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Analyses of yield and spawning stock biomass per recruit for the South Atlantic albacore (*Thunnus alalunga*)

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Abstract

Yield per recruit and spawning stock biomass per recruit models were developed to study the interaction between the Taiwanese longline and South African baitboat fisheries for South Atlantic albacore. The Taiwanese longline fleet was found to have a logistically-distributed selectivity pattern with many age classes contributing significantly to the catch. The South African baitboat fleet, on the other hand, had a normally-distributed selectivity pattern with relatively few ages contributing to the catch. This fact profoundly influenced the response of yield and spawning stock biomass per recruit to different levels of fishing mortality exerted by each fleet. The results indicated that, in order to maximize total equilibrium yield per recruit to about 2.2 kg, the South African fishing mortality rate should probably be increased substantially whereas the Taiwanese fishing mortality rate is near optimal. In order to keep the spawning potential ratio above the 20% minimum suggested by Goodyear [Coll. Vol. Sci. Pap. 32 (2) (1989) 487], the Taiwanese apical fishing mortality rate should not exceed 0.55 yr^{-1}, regardless of the South African apical fishing mortality rate. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Yield per recruit; Spawning stock biomass per recruit; Fishery interaction; South Atlantic albacore

1. Introduction

Albacore is a temperate tuna widely distributed throughout the Atlantic Ocean and Mediterranean Sea. For assessment purposes, the International Commission for the Conservation of Atlantic Tunas (ICCAT) has divided the population into three stocks: northern and southern Atlantic stocks (separated at 5°N) and a Mediteranean stock (ICCAT, 1998). The southern stock is mainly exploited by South African surface baitboat fishery and Taiwanese longline fishery. In 1996, e.g., the Taiwanese longline fishery contributed an estimate of 18,789 metric tons or 78% to the total landings, while South Africa was responsible for only 8.7% (i.e. 2097 metric tons) of the total landings. The results of an age-structured production model suggested that the stock was over-fished; the 1996 biomass was estimated to be 78% of that associated with MSY and the 1996 fishing mortality rate was estimated at 116% of that needed to achieve MSY (ICCAT, 1998).

Yield per recruit (*Y*/*R*) and spawning stock biomass per recruit (SSB/R) analyses provide an alternative means of assessing fish populations for which there is some knowledge of growth and mortality (Baranov,

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1918; Thompson and Bell, 1934; Ricker, 1945, 1958, 1975; Beverton and Holts, 1957). SSB/R analyses are often used to help develop long term management strategies to maintain or rebuild the reproductive capacity of the stock (Brown, 1990; Gabriel et al., 1989; Goodyear, 1989, 1993).

A number of investigators have conducted *Y/R* analyses of the North Atlantic albacore stock (Bartoo, 1979; Bard and González-Garcés, 1980; González-Garcés and Weber, 1985; ICCAT, 1992–1995). To date, however, comprehensive *Y/R* and SSB/R analyses of the South Atlantic albacore stock have not yet been conducted. The chief reason for this is the absence of reliable catch at age data for estimating the selectivity pattern. Accordingly, there is an obvious need to develop a better understanding of the response of the population age-structure of albacore to exploitation by the international fleets in the South Atlantic.

The age-structure production model used by ICCAT (1998) gets around the lack of reliable catch at age data for South Atlantic albacore by forcing the selectivity on the stock to follow a logistic function of age. It is our contention, however, that the selectivity of the South African baitboat fishery is very much different from that. This paper provides a first attempt to estimate the selectivity of the South African baitboat fleet and then incorporates the results into multi-fleet *Y/R* and SSB/R models to evaluate the potential interaction between the Taiwanese longline and South African baitboat fisheries. The analysis has been restricted to the Taiwanese longline and South African baitboat fleets because these two fleets account for nearly all of the fishing mortality inflicted on the stock.

2. Materials and methods

Y/R computations were made for a range of fleet-specific fishing mortality rates assuming fixed natural mortality, growth, and selectivity patterns. The individual components of the model and their rationale are described below.

2.1. Growth

Growth in length with age was modeled using the Von Bertalanffy growth equation of Lee and Yeh (1993)

$$L_t = 142.28(1 - \mathrm{e}^{-0.1454(t+0.6740)}) \tag{1}$$

where L_t is the fork length in cm at age *t*. Fork length was transformed to weight in kilograms using the length–weight relationship published by Penney (1994)

$$W_t = 1.3718 \times 10^{-5} L_t^{3.0973} \tag{2}$$

Both equations were based exclusively on South Atlantic albacore data.

2.2. Mortality

The rate of decline of a cohort of fish over time due to mortality was assumed to follow the familiar differential equation

$$\frac{\mathrm{d}N}{\mathrm{d}t} = -Z_t N_t \tag{3}$$

In this application, N_t is the number of fish at age *t*, and the instantaneous mortality rate (Z_t) is partitioned into age-specific fishing mortality rate attributable to Taiwanese longliners ($F_{\mathrm{TW},t}$), the age-specific fishing mortality rate attributable to South African baitboats ($F_{\mathrm{SA},t}$), and the instantaneous natural mortality rate (*M*).

The natural mortality rate, *M*, of South Atlantic albacore has generally been assumed to be independent of age and equal to 0.3 yr^{-1} (Sun, 1995). The sensitivity of the *Y/R* and SSB/R computations to the level of natural mortality was investigated by also examining the natural mortality rates of 0.2 and 0.4 yr^{-1}.

The age-specific fishing mortality rates for the two fleets were modeled as

$$F_{\mathrm{TW},t} = S_{\mathrm{TW},t} \times F_{\mathrm{apical,TW}} \tag{4}$$

$$F_{\mathrm{SA},t} = S_{\mathrm{SA},t} \times F_{\mathrm{apical,SA}} \tag{5}$$

where F_{apical} is the postulated apical fishing mortality rate, i.e., the fishing mortality rate on the age class at the peak of the selectivity ogive (the most vulnerable age). The quantities $S_{\mathrm{TW},t}$ and $S_{\mathrm{SA},t}$ represent the age-specific selectivities for the Taiwanese longline and South African baitboat fisheries, respectively.

2.3. Selectivity patterns

The selectivity pattern of the Taiwanese longline fleet targeting South Atlantic albacore is assumed in this study to be identical to that of the Taiwanese longline fleet targeting North Atlantic albacore. This assumption is believed to be robust inasmuch as the gear and deployment tactics are identical in both the fisheries.

The relative selectivity pattern of the Taiwanese longline fishery in the North Atlantic was computed by dividing estimates of the Taiwanese longline fishing mortality rates at age ($F_{\mathrm{TW},t}$) by the maximum F over all ages, i.e.,

$$S_{\mathrm{TW},t} = \frac{F_{\mathrm{TW},t}}{\mathrm{MAX}_t\{F_{\mathrm{TW},t}\}} \tag{6}$$

where,

$$F_{\mathrm{TW},t} = \frac{1}{4}\sum_{y=1989}^{1992} \frac{C_{\mathrm{TW},y}}{C_y} F_{y,t} \tag{7}$$

Here $C_{\mathrm{TW},y}$ is the catch attributable to Taiwanese longliners, C_y the total catch in year y and $F_{y,t}$ the total fishing mortality rate at age as estimated by a tuned VPA (Anon., 1997). The estimates of $F_{y,t}$ for the years before 1989 and subsequent to 1992 were excluded because they tend to be poorly estimated by VPAs.

The selectivity estimates from (6) were well-fit ($R^2 = 0.95$) by the logistic equation

$$\hat{S}_{\mathrm{TW},t} = \frac{1}{1 + \mathrm{e}^{1.6997-0.3558t}} \tag{8}$$

(see Fig. 1A).

The selectivity pattern of the South African baitboat fishery was deduced from the selectivity pattern of the Taiwanese longline fishery using the following procedure:

1. South Atlantic Taiwanese longline albacore length–frequency data for the period 1975–1992 and South African albacore length–frequency data for the period 1985–1992 (Fig. 7) were transformed to age composition using the growth equation.
2. The age composition data for each fleet were then averaged over the respective time periods and used to construct the relative selectivity ratio

   $$RS_t = \frac{n_{\mathrm{SA},t}}{n_{\mathrm{TW},t}} \tag{9}$$

   where $n_{\mathrm{SA},t}$ and $n_{\mathrm{TW},t}$ are the average relative numbers of fish aged t in the length–frequency samples of the South African and Taiwanese catches.

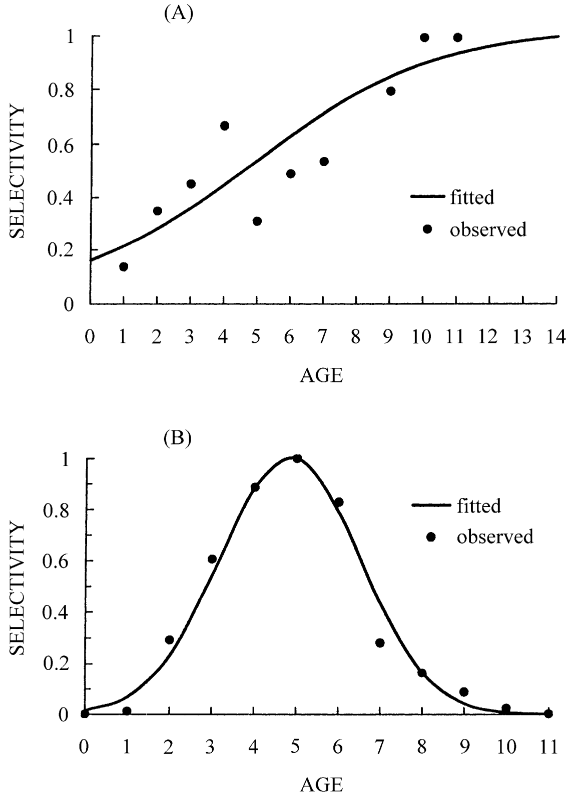

Fig. 1. Logistic selectivity curve for Taiwanese longline fishery (A) and normal selectivity curve for South African baitboat fishery (B).

3. Assuming the two fleets fish the same stock each year,

   $$S_{\mathrm{SA},t} = S_{\mathrm{TW},t} \times RS_t \tag{10}$$

The values calculated in step 3 were fitted by the normal distribution

$$\hat{S}_{\mathrm{SA},t} = \frac{C}{\sqrt{2\pi}\sigma}\mathrm{e}^{-(t-\bar{t})^2/2\sigma^2} \tag{11}$$

where $C=\sum_t S_{\mathrm{SA},t}=4.1807$, $\bar{t}=\sum_t tS_{\mathrm{SA},t}/\sum_t S_{\mathrm{SA},t} = 4.84$ yr and $\sigma = \sqrt{\sum_t (t-\bar{t})^2 S_{\mathrm{SA},t}/\sum_t S_{\mathrm{SA},t}} = 1.66$ yr.

The fitted selectivity curve is illustrated in Fig. 1B. The relative selectivities were computed by dividing the normal ogive above by its maximum.

2.4. Yield per recruit

The abundance of age t fish at the beginning of the year, N_t, is given by the solution to the differential equation (3)

$$N_t = \begin{cases} R_1 & (t = 1) \\ R_1\,\mathrm{e}^{-\sum_{i=1}^{t-1}(F_{\mathrm{TW},t}+F_{\mathrm{SA},t}+M)} & (t > 1) \end{cases} \tag{12}$$

Here recruitment is assumed to occur at age 1 so that R_1 is the initial abundance age 1 fish.

The corresponding equation for the annual catch in numbers at age t is

$$C_t = \frac{F_{\mathrm{TW},t}+F_{\mathrm{SA},t}}{F_{\mathrm{TW},t}+F_{\mathrm{SA},t}+M} N_t \left(1 - \mathrm{e}^{-(F_{\mathrm{TW},t}+F_{\mathrm{SA},t}+M)}\right) \tag{13}$$

The catch in weight (yield) is

$$Y_t = C_t \overline{W}_t \tag{14}$$

where $\overline{W}_t$ is the mean weight at age computed from the growth equations. The *Y/R* is

$$\frac{Y}{R} = \sum_{t=1}^{\max} \left(\overline{W}_t \frac{F_{\mathrm{TW},t}+F_{\mathrm{SA},t}}{Z_t} (1 - \mathrm{e}^{-Z_t})\,\mathrm{e}^{-\sum_{i=1}^{t-1} Z_i} \right) \tag{15}$$

where

$$Z_i = \begin{cases} F_{\mathrm{TW},t} + F_{\mathrm{SA},t} + M & (t > 1) \\ 0 & (t \le 1) \end{cases}$$

2.5. Spawning potential ratio

Goodyear (1989) defined the spawning potential ratio (SPR) as the equilibrium SSB/R corresponding to a given level of fishing mortality divided by the equilibrium SSB/R without fishing. He suggested SPR as a measure of the impact of fishing on the potential productivity of a stock, stating that SPR values below about 20% should be avoided unless there is evidence for exceptionally strong density dependence in the stock (Goodyear, 1993). Clark (1991, 1993) suggested SPR values of about 35% as a safer target management objective which may protect, or at least reduce, the risk of recruitment overfishing.

South Atlantic albacore are believed to reach maturity at 6 years of age (ICCAT, 1995; Punt et al., 1994) and fish older than 14 years of age are rare enough to be neglected. Accordingly, the formula for the SPR of South Atlantic albacore can be expressed as

$$\mathrm{SPR} = \frac{\sum_{t=6}^{14} B_t}{\sum_{t=6}^{14} B_t^*} \tag{16}$$

The quantity B_t is the potential spawning stock biomass of a cohort at age t under a given exploitation pattern and recruitment

$$B_t = W_t R_1\,\mathrm{e}^{-\sum_{i=1}^{t-1} Z_i} \tag{17}$$

$$Z_i = \begin{cases} F_{\mathrm{TW},t} + F_{\mathrm{SA},t} + M & (t > 1) \\ 0 & (t \le 1) \end{cases}$$

where W_t is the expected weight of a fish when it first turns age t. The quantity B_t^* is the potential spawning stock biomass of the same cohort if it were not fished. Note that the recruitment term, R_1, cancels out in the formula for SPR.

The sensitivity of the SPR to the age at first maturity was examined by increasing the age of first maturity from 6 to 8 years.

2.6. The relationship between the effective fishing mortality rate (F_{eff}) and the apical fishing mortality rate (F_{apical})

The results in the *Y/R* and SPR analyses are presented in terms of apical fishing mortality rates to facilitate the comparison of the two fleets. Of course it would be helpful in interpreting the results to know the actual apical fishing mortality rates exhibited by the fishery. Unfortunately, apical fishing mortality rates are not directly estimable from the types of data available for South Atlantic albacore. Estimates of the gross 'effective' fishing mortality rates, however, were obtained for each fleet by Sun (1995) using the dynamic production model ASPIC (Prager, 1994).

The effective fishing mortality rate is that necessary to produce a given total catch from a given average total abundance

$$F_{\mathrm{eff}} = \frac{\sum_t C_t}{\sum_t \overline{N}_t} = F_{\mathrm{apical}} \frac{\sum_t S_t \overline{N}_t}{\sum_t \overline{N}_t} \tag{18}$$

This equation cannot be solved for F_{apical} apart from information on the age-structure of the population.

One approximation is

$$F_{\mathrm{apical}} \approx \frac{F_{\mathrm{eff}}}{\overline{S}} \qquad (19)$$

where $\overline{S}$ is the average of the selectivity coefficients. This formula implicitly assumes that the abundance is the same for every age. A better approximation would be provided by assuming the age-structure of the population is similar to the equilibrium age-structure expected under constant recruitment. In that case, Eq. (18) may be rewritten as

$$F_{\mathrm{eff}} = F_{\mathrm{apical}} \frac{\sum_t S_t/Z_t(1 - \mathrm{e}^{-Z_t})\,\mathrm{e}^{-\sum_{i=1}^{t-1} Z_i}}{\sum_t 1/Z_t(1 - \mathrm{e}^{-Z_t})\,\mathrm{e}^{-\sum_{i=1}^{t-1} Z_i}} \qquad (20)$$

$$Z_i = \begin{cases} -M - S_i F_{\mathrm{apical}} & (t > 1) \\ 0 & (t \leq 1) \end{cases}$$

$$Z_t = -M - S_t F_{\mathrm{apical}}$$

which can be solved for F_{apical} in iterative fashion. This approximation is relatively robust to random variations in recruitment, but will be biased if there is a strong increasing or decreasing trend. Such a trend is not evident for northern Albacore (ICCAT, 1998) and we do not expect one for the perhaps less heavily exploited southern stock, therefore Eq. (20) was used to convert the effective fishing mortality rates obtained from Sun (1995) to apical fishing mortality rates (shown in Fig. 2).

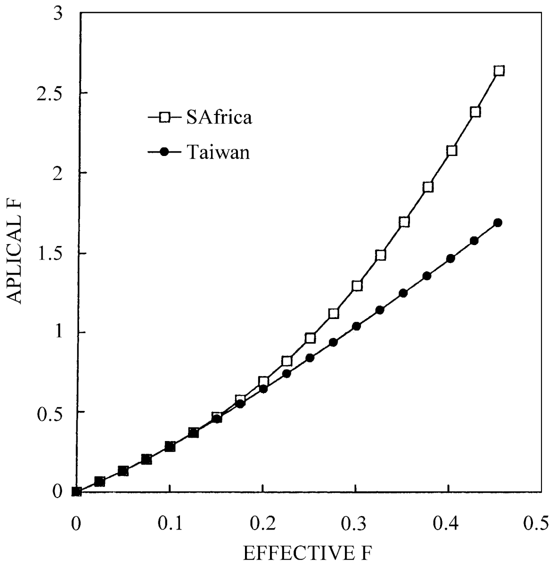

Fig. 2. The relationship between the effective and apical fishing mortalities for South African baitboat and Taiwanese longline fisheries.

3. Results

The predicted effect of the different combinations of Taiwanese and South African fishing mortalities on the total equilibrium *Y/R* under the base case assumption of $M = 0.3$ is illustrated in Fig. 3A. The maximum *Y/R* was estimated to be 2.2 kg and is expected to occur with South African apical fishing mortality rates of 2.2 yr^{-1} and Taiwanese apical fishing mortality rates between 0.1 and 0.4 yr^{-1}. This is substantially greater than the value of 1.7 kg corresponding to estimated apical fishing mortality rates for 1996 (South Africa = 0.0356 yr^{-1} and Taiwan = 0.2362 yr^{-1}). Fig. 3B suggests that the *Y/R* for the Taiwanese fleet could be increased from 1.65 kg to as much as 1.9 kg by increasing the Taiwanese apical fishing mortality rate to between 0.4 and 0.8 yr^{-1}. The South African fleet, however, could marginally improve its *Y/R* by increasing its apical fishing mortality rate, but would benefit greatly from a decrease in the Taiwanese fishing mortality rate (Fig. 3C).

The value of SPR is predominantly determined by the fishing mortality rate exerted by the Taiwanese fleet (Fig. 3D). The 20% level should be achieved provided the Taiwanese apical fishing mortality rate does not exceed 0.55 yr^{-1}. The estimates of the historical apical fishing mortality rates (Fig. 2) are all below this value and have corresponding SPR values of over 25%. The SPR estimated for 1996 is 45%. However, increasing the age of first maturity decreased the values of SPR predicted for a given combination of apical fishing mortality rates (Fig. 4). If South Atlantic albacore become mature 2 years later than is presently believed, then the Taiwanese apical fishing mortality rate would have to be below 0.4 yr^{-1} in order to maintain a 20% SPR (rather than 0.55 yr^{-1}).

The *Y/R* and SPR isopleths obtained with $M = 0.2$ and $M = 0.4$ are given in Figs. 5 and 6, respectively. The shape of the *Y/R* isopleth is relatively insensitive to the value of M, but the magnitude of *Y/R* decreases

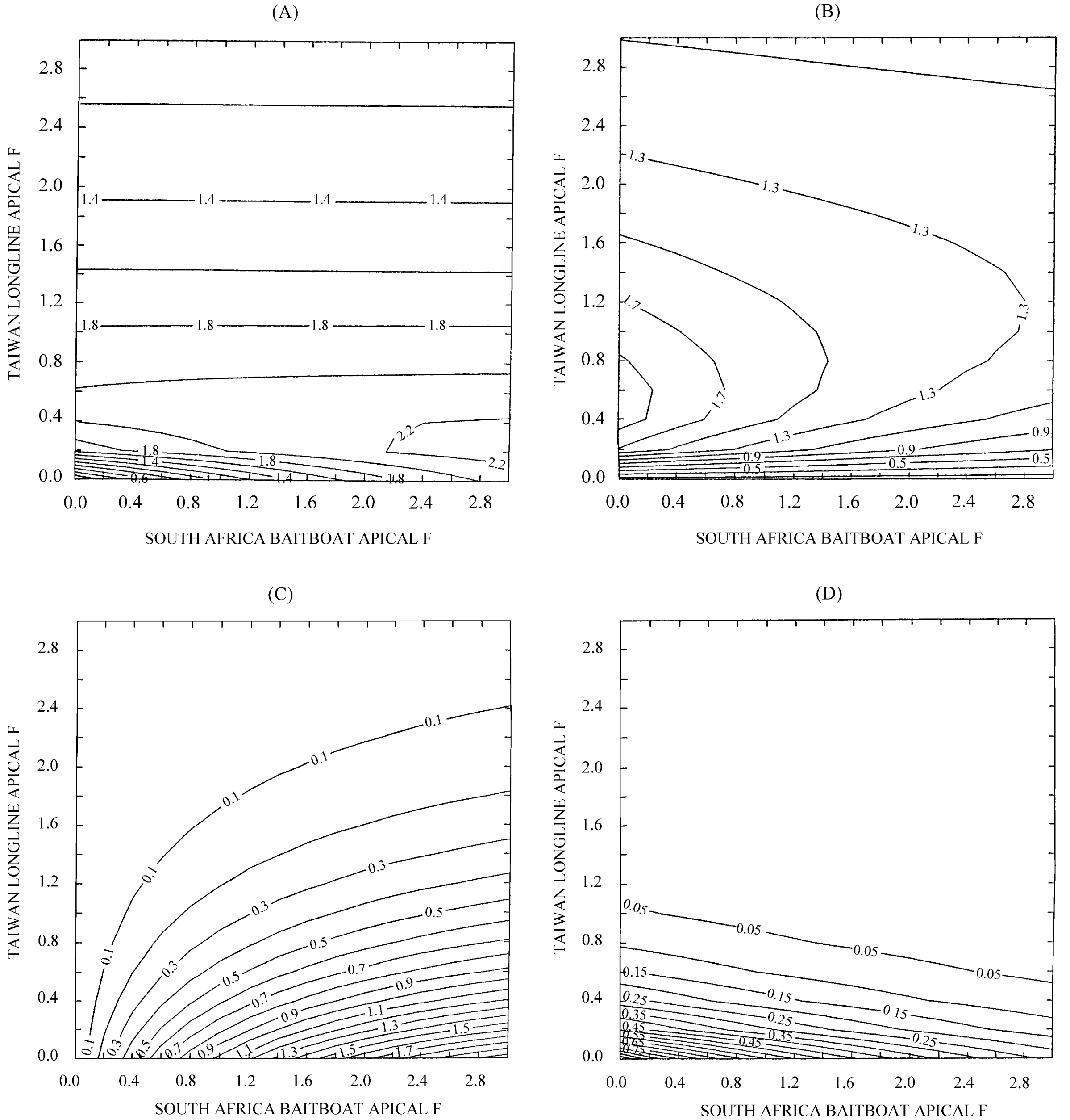

Fig. 3. *Y*/*R* isopleths for both fisheries combined (A), Taiwanese longline fishery (B) and South African baitboat fishery (C), and the SPR isopleths (D) in the base case ($M = 0.3$ and first maturity at age 6).

as M increases. The SPR trends (Figs. 5D and 6D) are similar to those for the base case (Fig. 3D), but the higher natural mortality rates allowed for greater fishing mortality rates at a given value of SPR. For example, in order to maintain an SPR of 20%, the Taiwanese apical fishing mortality rate would have to be below 0.45 yr^{-1} when M is 0.2 yr^{-1} as opposed to below 0.58 yr^{-1} when M is 0.4 yr^{-1}.

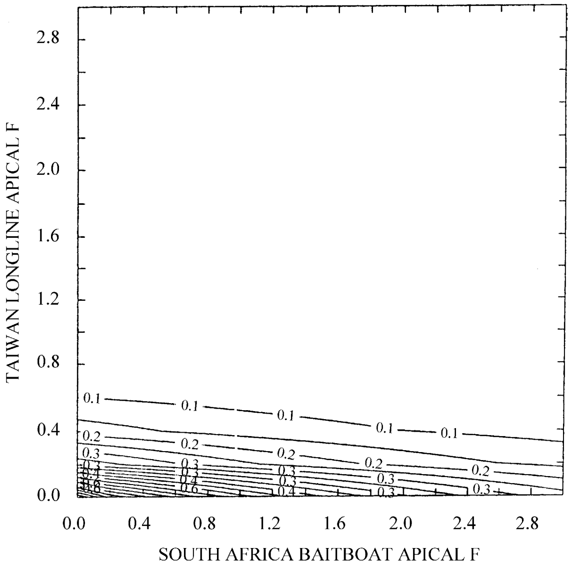

Fig. 4. SPR isopleths when $M = 0.3$ and first maturity at age 8.

4. Discussion

The present analysis considered the effect of varying the fishing mortality of Taiwanese longliners and South African baitboats on the equilibrium *Y/R* and SSB/R. The two fleets were considered simultaneously rather than separately because the catches of each fleet are necessarily interdependent unless they fish entirely distinct stocks. The analysis focused on the Taiwanese and South African fleets because they are by far the two most important harvesters of South Atlantic albacore. The landings reported for the remaining fleets are assumed negligible. Moreover, the size composition data for the two fisheries were recently revised, permitting the selectivity curve to be estimated for the South African baitboat fleet.

The very different selectivity patterns of the two fleets affect the outcome of the *Y/R* analysis significantly. The *Y/R* isopleths for the South African fleet are maximized at high levels of fishing mortality because the selectivities are normally distributed about a fairly young age. The South African fleet would benefit by increasing its fishing mortality rate because it does not catch larger fish. From a *Y/R* standpoint, there is no value allowing fish to grow larger if you can no longer catch them. The Taiwanese fleet, on the other hand, selects mostly larger fish and has less to gain by increasing its fishing mortality rate.

The different selectivity patterns of the South African and Taiwanese fleets also have important implications for the SPR. Because the South African fleet targets a narrower window of age groups than the Taiwanese fleet, the SPR is much less sensitive to changes in the level of South African fishing mortality than it is to changes in the Taiwanese fishing mortality.

The estimated magnitudes of *Y/R*, and, to a lesser extent, SPR, were sensitive to level of natural mortality. For example, the estimated maximum *Y/R* decreased from 3.4 to 1.5 kg when M was increased from 0.2 to 0.4 yr^{-1}. The 20% SPR isopleth, on the other hand, occurred at higher fishing mortality rates when M was 0.4 yr^{-1} than when M was 0.2 yr^{-1}. These results are not surprising since higher natural mortality rates leave fewer fish for the fleets to catch, decreasing the yield and mitigating the relative impact of fishing on the survival of spawners.

The values of *Y/R* estimated in this study are much lower than those published for North Atlantic albacore (Bartoo, 1979; Bard and González-Garcés, 1980; González-Garcés and Weber, 1985; ICCAT, 1995). Bartoo (1979) reported maximum values of *Y/R* ranging from 5.7 to 6.6 kg depending on the M value used, compared to 2.2 kg in this study. More recent studies have reported a range of values for North Atlantic albacore between 4.07 and 5.5 kg (Bard and González-Garcés, 1980; González-Garcés and Weber, 1985; ICCAT, 1995). The difference is largely due to the much slower growth rates estimated for South Atlantic albacore by Lee and Yeh (1993). For example, the estimated maximum *Y/R* increased from 2.2 to 4.0 kg when Bard's (1981) North Atlantic albacore growth equation was substituted for Lee and Yeh's (1993) South Atlantic albacore growth equation (Sun, 1995).

The results of this study also clearly depart from the age-structured production model analyses of South Atlantic albacore conducted by Punt et al. (1994, 1995). The differences are largely due to the fact that Punt et al. assumed that the selectivity of the entire fishery is the same as that of the Taiwanese fleet and follows a logistic curve. Since the landings of the South African baitboat fleet are not negligible, the present analyses should provide a better representation of the actual dynamics of the fishery.

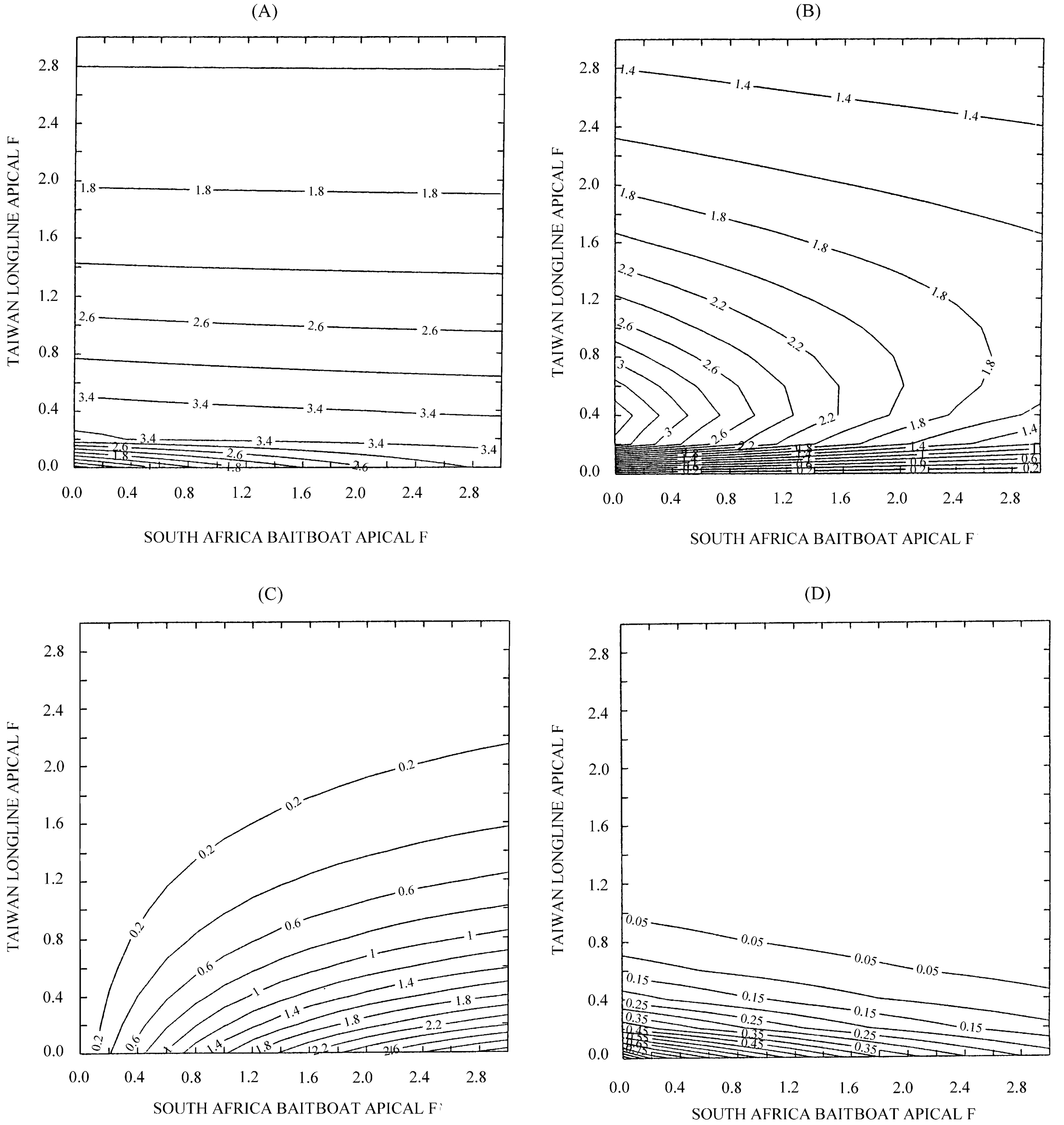

Fig. 5. *Y*/*R* isopleths for both fisheries combined (A), Taiwanese longline fishery (B) and South African baitboat fishery (C), and the SPR isopleths (D) when $M = 0.2$ and first maturity at age 6.

In terms of management strategies, if the goal is simply to maximize the overall *Y*/*R*, the results from the base case indicate that the South African fishing mortality rate should be increased to at least six times the current level whereas the Taiwanese fishing mortality rate is near optimal. This strategy, however, would probably decrease the SPR to below 15% and by that criteria is inappropriate.

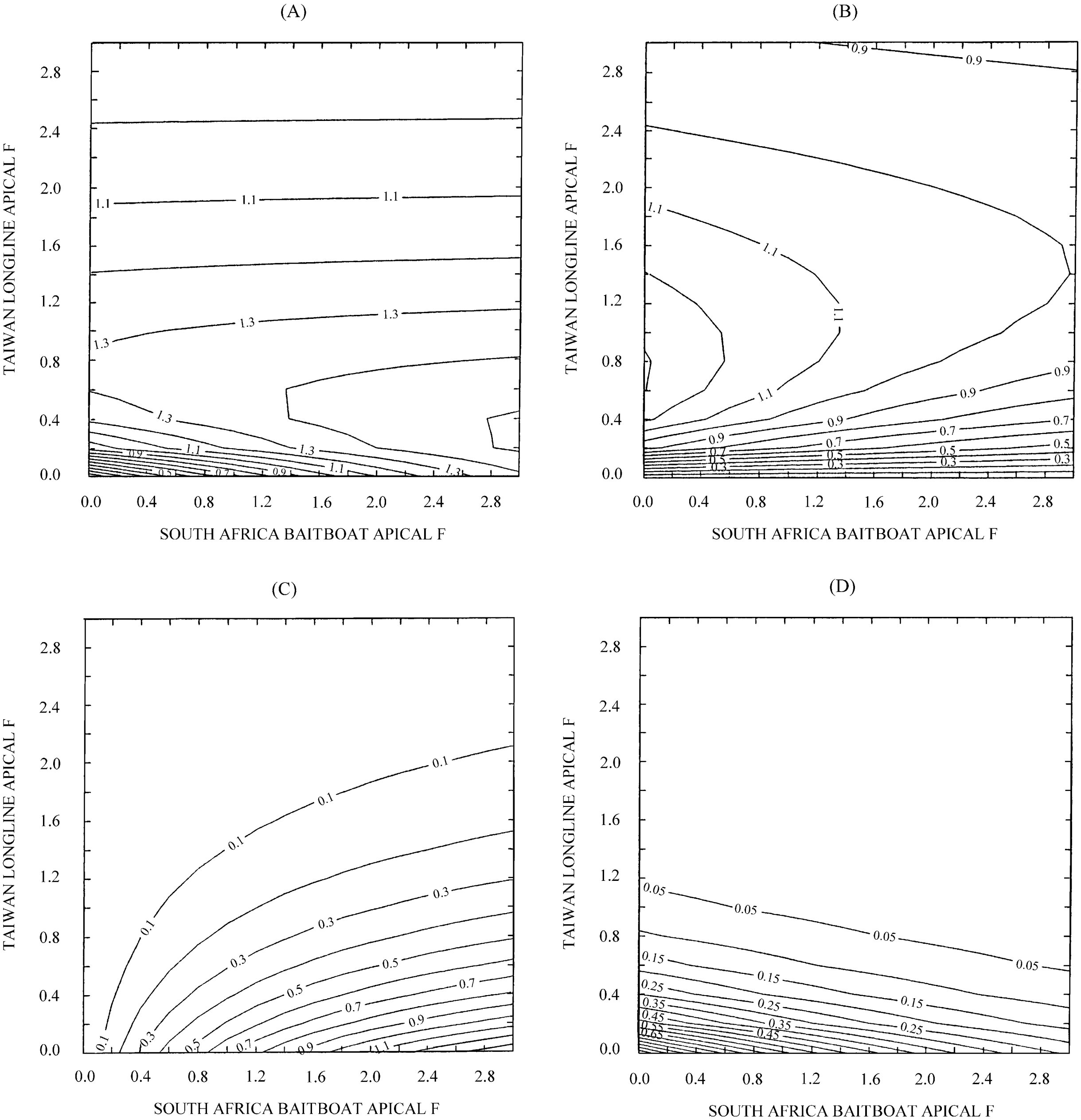

Fig. 6. *Y*/*R* isopleths for both fisheries combined (A), Taiwanese longline fishery (B) and South African baitboat fishery (C), and the SPR isopleths (D) when $M = 0.4$ and first maturity at age 6.

Inasmuch as the yield and spawning potential computations were done on a per-recruit basis, the results of this analysis are applicable regardless of the recruitment level experienced by the stocks. The effect of any prescribed change in the fishing mortality rates of each fleet can easily be inferred from the *Y*/*R* and SPR isopleths given above. In practice, however, prescribed changes in the fishing mortality rates are

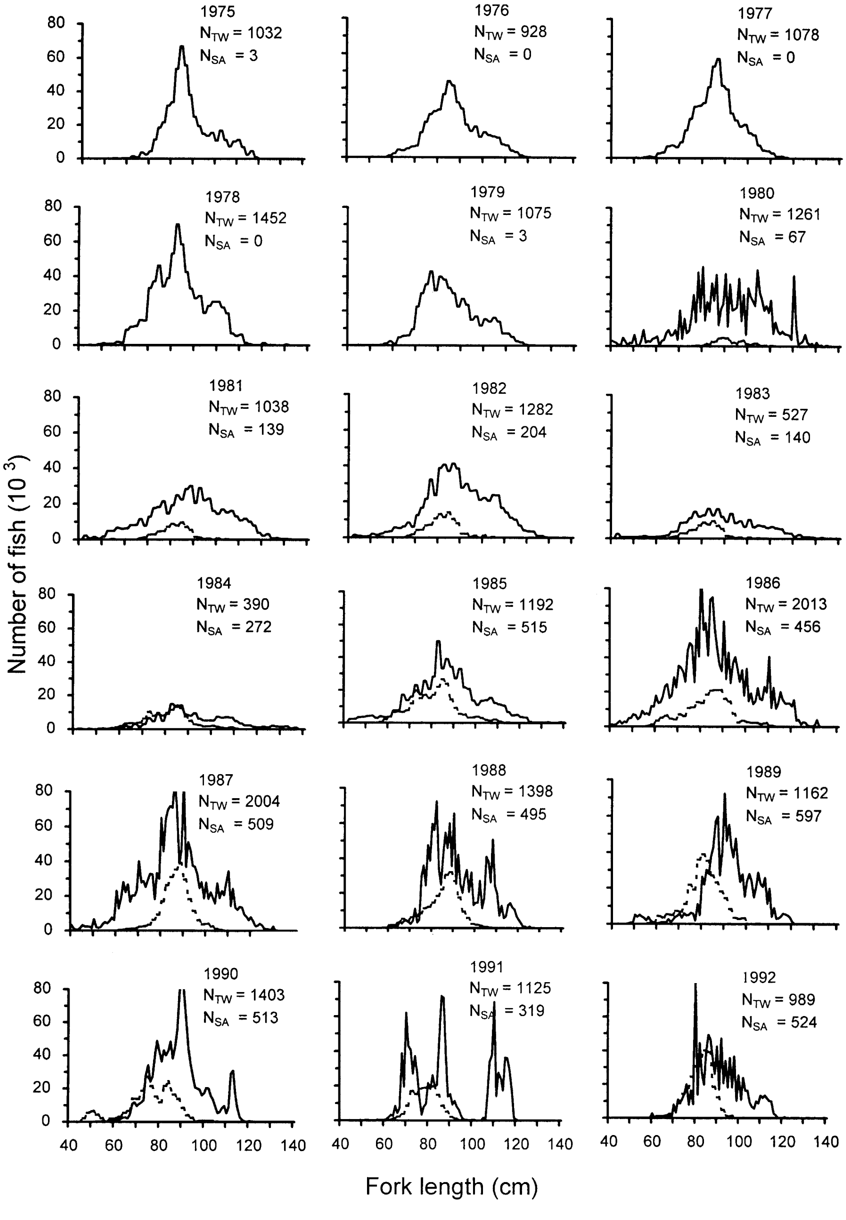

Fig. 7. Comparison of catch at size for the South Atlantic albacore between the Taiwanese longline fishery (solid line, N_{TW}) and the South African baitboat fishery (dash line, N_{SA}), 1975–1992. Sample size (N_{TW}, N_{SA}) in 1000 fish.

often implemented by imposing catch quotas rather than by limiting the fishing effort directly.

The immediate effect of a change in the allocation of annual quotas between the Taiwanese longline and South Africa baitboat can be inferred by assuming the population structure changes very little initially (Fig. 7). In that case, the effective fishing mortality rate corresponding to a proposed catch quota Q for fleet j is approximately

$$Q_{F_j} = \frac{Q_j}{C_j} F_j \tag{21}$$

where C_j and F_j are estimates of the current catch (in numbers or weight) and fishing mortality rate, respectively. The corresponding *Y/R* and SPR values can then be obtained from the isopleths given.

The long-term effect of a prescribed set of quotas on *Y/R* hinges on the relationship of the number of recruits to spawning stock biomass and other factors—none of which are well understood at present. Moreover, it is likely that the full benefits of implementing an optimal *Y/R* policy will not be realized immediately. This is because the fish that recruited to the fishery prior to the implementation of the optimal policy have previously been subjected to sub-optimal fishing policies. The length of the transition phase from sub-optimum to optimum yields per recruit depends of course on the number of ages that contribute to the catch and the degree to which the recent historical fishing policies have departed from the optimum policy.

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