDARD ERRORS

Consider the case of a quantity Q estimated from a data set **X**. The (conditioned) parametric bootstrap variance-estimation procedure (Efron 1981, 1982, 1985; Punt 1988, 1989; Punt and Butterworth 1993) estimates the standard error of as follows. A large number (U_{max}, where $U=1, \ldots, U_{max}$) of random bootstrap samples $\{\mathbf{X}^U: U=1, \ldots, U_{max}\}$ are generated, and the corresponding set $\{\hat{Q}^1, \hat{Q}^2, \ldots \hat{Q}^{U_{max}}\}$ is computed. The $U_{max}=500$ bootstrap resamples considered in this instance, each of which contains a fixed catch series and a random effort series, are generated from the predicted *CPUE* series obtained by fitting the model to the data. Error is then added to these predicted *CPUE* estimates according to the formulae:

$$(C/E)^{i,U}_y = (C/E)^i_y\, e^{\varepsilon^{i,U}_y} \qquad \varepsilon^{i,U}_y \sim N(0, (\hat{\sigma}^i)^2) \tag{C.1}$$

where $(C/E)^{i,U}_y$ is the *CPUE* in year y for *CPUE* series i in bootstrap data set U,

$(C/E)^i_y$ is the estimate of *CPUE* in year y for *CPUE* series i obtained by fitting the model to the actual data, and

$\hat{\sigma}^i$ is the estimate of the residual standard deviation for *CPUE* series i (see equation B.6).

The variance of $\hat{Q}$ is then estimated by:

$$VAR(\hat{Q}) = \frac{1}{U_{max}-1}\sum_{U=1}^{U_{max}} (\hat{Q}^U - Q_{(.)})^2 \tag{C.2}$$

where $Q_{(.)}$ is the mean of the $\hat{Q}^U$'s.

Use of GLM methods to calculate a *CPUE* series introduces temporal correlations, which strictly should be taken into account in the parameter and variance estimation processes. This factor has been ignored here in the interests of simplicity. The consequences for the results are unlikely to be substantial.