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STOCK ASSESSMENT AND RISK ANALYSIS FOR THE SOUTH ATLANTIC POPULATION OF ALBACORE *(THUNNUS ALALUNGA)*

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SUMMARY

The South Atlantic population of albacore is assessed by means of an age-structured population model using Taiwanese and Japanese catch rate data up to 1991. Risk Analysis calculations are carried out for a variety of future catch trajectories, and the implications of minimum size restrictions are evaluated. The resource is estimated to be markedly depleted, to probably little more than 20% of its pre-exploitation level, and to have an MSY slightly in excess of 20,000 MT/yr. This analysis indicates that recent average annual catches of some 28,000 MT need to be reduced to 20,000 MT, at least, to stabilize the population. Careful monitoring of the situation will be necessary, as even that action might not be sufficient to arrest the decline in abundance. Minimum size limitations do not appear to be of much potential benefit for this fishery.

RESUME

La population de germon de l'Atlantique sud est évaluée par un modèle de population structuré par âge en utilisant les données taiwanaise et japonaise du taux de capture jusqu'en 1991. Les calculs d'analyses de risque sont effectués pour une variété de trajectoires futures de capture et l'évaluation des implications de restrictions de taille minimum. La ressource est estimée être très faible --probablement à un peu plus de 20% de son niveau de pré-exploitation-- et d'avoir une PME légèrement au-dessus de 20.000 TM par an. Cette analyse indique que la moyenne des prises annuelles récentes de 28.000 TM doivent être réduites du moins à 20.000 TM, de façon à stabiliser la population. Un suivi strict de la situation sera nécessaire, même si l'action peut ne pas être suffisante pour arrêter le déclin de l'abondance. Des limites minimum de taille ne semblent pas être très favorables pour cette pêcherie.

RESUMEN

La población de atún blanco del Atlántico sur se evalúa por medio de un modelo de población estructurado por edad, que usa datos de tasa de captura de Taiwan y Japón hasta el año 1991. Se realizan cálculos analíticos de riesgo para una variedad de trayectorias futuras de captura y se evalúan las implicaciones de restricciones de talla mínima. Se estima que el recurso está muy bajo - probablemente algo menos del 20% de su nivel anterior a la explotación - y que su RMS es ligeramente superior a 20.000 t por año. Este análisis indica que la captura media anual de los años recientes, de unas 28.000 t, debe quedar reducida a 20.000 t, para estabilizar, al menos, la población. Es necesario hacer un atento seguimiento de la situación, ya que es posible que incluso la aplicación de esta medida no sea suficiente para detener el descenso de la abundancia. No parece que las limitaciones de talla mínima representen un gran beneficio potencial para esta pesquería.

INTRODUCTION

The fishery for albacore (*Thunnus alalunga*) in the south Atlantic commenced in the late 1950's. Catches increased steadily, and have, since 1964, exceeded 20,000t in most years (Table 1, Figure 1). The two largest catches were recorded in 1986 and 1987 (35,100 and 38,300t respectively). Since then, catches have decreased. Although the catch time series exhibits no obvious trend after the early 1960's, the Taiwanese catch rate time series (see Figure 2, for example) declines almost linearly throughout the period 1968 to 1991. An earlier Japanese catch rate series shows a declining trend from 1959 to 1971 (see Figure 2).

Assessments of this stock in recent years (e.g. ICCAT 1990, 1991, 1993) have been based on the effort-averaging estimator developed by Fox (1975) (e.g. Yeh *et al.* 1991, 1992). This approach suggests that the resource is currently "fully-exploited" and that *MSY* is 26-27,000t (ICCAT 1993). Effort-averaging estimation methods have been severely criticized in the literature (e.g. Sissenwine 1978, Roff and Fairbairn 1980, Butterworth and Andrew 1984, Punt 1988, Polacheck *et al.* 1993). Butterworth and Andrew (1984) and Punt (1988), for example, demonstrate that when applied to *CPUE* series which decline over time, these methods lead to severely positively biased estimates of *MSY* and optimal effort.

Punt *et al.* (1992) applied dynamic production model and age-structured production model estimation approaches to catch and catch rate data for the south Atlantic albacore resource and concluded that *MSY* was less than 25,000t and that the current replacement yield (the catch which will leave the biomass at its current size) was of similar magnitude.

The catch rate data upon which the analyses of Punt *et al.* (1992) were based have since been revised (Hsu and Chang 1992). This paper updates the assessment of Punt *et al.* (op. cit.) using the revised catch rate data, and examines the consequences of various possible candidate management measures (minimum size restrictions and *TAC*s) by means of Risk Analysis techniques.

STOCK ASSESSMENT

Methodology

Assessments of the stock of albacore in the north Atlantic (e.g. ICCAT 1991, 1993) have been carried out using *ad hoc* tuned VPA (e.g. Pope and Shepherd 1985; Butterworth *et al.* 1990) and ADAPT (Gavaris 1988), although, in principle, the statistically more defensible Integrated Analysis (e.g. Deriso *et al.* 1985; Lewy 1988; Kimura 1990) could have been used instead. Unfortunately, it is impossible to apply any of these assessment techniques to south Atlantic albacore because of the lack of reliable estimates of the age-composition of the historic catches.

It is therefore necessary to utilize an assessment technique which does not require estimates of the age-composition of the catches. The most obvious candidates are surplus production models (e.g. Schaefer 1954, 1957). However, given that one of the alternative actions to be investigated is the imposition of a minimum size restriction (which would change the current age-specific selectivity pattern), it is necessary to take account of the age-structure of the population. Standard surplus production models (e.g. Schnute 1977; Butterworth and Andrew 1984; Lleonart *et al.* 1985) treat the resource biomass as a lumped variable and therefore do not take direct account of the underlying age-structure. In contrast, the method used here does take 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 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 A, and the approach used to estimate the standard errors of the estimated quantities is given in Appendix B.

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 calculated using the growth curve of Bard (1981) and the length-mass relationship of Penney (1993) :

$$L_a = 124.74\left(1 - e^{-0.2284(a+0.9892)}\right) \qquad (1)$$

and

$$w = 1.3718\text{x}10^{-5}\, L^{3.0973} \qquad (2)$$

c) The fecundity schedule is given by :

$$f_a = \begin{cases} 0 & \text{if } a < 5 \\ 0.5 & \text{if } a = 5 \\ 1 & \text{if } a > 5 \end{cases} \qquad (3)$$

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

$$S_{y,a} = (S_a^e)^1 = \frac{1}{1 + e^{-(a-3.5)/0.5}} \qquad (4)$$

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

Data utilized

The catch-by-mass data for the entire fishery (all fleets and gears combined) for the period 1957-1991 are listed in Table 1. It is suspected that South African catches over the 1985-1991 period may have been under-reported. The extent of such under-reporting is currently under investigation, but is not expected to have exceeded 33%. Accordingly, the South African component of the 1985-1991 catches reported in ICCAT (1993) has been increased by 33% for the purposes of these analyses. If this adjustment is too large, the consequence will be a slight positive bias in estimates of sustainable yield. To bound the implications of this source of uncertainty, a sensitivity test (acronym "Catch adj") is conducted based on annual catch figures which exclude this 33% adjustment.

Table 1 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 first (Honma method) was calculated by applying the algorithm developed by Honma (1974), while the second (GLM method) was calculated using General Linear Modelling techniques (ICCAT 1993; Hsu and Chang 1992). As the latter technique is more commonly applied at ICCAT (e.g. Turner 1987; Brown and Turner 1988, 1989; Turner *et al.* 1992), the "base case" assessment utilizes the GLM method catch rate time series. The effects of replacing the GLM method catch rate time series by that obtained by means of the Honma method, and the use of the Japanese catch rate data in addition to the (GLM method) Taiwanese catch rate data are treated as sensitivity tests. The acronyms for these tests are "Honma *CPUE*" and "With Japan" respectively. ICCAT (1993) notes that the estimates of Taiwanese catch rate since 1987 may be biased because of inclusion of deep longline effort which targets bigeye rather than albacore. To assess the effects of such possible bias, another sensitivity test is conducted in which the catch rate data for 1987 onwards are excluded from the analysis. The acronym for this sensitivity test is "Less 87-91".

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 70cm instead of 80cm) (a_c=2.61).
d) The age-at-50%-selectivity is 4.61 years (corresponding to a length-at-50%-selectivity of 90cm instead of 80cm) (a_c=4.61).
e) The age-at-50%-selectivity changes from 4.61 in 1957 to 2.61 in 1991 (Decrease a_c).
f) The age-at-50%-selectivity changes from 2.61 in 1957 to 4.61 in 1991 (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 (1993) is replaced by that of Beardsley (1971) (Alt Lm).
i) The growth curve of Bard (1981) is replaced by that of Lee and Yeh (1992) (Alt Gr).
j) South African catches over the 1985-1991 period are not adjusted upwards by 33% (Catch adj).

The variance estimation procedure described in Appendix B (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 :

$$S_{y,a} = S_a e^{\phi_{y,a}} \qquad \phi_{y,a} \sim N(0,0.2^2) \qquad (5)$$

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 (5). 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.

Results and discussion - "base case" application

Table 2 contains the 'base case" estimates of six management-related quantities, their *CVs* 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 1992,
c) *RY*(92)	the 1992 replacement yield,
d) B_{1991}	the (exploitable) biomass in the middle of 1991,
e) B_{1991}/K	the (exploitable) biomass in the middle of 1991 as a fraction of the corresponding unexploited equilibrium biomass, and
f) B_{1991}/B_{MSY}	the (exploitable) biomass in the middle of 1991 as a fraction of the corresponding equilibrium biomass at which *MSY* is achieved.

Figure 2 plots the actual and model-predicted *CPUE* data and Figure 3 shows the exploitable biomass time series (in absolute terms and as a fraction of the corresponding unexploited equilibrium level).

There are no obvious indications of model mis-specification in Figure 2(a) [or 2(b)]. Comparing moduli of residuals for the first and second halves of the series, the average in absolute terms decreases by 40%, while in relative terms (residual/predicted value) the change is only 12%; this supports the assumption of a log-normal rather than a normal error structure, as is implicit in equation (A.5). The estimate of *MSY* (21,400t) is lower than any of the catches since 1984, and the model indicates that catches have consistently exceeded replacement yields since 1985, with the consequence that the biomass has been dropping over this period (Figure 3). The resource is estimated to be below the biomass at which *MSY* is achieved (B_{1991} is 78% of B_{MSY}). The current replacement yield is estimated to be 22,000t which is slightly larger than *MSY*. This is a consequence of transient age-structure effects, and catches of this magnitude cannot be sustained in the medium to long-term.

All of the management-related quantities except B_{1991} are estimated fairly precisely ("standard" and "alternative" method *CV*s of roughly 20% or less). The "standard" method *CV* for the $F_{status\text{-}quo}$ strategy *TAC* for 1992 seems unrealistically low compared to the *CV*s for the other quantities. This is probably because temporal fluctuations in selectivity are ignored by the "standard" method - this *CV* increases from 2.0% to 7.4% when the later source of variability is considered. The 90% confidence intervals for *MSY* and *RY*(92) are markedly skew, with the lower 5 percentiles much smaller than the point estimates. The upper 5 percentiles of the distributions for B_{1991}/B_{MSY} are only slightly larger than unity. This indicates strong evidence that the albacore population in the south Atlantic is currently biologically overexploited.

Results and discussion - sensitivity tests

In general, the results are insensitive to the values of the parameters of age-specific selectivity pattern, the form of the stock-recruitment relationship, the growth equation, the length-mass relationship, the value of natural mortality, whether or not previously reported South African catches over the 1985-1991 period are adjusted up by 33% and which of the catch rate series are used in the model fitting process (Table 3). The most optimistic appraisals (in terms of the B_{1991}/B_{MSY} ratio) are those for which M is assumed to be $0.2yr^{-1}$ and for which the Honma *CPUE* is used to estimate the model parameters - the estimate of this ratio in these cases marginally exceeds unity. Note, however, that this is not a reflection of a much larger biomass estimate, but rather a consequence of a lower value for B_{MSY}/K (0.22 and 0.23 compared to 0.32 for the "base case"). The least optimistic appraisal (i.e. that which indicates the greatest level of biological overexploitation) is that in which the Beverton-Holt form of the stock-recruitment relationship is replaced by the Ricker form ("Ricker" in Table 3). In this case, the resource is assessed to be only slightly larger than half 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 (0.178 to 0.273).

The estimate of current replacement yield ranges from 17,300 (Increase a_C) to 24,600t (Honma *CPUE*), and the *MSY* estimates range from 19,500 (Ricker) to 24,900t (Honma *CPUE*). Excluding the catch rate data for 1987 to 1991 (Less 87-91) does not affect the point estimates substantially although, as expected, the *CV*s are much larger (about double in most cases).

Comparison with other approaches

The sensitivity of the stock assessment results to the form of the model used has been examined by applying three forms of the dynamic production model to the data in Table 1. This model has the form:

$$\left.\begin{aligned} B^e_{y+1} &= B^e_y + g\left(B^e_y\right) - C_y \\ (C/E)_y &= q\frac{(B_{y+1}+B_y)}{2} \end{aligned}\right\} \qquad (6)$$

where the surplus production function is one of :

$$g(B) = \begin{cases} rB(1-B/K) & \text{– Schaefer form} \\ rB(1-\ell nB/\ell nK) & \text{– Fox form} \\ \frac{r}{p}B\left[1-(B/K)^p\right] & \text{– Pella–Tomlinson form} \end{cases}$$

and r is an intrinsic growth rate parameter,
K is the average unexploited equilibrium size ("carrying capacity"),
p is a shape parameter (which is estimated in the fitting process), 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 three forms of the dynamic production model are contrasted with those for the "base case" application of the age-structured production model in Table 4. The results for "base case" and "Fox" applications are very similar [as might have been expected - see Punt (1992, 1994) for details], although the "Fox" estimates are more pessimistic than those for the "base case". The results for the "Schaefer" application are much less optimistic than those for the "base case" assessment (B_{1991}/B_{MSY} is substantially lower and the current replacement yield estimate is also lower). The "Schaefer" application behaves rather similarly to the "Ricker" application, in accordance with Punt's (1992, 1994) generic suggestion.

RISK ANALYSIS

Methodology

Four Risk Analysis variants of increasing complexity are considered here. The differences between the four relate to the distribution of numbers-at-age at the start of the projections (either the "best fit" values or the results of the bootstrap calculations) and whether recruitment and selectivity fluctuations are taken into account when projecting the model forward in time. The four options (all of which relate to the "base case" assessment) are as follows.

a) All projections start from the "best fit" estimates of the numbers-at-age at the start of 1992 - recruitment is deterministic and there are no fluctuations in selectivity-at-age.

b) As in a), except that recruitment is log-normally distributed about its expected value - the *CV* of the log-normal distribution is 0.4 [the standard deviation of the logs of the ADAPT recruitment estimates for the north Atlantic stock of albacore is 0.2 and the corresponding *ad hoc* tuned VPA standard deviation is 0.5 (ICCAT 1993) - the choice of 0.4 amounts to taking the average of the two associated variances]. A total of 1000 simulations are carried out to calculate the performance indices.

c) As in b), except that selectivity-at-age is log-normally distributed about its expected value for each age and year - the *CV* of the log-normal distribution is 0.2.

d) Projections are carried out from each of the 500 bootstrap numbers-at-age vectors for the start of 1992 (with 10 projections for each such vector), recruitment is log-normally distributed with a *CV* of 0.4 and selectivity-at-age is log-normally distributed with a *CV* of 0.2.

Performance indices

The seven performance indices considered are as follows.

i) Risk - considered here to be defined by the probability that the biomass drops below 0.2*K* during the projection.

ii) Catch - the average catch over the projection period.

iii) $E(B_{fin}/B_{MSY})$ - the ratio of the exploitable biomass at the end of the projection period to the corresponding biomass at which *MSY* is achieved.

iv) $P(B_{fin} > B_{MSY})$ - the probability that the exploitable biomass will exceed that corresponding to *MSY* at the end of the projection period.

v) $P(B_{fin} > B_{1991})$ - the probability that the exploitable biomass will exceed the current biomass at the end of the projection period.

vi) $E(B_{fin}/K)$ - the ratio of the exploitable biomass at the end of the projection period to the corresponding unexploited equilibrium level.

vii) $5\%(B_{fin}/K)$ - the lower 5%-ile of the distribution of the ratio of the exploitable biomass at the end of the projection period to the corresponding unexploited equilibrium level.

Future catch trajectories

The various future catch trajectories considered are listed in Table 5. Though the assessment goes no further than the start of 1992, (almost) two further years have already passed. The choice of catches of 28,000t for both these years (1992 and 1993) for all the trajectories assumes that these catches will not have deviated markedly from the average catch over the preceding three years.

The first scenario considered (A) corresponds essentially to an absence of future management restrictions, with the allied assumption that annual catches remain unchanged. All the other scenarios reflect a catch limitation of 20,000t for 1994. In circumstances where the assessments considered indicate the biomass to be a low fraction of *K* (typically a little more than 20%) and for the most part below the level yielding *MSY*, and *MSY* itself to be scarcely in excess of 20,000t, immediate reduction of the annual catch to a level rather closer to that estimated to be sustainable at present seems imperative - hence this consistent choice of 20,000t.

While scenario B retains that 20,000t catch throughout the projection period, the remaining scenarios consider further phased reductions of the catch after 1994 (at different rates and continuing for different periods). Their purpose is to illustrate the various levels of catch reduction necessary to achieve different rates of recovery of the population to a larger fraction of *K*.

Results and discussion

The results of the fully-deterministic projections [i.e. Risk Analysis method (a)] for the various future catch trajectories of Table 5 are illustrated in Figure 4. The associated performance indices are reported in Table 6 for 5- and for 10-year projection periods. Table 7 gives corresponding results for the fully-stochastic analyses [i.e. Risk Analysis method (d)], and Table 8 compares results from the four methods for catch trajectory C.

The projections shown in Figure 4 have qualitative features which are hardly unexpected, given the estimates for *MSY* and stock status reported in Table 3. Trajectory A, reflecting an unchanged level of catch under an absence of restrictions, leads to virtual extinction of the resource by the end of the decade. Certainly the enactment of management measures to effect, at minimum, the sustainability indicated for trajectory B (a *TAC* set at 20,000t from 1994 onwards) appears to be an urgent priority.

Given that trajectory B is indicated in Figure 4 and Table 6 to achieve maintenance of the *status-quo*, why might there be any need to consider the possibility of further catch reductions in subsequent years, as reflected by trajectories C to H? There are a number of reasons for this.

i) This apparent sustainability under trajectory B is a deterministic "best fit" result. Risk Analysis Method (d), which is the most realistic in that it takes the greatest number of contributions to uncertainty into account, reflects a 5% chance that such an approach could lead to a biomass below 6% of K by 2001 (Table 7).

ii) While in terms of the "base case" (and many of the related sensitivity tests), the resource is estimated to be not too far below a level yielding *MSY*, it is important to appreciate that this "*MSY* level" itself (0.32 K for the "base case") is relatively low because of the shape of the Beverton-Holt stock-recruitment relationship assumed. Other plausible relationships (e.g. the Ricker curve, see Table 3) indicate a resource well below its *MSY* level, and hence would suggest a preference for catch trajectories that secure some increase in the current stock level. The Pella-Tomlinson model estimates *MSY* level to be 0.49K, but with a wide 90% confidence interval of [0.17 K; 0.88 K]. Clearly, therefore, there is no basis in the data to greatly prefer an analysis based on the Beverton-Holt relationship to one on the Ricker curve.

iii) To illustrate point ii) further, Figure 5 compares fully-deterministic projections [Risk Analysis method (a)] for catch trajectory B for the "base case" assessments, and for the assessments corresponding to two of the sensitivity tests. While trajectory B secures resource recovery in one of these cases, resource extinction occurs in another ("Ricker") within the next five years.

All these aspects point to the conclusion that, even if an immediate catch limitation to, say, 20,000t was agreed, continued careful monitoring will be necessary to ascertain whether yet further catch reductions will be required to arrest the decline of the resource.

MINIMUM SIZE RESTRICTIONS

Methodology

The "base case" assessment assumes a length-50%-selectivity in the fishery (L_{50}) of 80 cm [see Equation (4)]. The results of the assessment can readily be applied to calculate the curve relating sustainable yield to resource "depletion" (B/K).

By changing the value of L_{50}, but maintaining the same values for all other parameters either input or estimated for the "base case" assessment, and replotting this curve, an indication can be obtained of whether minimum size limitations might be advantageous in this fishery.

Results and discussion

These sustainable yield *vs.* biomass (depletion) curves are plotted in Figure 6 for a range of values of L_{50} (which would relate closely to the value of the minimum size, if imposed). Given uncertainty about the value of M to which such results may be sensitive, the plots are shown not only for the "base case" assessment for which $M = 0.3$ yr^{-1} [Figure 6(b)], but also for assessments for which $M = 0.2$ and $M = 0.4$ yr^{-1}.

The results show very little difference in the sustainable yields achievable for different L_{50}'s for B/K in excess of 35%. Even at the lower levels of B/K at which *MSY* is achieved in these cases, the differences in *MSY* for different L_{50}'s are not that large. Further, attempting to achieve the higher yield indicated for L_{50} = 90 cm would scarcely seem warranted, given the probably unrealistically low level of B/K to which this corresponds, and the consequent implication of reducing the resource to a still lower level.

CONCLUSIONS

The assessments of this paper indicate that the South Atlantic albacore resource has been markedly reduced by harvesting to probably little more than 20% of its pre-exploitation level. *MSY* is estimated to be only slightly in excess of 20,000t p.a., which is substantially less than the average of recent annual catches of some 28,000t.

Risk Analysis, in the form of 10-year projections under alternative series of future catches, suggests that the decline of the resource will continue unless catches are immediately restricted to some 20,000t p.a. Even in this situation, continued decline is not improbable, so that careful monitoring would be essential to check whether further catch reductions would be needed in subsequent years.

Sustainable yield estimates are not particularly sensitive to alternative minimum size limitation scenarios, so that such measures would not seem a priority or of much potential benefit to the fishery at this time.

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REFERENCES

BARD, F.X. 1981. Le thon germon (*Thunnus alalunga*) de l'Ocean Atlantique. *These Doc. Sc. Paris* (336pp).

BEARDSLEY, G.J. 1971. Contribution to the population dynamics of Atlantic albacore with comments on potential yields. *Fish. Bull. US.* 69: 845-857.

BROWN, C.A. and S.C. TURNER. 1988. Standardized catch rates of large bluefin tuna in the New England (U.S.) rod and reel/handline fishery. *Colln Vol. Sci. Pap. ICCAT.* 30: 302-310.

BROWN, C.A. and S.C. TURNER. 1989. Standardized catch rates of large bluefin tuna in the New England (U.S.) rod and reel/handline fishery. *Colln Vol. Sci. Pap. ICCAT.* 32: 248-254.

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

BUTTERWORTH, D.S., G.[S.] HUGHES and F. STRUMPFER. 1990. VPA with *ad hoc* tuning: implementation for disaggregated fleet data, variance estimation, and application to the Namibian stock of Cape horse mackerel *Trachurus trachurus capensis*. *S. Afr. J. Mar. Sci.* 9: 327-357.

DERISO, R.B. T.J. QUINN and P.R. NEAL. 1985. Catch-age analysis with auxiliary information. *Can. J. Fish. Aquat. Sci.* 42: 815-824.

EFRON, B. 1981. Nonparametric estimates of standard error: the jackknife, the bootstrap and other methods. *Biometrika* 68(3): 589-599.

EFRON, B. 1982. *The Jackknife, the Bootstrap and Other Resampling Plans.* Society for Industrial and Applied Mathematics, Philadelphia (92pp).

EFRON, B. 1985. Bootstrap confidence intervals for a class of parametric problems. *Biometrika* 72(1): 45-58.

FOX, W.W. 1975. Fitting the generalized stock production model by least-squares and equilibrium approximation. *Fish. Bull.* 73(1): 23-37.

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

HONMA, M. 1974. Estimation of overall fishing intensity of tuna longline fishery. *Bull. Far. Seas. Fish. Res. Lab.* 10: 63-85.

HSU, C.C. and S.K. CHANG. 1992. The adjusted longline CPUE of north and south Atlantic albacore stock by three methods. *ICCAT Document SCRS/92/104* (18pp).

ICCAT. 1990. Report of the 1989 ICCAT albacore workshop, 19-28 September 1989, Madrid. *Colln. Vol. Sci. Pap. ICCAT.* 33 (171pp).

ICCAT. 1991. Report of the 2nd ICCAT albacore workshop, 2-9 October 1990, Madrid, *Colln. Sci. Pap. ICCAT.* 34 (170pp).

ICCAT. 1993. Report for the biennial period. 1992-1993. Part 1 (1992). (In press)

KIMURA, D.K. 1990. Approaches to age-structured separable sequential population analysis. *Can. J. Fish. Aquat. Sci.* 47: 2364-2374.

LEE, L.K. and S.Y. YEH. 1992. Studies on the age and growth of south Atlantic albacore (*Thunnus alalunga*) specimens collected from Taiwanese longliners. *ICCAT Document SCRS/92/108* (16pp).

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

LLEONART, J., J. SALAT and B. ROEL. 1985. A dynamic production model. *Colln scient. Pap. int. Commn SE. Atl. Fish.* 12(1): 119-146.

POLACHECK, T. R. HILBORN and A.E. PUNT. 1993. Fitting surplus production models: comparing methods and measuring uncertainty. *Can. J. Fish. Aquat. Sci.* (In press)

POPE, J.G. and J.G. SHEPHERD. 1985. A comparison of the performance of various methods for tuning VPAs using effort data. *J. Cons. int. Explor. Mer.* 42: 129-151.

PENNEY, A.J. 1993. Morphometric relationships, annual catches and catch-at-size for South African caught south Atlantic albacore. *ICCAT SCRS Document* (Presented to this meeting)

PUNT, A.E. 1988. Model selection for the dynamics of southern African hake resources. *Rep. Benguela Ecol. Progm. S. Afr. 15:* [vii] + 395pp.

PUNT, A.E. 1989. A further preliminary comparative investigation into the performance of catch-effort model estimation procedures used in the management of the ICSEAF hake stocks. *Colln scient. Pap. int. Commn SE. Atl. Fish.* 16(2): 63-122.

PUNT, A.E. 1992. Management procedures for Cape hake and baleen whale resources. *Rep. Benguela Ecol. Progm. S. Afr.* 23: [viii]+689pp.

PUNT, A.E. 1994. Assessments of the stocks of Cape hake (*Merluccius* spp.) off South Africa. *S. Afr. J. Mar. Sci.* 14. (In press)

PUNT, A.E. and D.S. BUTTERWORTH. 1993. Variance estimates for fisheries assessment: their importance and how best to evaluate them. p. 283-299. In Risk Evaluation and Biological Reference Points for Fisheries Management. Smith, S.J., J.J. Hunt and D. Rivard (eds). *Can. J. Fish. Aquat. Sci. Spec. Publ.* 120.

PUNT, A.E., A.J. PENNEY and C.G. WILKE. 1992. Stock assessment of south Atlantic albacore using an age-structured production model. *Colln Vol. Sci. Pap. ICCAT.* 39: 215-224.

ROFF, D.A. and D.J. FAIRBAIRN. 1980. An evaluation of Gulland's method for fitting the Schaefer model. *Can. J. Fish. Aquat. Sci.* 37: 1229-1235.

SCHAEFER, M.B. 1954. Some aspects of the dynamics of populations important to the management of commercial marine fisheries. *Inter-Am. Trop. Tuna Commn Bull.* 1: 25-56.

SCHAEFER, M.B. 1957. A study of the dynamics of fishery for yellowfin tuna in the Eastern tropical Pacific Ocean. *Inter-Am. Trop. Tuna Commn Bull.* 2: 247-285.

SCHNUTE, J. 1977. Improved estimates from the Schaefer production model: theoretical considerations. *J. Fish. Res. Board Can.* 34: 583-603.

SHIOHAMA, T. 1976. Overall fishing intensity and catch by length-class of albacore in the Japanese Atlantic longline fishery, 1956-1973. *Colln Vol. Sci. Pap. ICCAT.* 5: 210-215.

SISSENWINE, M.P. 1978. Is MSY an adequate foundation for optimum yield? *Fisheries* 3(6): 22-42.

TURNER, S.C. 1987. Catch rates of bluefin tuna in the Japanese longline fishery recorded by United States observers. *Colln Vol. Sci. Pap. ICCAT.* 26: 323-338.

TURNER, S.C., J. CRAMER and C.A. BROWN. 1992. Indices of abundance for large bluefin tuna, *Thunnus thynnus*, from the rod and reel and handline fishery off the northeast United States. *Colln Vol. Sci. Pap. ICCAT.* 39: 758-777.

YEH, S.Y, T.S TSOU and H.C. LIU. 1991. Assessment of the south Atlantic albacore resource using surplus production models, 1976-1988. *Colln Vol. Sci. Pap. ICCAT.* 34: 166-170.

YEH, S.Y, T.S TSOU and H.C. LIU. 1992. Assessment of the south Atlantic albacore resource by using surplus production models, 1967-1990. *Colln Vol. Sci. Pap. ICCAT.* 39: 265-268.

Table 1 : Catch and catch rate data for the albacore resource in the South Atlantic. The catches for 1985 to 1991 are marked with an asterisk because the South African component of the total catch indicated in ICCAT (1993) has been adjusted in a manner and for reasons described in the text.

Year	Catch ('000t)	Taiwanese *CPUE*		Japanese *CPUE*
		Honma Method	GLM Method	
1957	0.7			
1958	1.0			
1959	4.8			5.80
1960	10.5			5.08
1961	10.8			4.18
1962	18.9			2.81
1963	17.3			3.15
1964	25.9			2.96
1965	29.8			2.37
1966	27.3			2.16
1967	15.9			2.27
1968	25.7	18.18	36.35	2.35
1969	28.4	17.90	51.34	1.85
1970	23.6	16.49	50.40	1.96
1971	24.9	18.39	57.61	1.34
1972	33.3	15.14	41.01	
1973	28.2	12.97	30.36	
1974	19.7	14.60	35.31	
1975	17.7	17.23	37.23	
1976	19.3	15.36	33.28	
1977	21.6	16.13	36.86	
1978	23.1	17.14	30.08	
1979	22.5	15.50	40.26	
1980	22.6	16.79	42.49	
1981	23.6	14.85	29.85	
1982	29.0	13.97	28.94	
1983	14.5	13.70	29.04	
1984	13.1	16.58	35.67	
1985	30.2*	13.90	34.06	
1986	36.7*	14.25	34.25	
1987	40.3*	11.81	29.09	
1988	29.3*	10.06	25.60	
1989	27.2*	9.32	24.96	
1990	30.1*	9.07	18.72	
1991	25.8*	8.25	17.49	

Source : 1957-1959 catch - ICCAT (1990)
1960-1961 catch - ICCAT (1991)
1962-1991 catch - ICCAT (1993)
Taiwanese *CPUE* data - ICCAT (1993)
Japanese *CPUE* data - Shiohama (1976)

Table 2: Management variable estimates, their estimated *CV*s (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.

Quantity Quantity	Estimate	No selectivity variance		With selectivity variance	
		CV	90% C.I.	*CV*	90% C.I.
MSY	21.4	17.9	2.4 ; 25.7	21.8	0.5 ; 25.2
TAC_{sq}	24.8	2.0	24.0 ; 25.9	7.4	21.6 ; 29.0
$RY(92)$	22.0	12.4	9.7 ; 25.0	14.2	8.6 ; 25.0
B_{1991}	60.4	57.5	34.7 ; 214.6	77.2	34.9 ; 227.5
B_{1991} / K	0.252	21.0	0.184 ; 0.375	21.4	0.180 ; 0.399
B_{1991} / B_{MSY}	0.778	17.1	0.610 ; 1.121	16.3	0.572 ; 1.083

Table 3 : Management variable estimates and their *CV*s 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	Honma *CPUE*	With Japan	Less 87-91	Catch adj
MSY	21.4 (17.9)	24.9 (4.2)	24.2 (6.7)	21.3 (27.2)	21.3 (14.7)
TAC_{sq}	24.8 (2.0)	25.7 (1.0)	25.4 (2.3)	24.6 (5.1)	23.9 (2.0)
$RY(92)$	22.0 (12.4)	24.6 (5.6)	20.3 (11.9)	21.6 (23.0)	21.6 (10.0)
B_{1991}	60.4 (57.5)	47.9 (13.6)	38.1 (23.5)	52.5 (229)	51.4 (55.4)
B_{1991} / K	0.252 (21.0)	0.241 (8.7)	0.200 (15.5)	0.228 (54.4)	0.234 (21.8)
B_{1991} / B_{MSY}	0.778 (17.1)	1.045 (8.6)	0.894 (15.0)	0.720 (36.0)	0.769 (16.0)

Quantity	Acronym			
	a_C=2.61	a_C=4.61	Increase a_C	Decrease a_C
MSY	21.5 (13.3)	21.1 (25.4)	23.1 (18.1)	19.7 (15.9)
TAC_{sq}	24.6 (2.2)	25.5 (1.7)	-	-
$RY(92)$	21.4 (11.4)	23.1 (12.7)	17.3 (11.3)	20.6 (12.0)
B_{1991}	61.9 (49.9)	62.8 (61.8)	52.4 (57.3)	44.6 (84.3)
B_{1991} / K	0.242 (20.2)	0.273 (20.9)	0.248 (21.4)	0.178 (41.0)
B_{1991} / B_{MSY}	0.719 (18.4)	0.894 (47.7)	0.942 (16.5)	0.511 (29.5)

Quantity	Acronym				
	M=0.2yr^{-1}	M=0.4yr^{-1}	Alt-Gr	Alt-Lm	Ricker
MSY	23.7 (18.3)	20.5 (25.4)	22.3 (16.2)	21.5 (17.3)	19.5 (>1000)
TAC_{sq}	25.3 (1.5)	24.3 (2.1)	25.1 (1.7)	24.9 (2.0)	23.9 (2.8)
$RY(92)$	24.1 (12.4)	20.4 (15.9)	23.0 (10.9)	22.1 (12.0)	18.3 (19.1)
B_{1991}	65.1 (58.6)	55.5 (83.8)	62.7 (50.8)	60.4 (55.6)	64.2 (309)
B_{1991} / K	0.232 (19.0)	0.265 (20.4)	0.239 (20.5)	0.251 (20.7)	0.265 (21.1)
B_{1991} / B_{MSY}	1.036 (38.2)	0.726 (14.3)	0.820 (14.4)	0.783 (17.2)	0.568 (21.8)

Table 4 : Comparison of the results of the "base case" assessment, set out as in Table 3, with those of the Fox, Schaefer and Pella-Tomlinson forms of the dynamic production model. Biomass and catch units are '000t.

Quantity	Acronym			
	Base case	Schaefer	Fox	Pella-Tomlinson
MSY	21.4 (17.9)	20.1 (11.7)	20.9 (13.3)	20.3 (16.0)
TAC_{sq}	24.8 (2.0)	-	-	-
$RY(92)$	22.0 (12.4)	15.3 (13.7)	20.0 (13.4)	14.9 (43.9)
B_{1991}	60.4 (57.5)	79.3 (53.8)	71.3 (78.0)	79.3 (79.4)
B_{1991} / K	0.252 (21.0)	0.252 (16.0)	0.239 (17.1)	0.252 (21.9)
B_{1991} / B_{MSY}	0.778 (17.1)	0.504 (16.0)	0.649 (17.1)	0.493 (>1000)

Table 5 : The eight alternative future *TAC* trajectories considered in this analysis. Units are '000t.

Year	Catch Trajectory							
	A	B	C	D	E	F	G	H
1992	28	28	28	28	28	28	28	28
1993	28	28	28	28	28	28	28	28
1994	28	20	20	20	20	20	20	20
1995	28	20	17	17	17	17	15	15
1996	28	20	17	14	14	14	15	10
1997	28	20	17	14	11	11	15	10
1998	28	20	17	14	11	9	15	10
1999	28	20	17	14	11	9	15	10
2000	28	20	17	14	11	9	15	10
2001	28	20	17	14	11	9	15	10

Table 6 : The results of fully-deterministic projections [i.e. Risk Analysis method (a) - see text]. The definitions of the various performance indices are given in the text.

Performance Index	Catch Trajectory							
	A		B		C		D	
	1996	2001	1996	2001	1996	2001	1996	2001
Risk	1	1	0	0	0	0	0	0
Catch	28.0	28.0	23.2	21.6	22.0	19.5	21.4	17.7
$E(B_{fin} / B_{MSY})$	0.483	0.069	0.690	0.683	0.739	0.865	0.756	1.014
$P(B_{fin} > B_{MSY})$	0	0	0	0	0	0	0	1
$P(B_{fin} > B_{1991})$	0	0	0	0	0	1	0	1
$E(B_{fin} / K)$	0.157	0.022	0.224	0.221	0.239	0.280	0.245	0.329

Performance Index	Catch Trajectory							
	E		F		G		H	
	1996	2001	1996	2001	1996	2001	1996	2001
Risk	0	0	0	0	0	0	0	0
Catch	21.4	16.2	21.4	15.4	21.2	18.1	20.2	15.1
$E(B_{fin} / B_{MSY})$	0.756	1.138	0.756	1.206	0.771	0.983	0.800	1.228
$P(B_{fin} > B_{MSY})$	0	1	0	1	0	0	0	1
$P(B_{fin} > B_{1991})$	0	1	0	1	0	1	1	1
$E(B_{fin} / K)$	0.245	0.369	0.245	0.391	0.250	0.319	0.259	0.398

Table 7 : The results of the fully-stochastic projections [i.e. Risk Analysis method (d) - see text]. The definitions of the various performance indices are given in the text.

Performance Index	Catch Trajectory							
	A		B		C		D	
	1996	2001	1996	2001	1996	2001	1996	2001
Risk	0.757	0.938	0.437	0.647	0.418	0.526	0.417	0.468
Catch	28.0	26.8	23.2	21.6	22.0	19.5	21.4	17.7
$E(B_{\text{fin}} / B_{MSY})$	0.450	0.160	0.657	0.671	0.706	0.851	0.724	1.000
$P(B_{\text{fin}} > B_{MSY})$	0.011	0.022	0.104	0.219	0.151	0.340	0.169	0.464
$P(B_{fin} > B_{1991})$	0.006	0.030	0.224	0.354	0.357	0.540	0.404	0.681
$E(B_{\text{fin}} / K)$	0.165	0.065	0.229	0.222	0.244	0.278	0.250	0.324
$5\%(B_{fin} / K)$	0.083	0.000	0.154	0.063	0.170	0.118	0.176	0.159

Performance Index	Catch Trajectory							
	E		F		G		H	
	1996	2001	1996	2001	1996	2001	1996	2001
Risk	0.417	0.441	0.417	0.432	0.416	0.476	0.416	0.426
Catch	21.4	16.2	21.4	15.4	21.2	18.1	20.2	15.1
$E(B_{\text{fin}} / B_{MSY})$	0.724	1.125	0.724	1.194	0.739	0.968	0.765	1.214
$P(B_{\text{fin}} > B_{MSY})$	0.169	0.563	0.169	0.612	0.185	0.440	0.215	0.629
$P(B_{fin} > B_{1991})$	0.404	0.781	0.404	0.821	0.447	0.656	0.533	0.833
$E(B_{\text{fin}} / K)$	0.250	0.363	0.250	0.384	0.254	0.315	0.263	0.391
$5\%(B_{fin} / K)$	0.176	0.189	0.176	0.206	0.180	0.151	0.190	0.211

Table 8 : Performance indices for catch trajectory C for the four methods considered for calculating risk.

Performance Index	Risk Analysis Method							
	(a)		(b)		(c)		(d)	
	1996	2001	1996	2001	1996	2001	1996	2001
Risk	0	0	0.001	0.221	0.000	0.213	0.418	0.526
Catch	22.0	19.5	22.0	19.5	22.0	19.5	22.0	19.5
$E(B_{\text{fin}} / B_{MSY})$	0.739	0.865	0.739	0.863	0.740	0.861	0.706	0.851
$P(B_{\text{fin}} > B_{MSY})$	0	0	0.000	0.246	0.000	0.251	0.151	0.340
$P(B_{fin} > B_{1991})$	0	1	0.157	0.628	0.158	0.622	0.357	0.540
$E(B_{\text{fin}} / K)$	0.239	0.280	0.240	0.280	0.240	0.279	0.244	0.278
$5\%(B_{fin} / K)$	0.239	0.280	0.222	0.168	0.223	0.168	0.170	0.118

APPENDIX A : THE AGE-STRUCTURED PRODUCTION MODEL

The resource dynamics are modelled by the equations:

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

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 in 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 deterministically related to spawner stock size by the Beverton-Holt stock-recruitment relationship:

$$N_{y,0} = \frac{\alpha B_y^s}{\beta + B_y^s} \qquad (A.2)$$

$$B_y^s = \sum_{a=1}^{m} f_a\, w_a\, N_{y,a} \qquad (A.3)$$

where B_y^s 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 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:

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

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, β 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:

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

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

$$\hat{\sigma}^i = \sqrt{\frac{1}{n^i} \sum_y \left(\ell n(C/E)^i_y - \ell n(q^i (B^e_y)^i) \right)^2} \qquad (A.6)$$

$(C/E)^i_y$ 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 :

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

$(S^e_a)^i$ 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 B : 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 $\hat{Q}$ as follows. A large number (U_{max}, where U=1, ... U_{max}) of random bootstrap samples $\{X^U : U = 1, \ldots, U_{max}\}$ are generated, and the corresponding set $\{\hat{Q}^1, \hat{Q}^2, \ldots, \hat{Q}^{U_{max}}\}$ 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:

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

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

$(C\hat{/}E)^i_y$ 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 A.6).

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

$$VAR(\hat{Q}) = \frac{1}{U_{max} - 1} \sum_{U=1}^{U_{max}} \left(\hat{Q}^U - Q_{(.)} \right)^2 \qquad (B.2)$$

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.

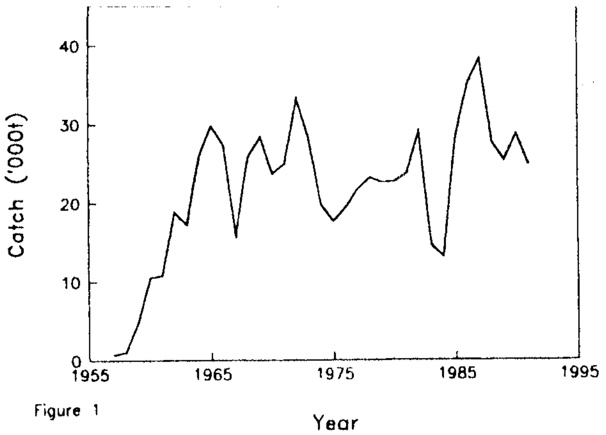

Figure 1

Figure 1 : Catch time series for the albacore population in the south Atlantic.

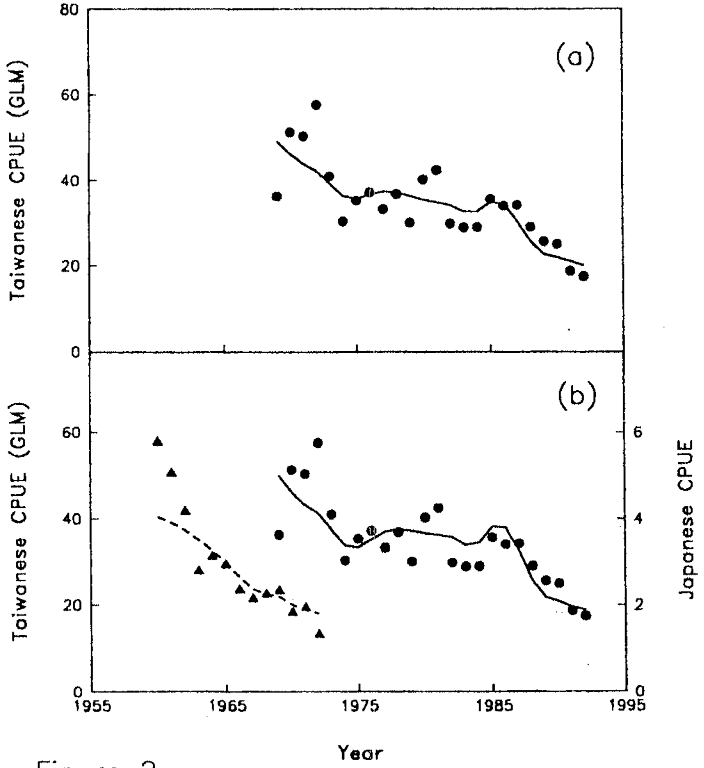

Figure 2

Figure 2: Comparison of observed and model-predicted *CPUE* series. The "base case" assessment is shown in (a) by the continuous line, and the Taiwanese *CPUE* data by dots. The plots in (b) are for the "With Japan" assessment, for which the triangles show the Japanese *CPUE* data and the dashed line indicates the fit of the assessment model to those data.

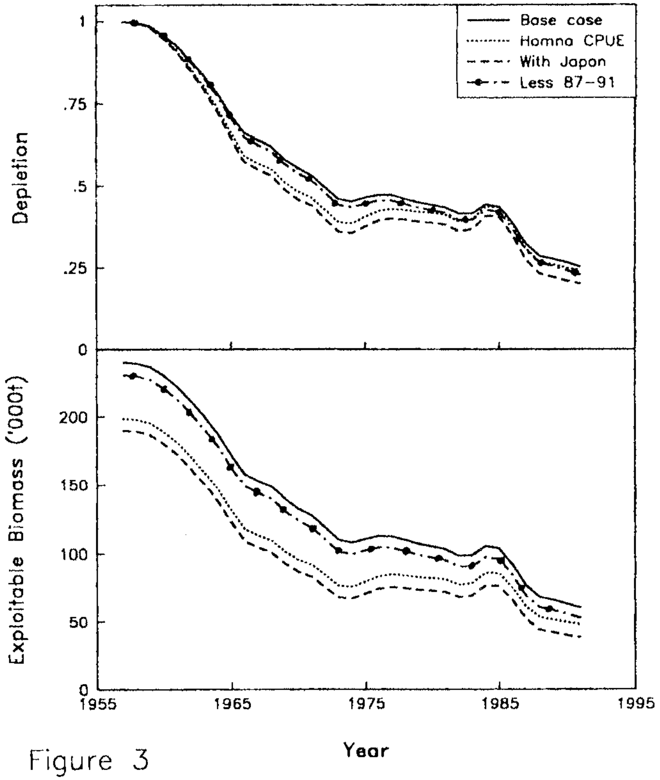

Figure 3

Figure 3 : Exploitable biomass trajectories for south Atlantic albacore obtained from the "base case" application of the age-structured production-model and a subset of the sensitivity tests. The upper panel shows the biomass as a fraction of its unexploited equilibrium level, while the lower panel shows the estimates of exploitable biomass in absolute terms.

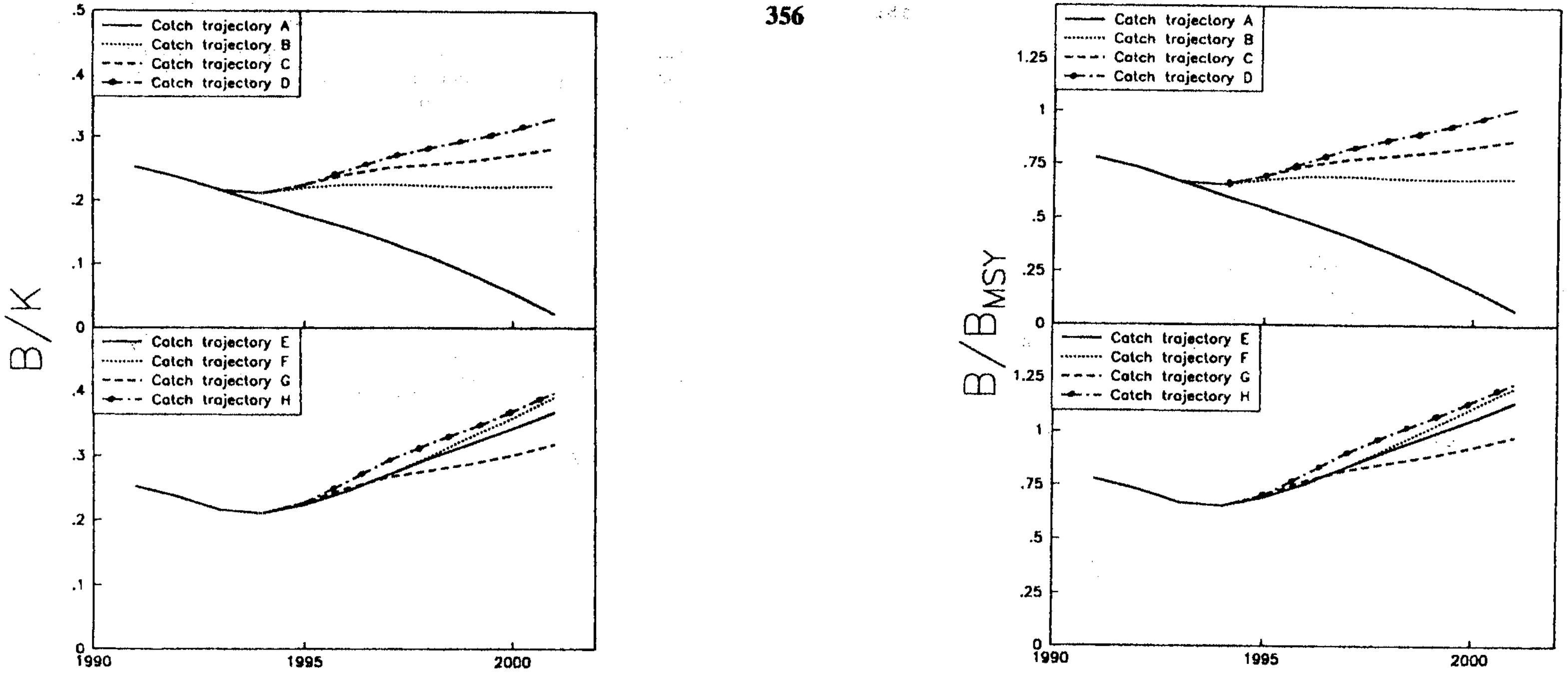

Figure 4(a)

Figure 4(b)

Figure 4: Biomass projections for fully-deterministic calculations [Risk Analysis method (a)] for the "base case" assessment and the various future catch trajectories of Table 5. Results are shown in terms of both (a) B/K and (b) B / B_{MSY}.

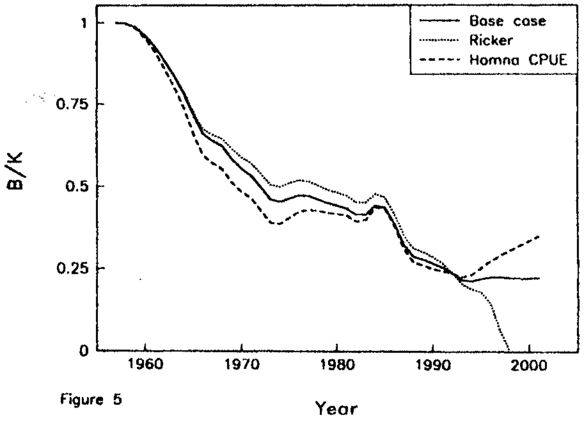

Figure 5

Figure 5: Fully-deterministic projections of resource status under catch trajectory B of Table 5 (an annual fixed catch of 20,000t commencing in 1994) for the "base case" assessment, and for the assessments related to two of the sensitivity tests (see Table 3).

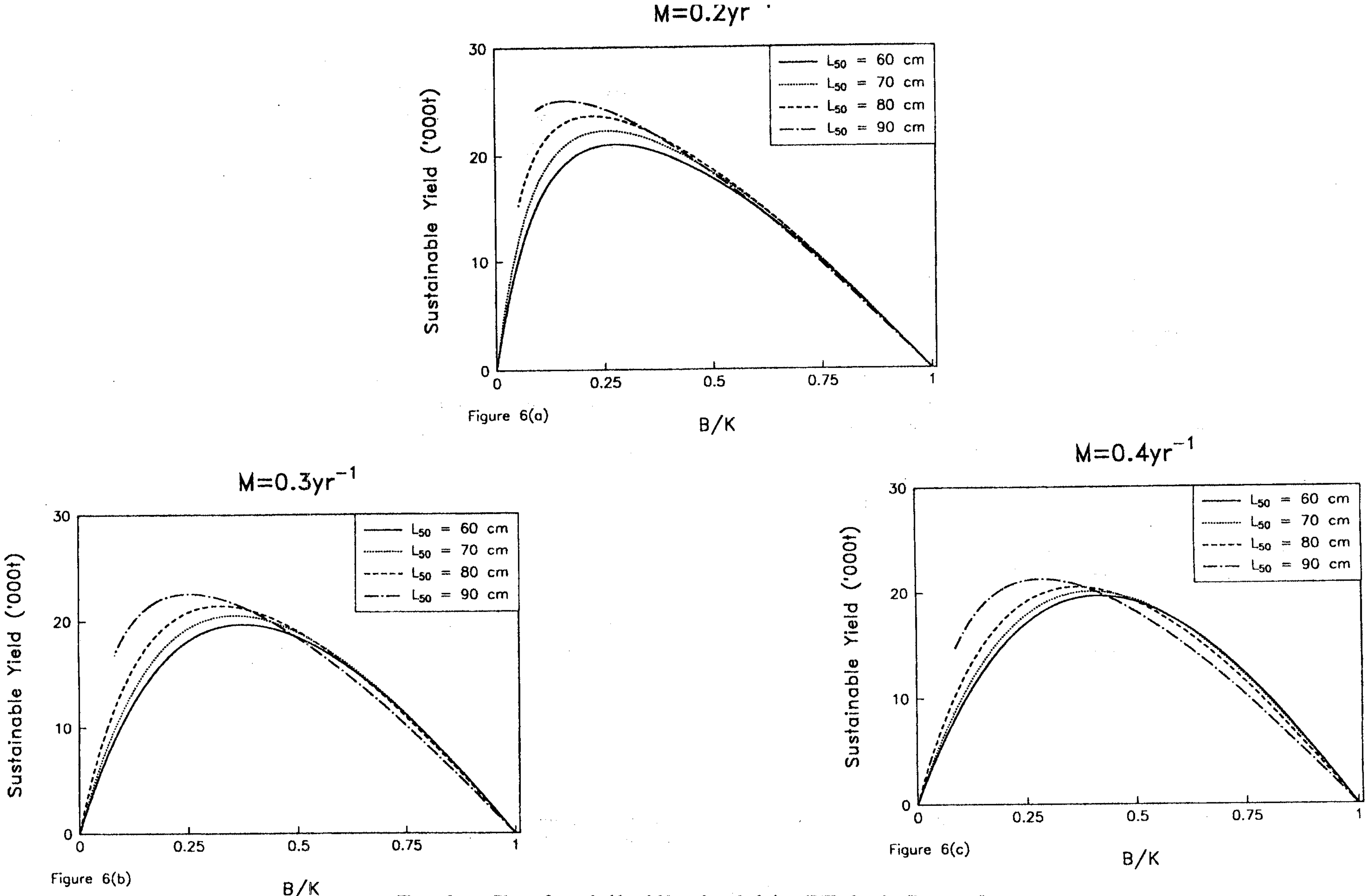

Figure 6(a)

Figure 6(b)

Figure 6(c)

Figure 6: Plots of sustainable yield against depletion (*B/K*) for the "base case" assessment. Results are shown for various lengths-at-50%-selectivity (L_{50}), and for assessments corresponding to different values of natural mortality *M*: (a) $M = 0.2yr^{-1}$; (b) $M = 0.3yr^{-1}$ (the "base case") and (c) $M = 0.4yr^{-1}$.