OPTIMAL AUSTRALIAN AND JAPANESE HARVESTING

OF

SOUTHERN BLUEFIN TUNA

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Paper presented at 35th Annual Conference of the
Australian Agricultural Economics Society
University of New England, Armidale, NSW
February 11-14, 1991

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by

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Introduction

Southern bluefin tuna (SBT) are fished primarily by Japan and Australia. Small quantities are taken by fishermen from New Zealand, Taiwan, Korea, South Africa and Indonesia. Australian fishermen mainly catch juveniles aged between 2 to 6 years within the Australian Fishing Zone (AFZ). The Japanese catch mainly adult fish above 6 years of age. In 1990 Japanese fishermen took about 30 per cent of their total catch from within the Australian Fishing Zone. The rest of the Japanese catch was caught in oceanic areas stretching from South Africa to New Zealand.

In 1983, after scientists had expressed concern over the biological viability of the fishery, the Australian, Japanese and New Zealand Governments agreed to limit SBT catches. In 1984, the Australian Government introduced an individual transferable quota scheme for the Australian fishery. Tradeable quota entitles the holder to catch a proportion of the total allowable catch declared by the Government each year. Since then, quotas have

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* Dr Hanoch Pasternak is a Visiting Research Fellow from the Volcani Institute in Israel. Subject to the usual caveat, we would like to thank the following for data and helpful discussion: Albert Caton, Martin Excel, Gerry Geen, Bob Kearney, Geoff Kirkwood and Neil Klaer. Work reported in this paper was made possible by a large grant from the Australian Research Council and by a supplementary research grant from the School of Economics and Commerce at La Trobe University.

been steadily reduced so that by 1990-91 they were about 24 per cent of the 1983 quotas. The global SBT quota for 1990-91 has been set at 11,750 tonnes, with quota tonnages allocated 6,065 to Japan, 5,265 to Australia and 420 to New Zealand (Kerin, 1990).

The aim of this paper is to explore what harvesting strategies through time would appear to be optimal for the two major harvesting nations, Australia and Japan. A major question of interest is whether quotas on harvest levels should continue to be cut back or whether they should be relaxed. Different answers will be obtained depending on the uncertain estimates of the relevant biological and economic parameters, and on the degree of cooperation between Australia and Japan in setting quotas through time. Australia fishes SBT in their juvenile phase and thereby exerts considerable control over the fishable adult biomass available to Japan. It is in the juvenile phase that weight gain is greatest. To the extent that the recruitment of new stock to the fishery depends on the parental biomass, Japan exerts control over juvenile stocks available to Australia by harvesting the parental biomass. There are other economic interdependencies. Most of the Australian catch is now sold on the Japanese market, access to which could be controlled. Australia can control Japanese access to grounds within the AFZ.

Because SBT live up to about 20 years of age, and are fished by different nations using different harvesting technologies during different phases of their life cycle, it is important to model the stock dynamics with a multicohort approach. An important limitation of the SBT duopoly model developed by Kennedy (1987) was the characterization of the fishery by only two stocks, juvenile and adult, instead of by stocks for all year classes.

Several multicohort models have been developed to determine harvesting levels through time which maximize economic welfare. Kennedy and Watkins (1986) used a dynamic programming model to find optimal time-dependent quotas in the SBT fishery. Kennedy (1989) developed a model incorporating an efficient algorithm for finding approximately optimal harvest sequences starting with a depleted stock. This model captures the multi-cohort aspect of the fishery but does not deal with the multination exploitation of the SBT fishery. Horwood and Whittle (1986) applied locally optimal linear control theorems to maximize the return from stocks of western mackerel modelled as a multi-cohort fishery. Horwood (1987) used a non-linear programming package to solve finite time horizon problems for the same fishery.

The model described in this paper for the SBT fishery is more extensive than other applied models because the fishery is treated as a multicohort, multinational resource, and because demand and harvesting cost functions are estimated and incorporated. Numerical solutions for the maximization of the joint objective function of Australia and Japan are obtained using the non-linear software package MINOS (see Murtagh and Saunders, 1987). Further, a game theoretic approach is used to obtain non-cooperative harvesting strategies for Australia and Japan. The duopoly solution is characterized by a pair of harvesting trajectories (one for each nation) each of which maximizes one nation's objective function subject to the other nation's fishing effort trajectory. An iterative process of obtaining solutions for the objective function of each nation alternately given the fishing mortalities previously determined as optimal for the other nation is followed until the non-cooperative Nash solution is obtained. The results are expected to be of value in highlighting the bargaining position of Australia and Japan in the SBT fishery, as well as in modelling other multicohort, multinational fisheries.

The Model

For modelling purposes one or two fishing grounds are defined for Japan, and one for Australia. The Japanese operate longliners to harvest mainly adult SBT above 6 years of age which swim alone or in small groups. One of the Japanese grounds is referred to as "high seas" (ground 1), consisting of the oceanic water from New Zealand to South Africa. In some runs of the model, a second Japanese ground in included, referred to as "off Tasmania" (ground 2). The effect of including the second ground is of interest because Australia can control Japanese access. The two Japanese grounds are known to differ in relation to age composition of the catch and meat quality. The Australian ground is ground 3. The Australian fishery is based on pole boats and purse seiners to capture mainly juvenile fish from large surface schools which inhabit the coastal water of southern Australia.

The fish stock was divided into 19 age classes or cohorts. The SBT is known to be a highly migratory fish with one spawning ground. Therefore common age categories for all the fishing grounds are defined. The rather unsatisfactory simplification was made that Japanese stock numbers applied to both high seas and off Tasmania grounds, for lack of information about splits in the migration paths between the grounds. Associated with each fishing ground, a set of 19 catchability coefficients was used. The coefficients are estimates of the ratio between catch numbers and stock numbers in each cohort. It was assumed that the relativities between these coefficients are stable and independent of stock size and harvest level. There are up to three decision variables for each year of the model run: the instantaneous rates of fishing mortality in each ground. The instantaneous rate of fishing mortality for each combination of cohort, ground and year is calculated as the product of the ground's fishing mortality rate and the catchability coefficient. The relationship between harvest and the proportion of fish surviving in each cohort to the next year is similar to that used by Kope (1987) for a multiground fishery model. Harvests and stock survival are functions of the instantaneous fishing mortality rate in each ground and the instantaneous natural rate of mortality. Age-specific natural mortality rates could be incorporated in this model but, in the absence of other estimates, the instantaneous natural mortality rate was taken to be 0.2 for all cohorts (see Hampton and Majkowski, 1986).

The objective function depends on the type of strategy modelled. Under joint maximization for a cooperative strategy, the objective is to maximize the present value of the sum of annual social rents generated in each ground. The value of catch is measured by willingness to pay for the catch, equal to the relevant area under the processors' demand schedule. Social rent is defined as the social value of the catch, less harvesting costs and any crew costs directly related to the value of the catch. Under duopoly for a nation's non-cooperative strategy, the objective is to maximize the nation's present value of annual social rents generated form its ground(s), given the fishing mortality rates set by the other nation.

The model is fully specified in the Appendix. The Appendix also contains tables giving the parameter values used. The following two sections describe the estimation of the demand and harvesting cost functions used for each ground. There are two final sections presenting results and conclusions.

Demand Functions

The main outlet for SBT is the sashimi (raw seafood) market. Quality factors strongly affect the price of SBT. Large size, high fat content, appropriate colour, and meat structure are desired. To obtain a high price, the fish should be caught by a method such as longlining which reduces the stress of capture and preserves meat quality (Williams, 1986). Because much sashimi fish is eaten away from home, reliability of supply and quality affects price (Williams, 1989).

The average wholesale market price of SBT landed by Japanese vessels in 1989 was above 5,000 yen per kg, which classes it as a "high value" fish. Kitson and Maynard (1983) estimated price and income elasticities of "high value" fish to be 1.39 and 1.77 respectively, defining "high value" as species valued at more than 1,000 yen per kg at the Tokyo wholesale market in 1980. Price and income elasticities for "low value" fish were found to be lower (Kitson and Maynard, 1983; Kingston et al., 1990).

To guage the price elasticity of demand for high value SBT, various linear and log linear functions were fitted for annual data covering the period 1975 to 1987. Price of SBT on the Yaizu market, deflated by the overall wholesale price index, was regressed on consumption per head and on deflated gross domestic product as a proxy for household income.

When consumption was the only explanatory variable in the price functions, the standard errors of the consumption parameters were relatively small and the price elasticities of demand were stable and close to 1.0. Poor fits were obtained when income was added as an explanatory variable. It was concluded therefore that the price elasticity of demand for high value SBT should be estimated to be 1.0. A linear function gave a comparable fit to log linear functions in terms of R^2 and asymptotic standard errors, and was therefore selected on grounds of simplicity.

Separate and independent demand functions were assumed for landings from each of the three grounds. This is probably a reasonable approximation given the different age composition and quality of catches from the three grounds. Lack of appropriate data makes it difficult to estimate the degree of substitution between landings. Price for the Japanese off Tasmania (ground 2) catch is estimated to be about 70 per cent of the price for the Japanese high seas (ground 1) catch. The Australian harvest (from ground 3) is sold on the low-grade sashimi market, and fetches only about 10 per cent of the Japanese high seas price. Geen (personal communication, 1990) reports a price A$4 per kg liveweight for SBT delivered to Japanese boats for processing and marketing. The price for SBT marketed frozen by Australia in Japan is significantly lower.

Parameters for the three linear demand schedules are given in Table A2. They were calculated consistent with each schedule passing through the average price and quantity for the years 1987 to 1989 with an elasticity of one.

Harvesting Cost Functions

Japanese and Australian harvesting costs are determined for any catch via a constant cost per unit effort coefficient, and a harvest function relating harvest to effort and stock size. The empirical fisheries literature contains few studies of harvesting production functions. The well-known Schaefer function which is linear in both effort and stock-size is commonly used (Bjorndal, 1987). The assumptions underlying this model include: 1) the distribution of fish is uniform; and 2) catch per unit of effort is proportional to stock size at all effort levels.

Theoretical analysis by Clark (1985) indicates that the stock elasticity of catch should be one when the stock density is uniform, and in the range zero to one in schooling fisheries. Empirical evidence published by Clark (1985) and Bjorndal (1987) supports this conclusion. These considerations influenced the choice of harvest functions for the SBT fishery.

Harvesting Cost Function for Japan

Three harvesting functions relating catch to effort and stock size were estimated for the Japanese fishery from annual data covering 1957 to 1987. Effort is represented by the measure accepted by the SBT industry - the number of hooks set (Kono and Warashina, 1990). The stock is represented by parental biomass (above 8 years old) and was estimated by virtual population analysis (Klaer, 1990). Most of the longliners' SBT catch consists of this age group. Detailed information on the Japanese catch was obtained from Warashina (1990).

Three functions were fitted for the years 1957 to 1979. Two are Cobb-Douglas-type functions similar to those used by Bjorndal (1987) and the third is similar to one used by Mangel (1985). Results for the full data set covering 1957 to 1987 showed poor R^2 values. From 1980 to 1987, reported catch declined rapidly compared to the decline in estimated stock, while reported effort remained relatively constant. A justification for using functions based on 1957 to 1979 data only would be that the more recent data are unreliable, perhaps due to under-reporting of catches. It should be noted that if there are other explanations for recent trends, use of the functions may lead to overly optimistic projections of returns from the fishery.

The correlation coefficients between catch, stock size and effort are given in Table 1.

TABLE 1

Correlations between catch stock-size and effort*

	Effort	Stock
Effort	-	-0.9614
Catch	-0.1619	0.2973
Catch:stock ratio	0.8266	-0.7445

* A correlation of 0.52 is significant at the 1 per cent level.

Catch was found to be little correlated with stock and even slightly negatively correlated with effort. These results may be explained by the strongly negative correlation between effort and stock reflecting the trend of decreasing stocks together with increasing effort. However, models incorporating both effort and stock size as explanatory variables resulted in high values of R^2.

The form of the harvesting production functions and the parameters estimated are presented in Table 2.

TABLE 2

Estimation of harvesting production function parameters*

$$\text{Catch} = \underset{(0.00037)}{0.0002596} \,.\, \underset{(0.19)}{\text{Stock}^{1.8007}} \,.\, \underset{(0.10)}{\text{Effort}^{0.8089}} \qquad R^2 = 0.846 \qquad (1)$$

$$\frac{\text{Catch}}{\text{Stock}} = \underset{(0.0075)}{0.03009} \,.\, \underset{(0.059)}{\text{Effort}^{0.396}} \qquad R^2 = 0.776 \qquad (2)$$

$$\frac{\text{Catch}}{\text{Stock}} = \underset{(0.008)}{0.1803} \,.\, (1 - \exp(\underset{(0.0060)}{-0.0394} \,.\, \text{Effort})) \qquad R^2 = 0.829 \qquad (3)$$

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* Asymptotic standard errors are given in brackets below the parameter values.

Units: Catch - thousand fish
Stock - thousand tonnes
Effort - million hooks set per year

Fitting isoelastic production function (1) resulted in stock elasticities greater than one. As the adult SBT caught by Japanese longliners tend to be solitary or swim in small groups, it was concluded that the stock elasticity should be set at one, the maximum value on a priori grounds.

Function (3) was selected as the harvest production function because of the low standard error values associated with its parameters and the relatively high value of R^2.

The Japanese harvest cost for ground n was assumed equal to the product of effort and the cost per unit effort coefficient, c_n. This leads to equation (A9a) in the Appendix, with $v_n = 0.0394$ and $d_n = 0.1803$. Because c_n is calculated for 1988, a relative weighting factor

$$s_n = (h_1 + h_2)/h_n \qquad (n=1,2)$$

for harvests h_1 and h_2 in 1988 is applied to the catch/stock ratio for each ground. If $s_n \cdot h_{nt}/BIOM_n$ is greater than d_n, (A9a) results in an undefined harvesting cost. In this case the harvesting cost function becomes Schaefer function (A9b), where u_n is calculated so that harvesting cost is equal under (A9a) and (A9b) for $s_n \cdot h_{nt}/BIOM_n$ set arbitrarily close to d_n at 0.18. However, in all runs of the model (A9a) applied.

The Japanese cost per unit effort coefficients, shown in Table A2, are based on the cost of SBT caught per tonne liveweight (calculated as A$26,353 per tonne liveweight for 1988), and data on the 1988 catch and catch-per-hook-set for the two grounds (Green, 1990).

Harvesting Cost Function for Australia

Australian fishermen catch SBT mainly from 2 to 6 years of age in the coastal waters of southern Australia. In 1989, 10 pole boats together with 4 purse seiners cooperated in exploiting the schools of SBT in the South Australia fishery and caught about 92 per cent of the total Australian catch (Caton and Williams, 1990). The size of the South Australia SBT fleet has decreased significantly from 44 boats in the 1983-84 season to 20 boats in the 1987-88 season, while the annual catch has remained at about 10,000 tonnes over the period (Geen and Nayar, 1989, Table 6). Therefore it was decided not to estimate a function relating catch to effort and stock employing time series analysis. Instead, a Cobb-Douglas-type function was assumed with a stock exponent set at 0.6, similar to the value empirically estimated by Bjorndal (1987) for another schooling fishery, North Sea herring. This results in the cost function (A9c) in the Appendix. Stock biomass in (A9c) is for the age group 2 to 6 years of age. The cost per unit of effort coefficient, c_3, is based on costs listed by Geen (personal communication, 1990). Crew costs are a proportion $\beta_3 = 0.15$ of the value of the Australian catch.

Results

The non-linear programming package MINOS was used to find solutions for the joint maximization and duopoly problems. In all model runs the number of years in the time horizon (T) was 20, taken to cover the years 1989 to 2008. The rate of discount (r) was 10 per cent per annum. The solution time profiles of harvest by ground are shown in

TABLE 3

Total harvests and economic welfare under alternative strategies for fishing grounds: Japanese high seas (JHS), Japanese off Tasmania (JOT) and Australian (A)

	Joint maximization			Duopoly 3 grounds			Duopoly 2 grounds	
	JHS	JOT	A	JHS	JOT	A	JHS	A
Total harvest over 20 years (thousand tonnes)								
By ground	291	46	181	223	34	350	237	351
By country	......337......		181	......257......		350	237	351
Total	............518...........			............607...........			.........588.........	
Spawning stock biomass peak (thousand tonnes)								
Total	............322...........			............180...........			.........193.........	
Present value of social rents (A$million)								
By ground	4,036	401	220	3,301	296	486	3,396	487
By country	......4,437......		220	......3,597......		486	3,396	487
Total	..........4,657.........			..........4,083.........			........3,883........	
Value of social rent in the first year (A$million)								
By ground	262	21	0	260	21	53	261	53
By country	......283......		0	......281......		53	261	53
Total	............283...........			............334...........			.........314.........	

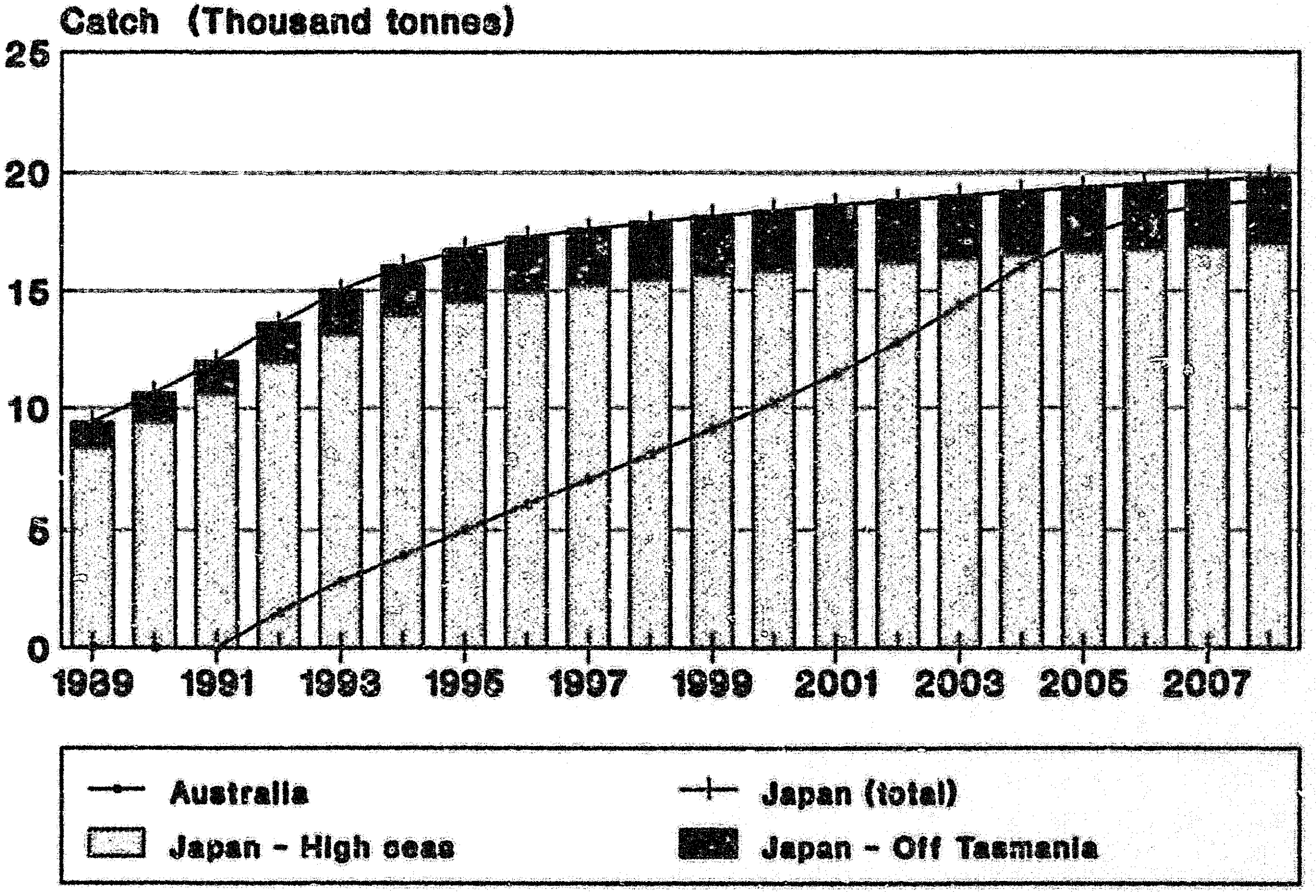

Figure 1: Catches for 3 grounds under joint maximisation

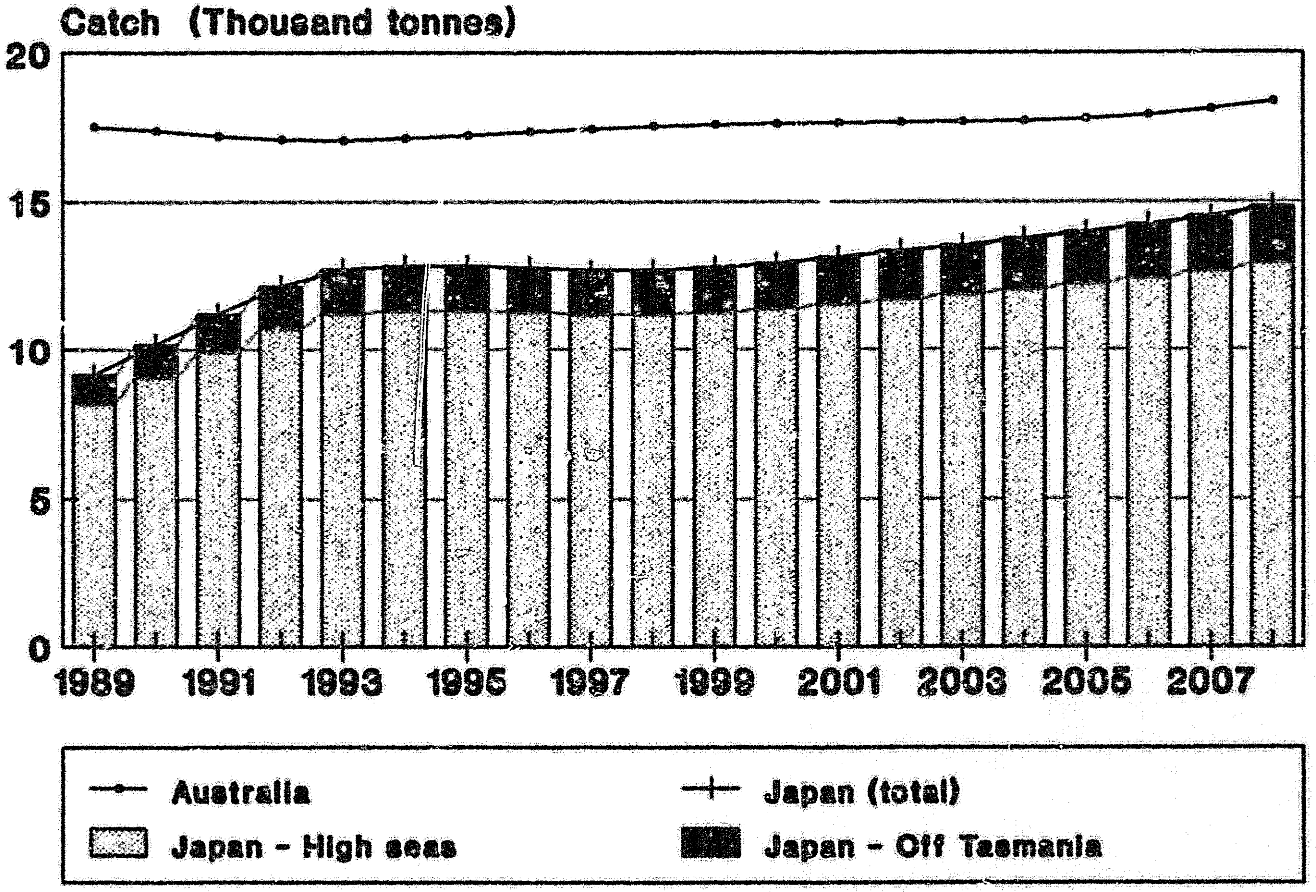

Figure 2: Catches for 3 grounds under duopoly

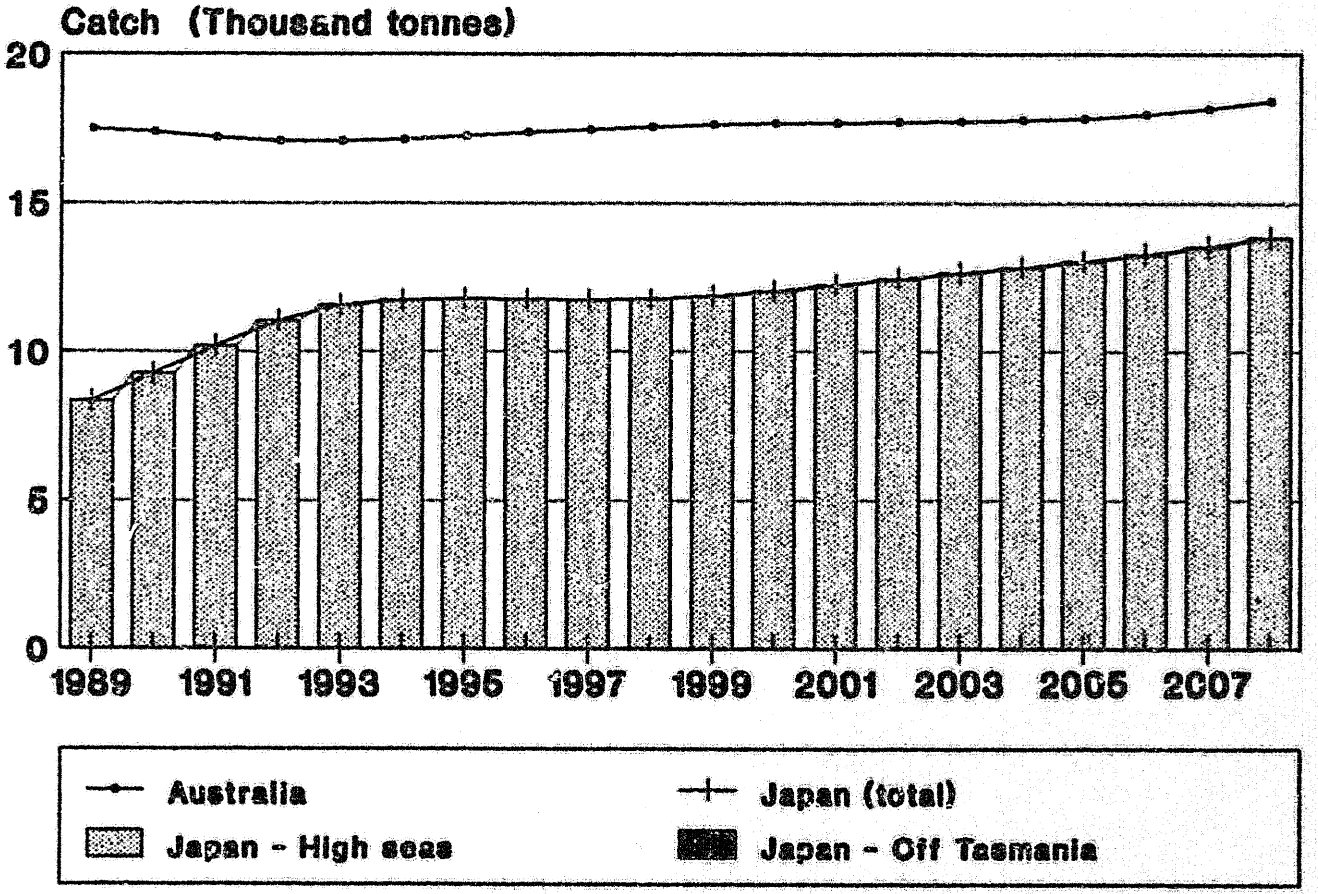

Figure 3: Catches for 2 grounds under duopoly

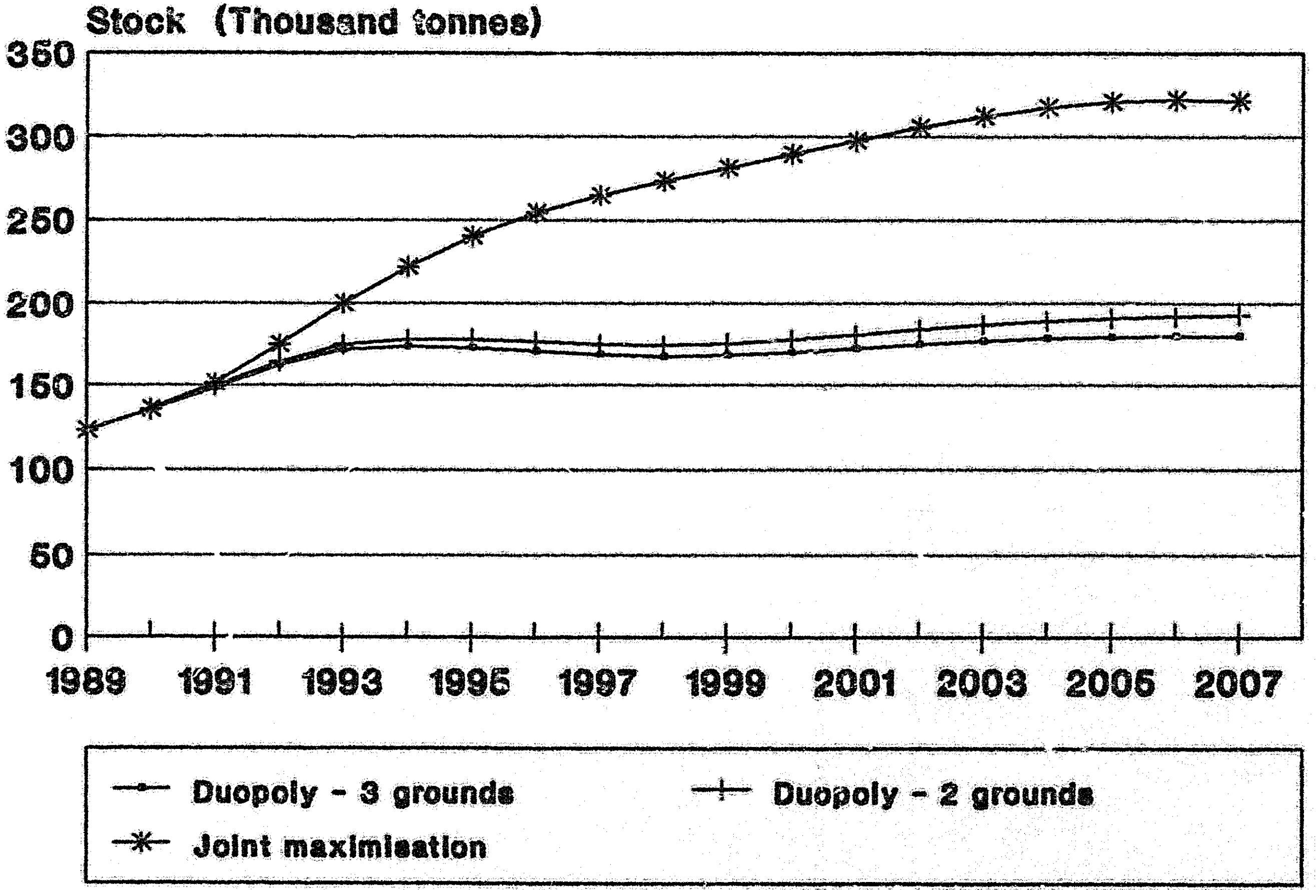

Figure 4: Parental biomass under joint max and duopoly

Figures 1 to 3, and of parental (or spawning stock) biomass in Figure 4, under joint maximization and duopoly. Two duopoly results are presented, one for all grounds, including off Tasmania, and one for Japanese high seas and Australian grounds only. Summary figures on total harvests, peak stock biomass and social rents are displayed in Table 3.

There is a marked contrast in harvesting profiles under joint maximization and under duopoly. Under joint maximization Japanese harvests rise gradually from 9,400 tonnes in 1989 to 17,300 tonnes in 2008 (see Figure 1). The Australian ground is closed for the initial three years 1989 to 1991. Thereafter Australian harvests rise steadily each year, eventually reaching Japanese harvests by 2008. As Figure 4 shows, cooperative constraint in the early years, with combined catches less than current combined quotas, permits parental biomass to expand from 120,000 tonnes to 320,000 tonnes. The rise in parental biomass leads to lower Japanese harvesting costs per tonne of SBT landed due to the strong stock effect in the Japanese harvest production functions, and increases recruitment to the Australian fishery.

If Australia and Japan act as Cournot-Nash-type duopolists, with Japan harvesting the high seas and off Tasmania grounds, Australia pursues a very different harvesting strategy. As shown in Figure 2, Australia maintains a high level of harvesting throughout the 20-year period at about 17,500 tonnes per year, significantly higher in all years than Japan. Japan's harvest starts at 9,000 tonnes in 1989 as under joint maximization, but levels out at only 14,800 tonnes by the end of 20 years, compared to 19,800 tonnes. It can be seen from Figure 4 that parental biomass growth is much less, rising to only 180,000 tonnes by 2007.

The present value of social rents accruing to Japan is much lower under duopoly than under a harvesting profile consistent with maximization of joint social rents, at A$3,597 million compared to A$4,437 million. The high level of Australian harvesting leads to lower parental biomass after 1991 and hence to higher Japanese harvesting costs per tonne harvested, and eventually to lower recruitment as well. In contrast, the present value of social rents accruing to Australia is significantly higher under duopoly in relative terms for Australia, at A$486 million compared to A$220 million. Because the stock effect in Australia's harvesting function is relatively weak, Australian harvesting costs per tonne harvested are not much higher under the lower Australian stocks. However, Japan's loss of A$840 million under duopoly is much greater than Australia's gain of A$266 million. There is a clear incentive for Japan to pay Australia to pursue the relatively low harvest profile shown in Figure 1 if the 20-year view is taken. This is not the case under a myopic view, as the last row of Table 3 suggests.

Comparing the 3-ground duopoly results with the 2-ground duopoly results, Australia does not gain by closing the off Tasmania ground to the Japanese, but Japan's present value of social rents over 20 years falls by A$201 million or 6 per cent. This gives some indication of the maximum access fee Australia could ask the Japanese for access to the off Tasmania ground if the two nations behaved as duopolists.

Discussion and Conclusions

A striking feature of the duopoly results is the high harvest levels which the model shows could be taken now and sustained. The combined annual harvests are about 27,000 tonnes. Although this is low compared with aggregate catches which have been achieved in the past, it is high compared with the current aggregate quota of 11,750 tonnes. This means that for the biological parameters used there does not appear to be a threat to the biological viability of the SBT fishery. However, caution is in order. Although we have attempted to use the best data available, many of the parameter values are very uncertain estimates of true values. Further, many parameters have been treated as deterministic which would be more appropriately treated as stochastic. An important example is the stochastic nature of recruitment. Policies aimed at maximizing the present value of expected social rents under stochastic recruitment could be quite different.

The potential gains from both nations following policies cooperatively to maximize joint social rents instead of duopoly policies are significant. The reduction in Australian harvest levels under joint maximization is substantial, and suggests that it would be in Japanese interests to buy Australian individual transferable quota without using them. The Japanese Government would want an agreement with the Australian Government that Australia's annual total allowable catch would not be increased merely to defeat Japan's attempt to reduce the Australian harvest.

The results also suggest that it may be in Australia's interest to move to using the Japanese longlining method of harvesting adult SBT. It appears that Australia is already beginning to explore this possibility. The model could be used to evaluate such a change.

There are many interesting ways in which the game situations in exploiting SBT stocks could be further developed and modelled. Although Japan and Australia are currently still the major participants, it would be of interest to determine the effects of competition from other participants such as Korea, Taiwan and New Zealand. Other developments would be the modelling of further control variables which nations can manipulate on an annual basis. Examples are the access fee charged by Australia to harvest SBT in the AFZ, and import duties which could be levied by Japan on landings by other nations.

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APPENDIX

Model Specification

The joint maximization problem can be formally expressed as follows:

$$\text{Max } z = \sum_{t=1}^{T} (1+r)^{1-t} \cdot \left\{ \sum_{n=1}^{N} (1-\beta_n)\, a_n \cdot h_{nt} + (0.5-\beta_n)\, b_n \cdot h_{nt}^2 - hc_{nt} \right\} \qquad (A1)$$

with respect to fishing mortality f_{nt} $(n=1, \ldots, N;\ t=1, \ldots, T)$

and given initial stock numbers x_{i1} $(i=1, \ldots, I)$

Writing instantaneous annual rate of fishing and natural mortality as:

$$g_{it} = m + \sum_{n=1}^{N} q_{ni} \cdot f_{nt} \qquad (A2)$$

it follows from integration that the harvest from ground n in year t is:

$$h_{nt} = \sum_{i=1}^{I} x_{it} \cdot w_i \cdot f_{nt} \cdot q_{ni} \cdot \frac{1-\exp(-g_{it})}{g_{it}} \qquad (A3)$$

The stock dynamics equations are:

The Shepherd recruitment equation relating numbers entering the first age class and the spawning stock biomass

$$x_{1,t+1} = \frac{\alpha \cdot SSB_t}{1 + \left(\frac{SSB_t}{\gamma}\right)^{\delta}} \qquad (t=1, \ldots, T-1) \qquad \text{(A4)}$$

where $SSB_t = \sum_{i=1}^{I} x_{it} \cdot w_i \cdot pm_i$ (A5)

$$x_{i+1,t+1} = x_{it} \cdot \exp(-g_{it}) \qquad (i=1, \ldots, I-2;\ t=1, \ldots, T-1) \qquad \text{(A6)}$$

$$x_{I,t+1} = x_{I-1,t} \cdot \exp(-g_{I-1,t}) + x_{It} \cdot \exp(-g_{It}) \qquad (t=1, \ldots, T-1) \qquad \text{(A7)}$$

The biomass of catchable fish is:

$$BIOM_{nt} = \sum_{i=ln}^{un} x_{it} \cdot w_i \qquad (n=1, \ldots, N) \qquad \text{(A8)}$$

The harvest cost functions for the Japanese fishing grounds are:

$$hc_{nt} = \begin{cases} -(c_n/v_n) \cdot \left[\log\left(d_n - \dfrac{s_n \cdot h_{nt}}{BIOM_{nt}}\right) - \log(d_n)\right] & \text{for } \dfrac{s_n \cdot h_{nt}}{BIOM_{nt}} \le d_n \qquad \text{(A9a)} \\ (c_n/v_n) \cdot u_n \cdot \dfrac{s_n \cdot h_{nt}}{BIOM_{nt}} & \text{otherwise} \qquad \text{(A9b)} \\ & (n=1;\ 2;\ t=1, \ldots, T) \end{cases}$$

and for the Australian fishing ground is:

$$hc_{3t} = c_3 \cdot h_{3t} / (BIOM_{3t})^{v_3} \qquad (t=1, \ldots, T) \qquad \text{(A9c)}$$

Symbols are assigned as follows:

n = fishing grounds $\quad n = 1, ..., N$
i = age categories $\quad i = 1, ..., I$
t = years $\quad t = 1, ..., T$

z = present value of social returns to year T.

r = annual rate of discount.

m = instantaneous annual rate of natural mortality.

f_{nt} = instantaneous fishing mortality, the decision variable set throughout year t in fishing ground n.

q_{ni} = proportion of f_{nt} effective on fish in age category i in fishing ground n (catchability coefficient).

$f_{nt} \cdot q_{ni}$ = instantaneous fishing mortality rate set throughout year t in age category i in fishing ground n.

g_{it} = instantaneous annual rate of fishing and natural mortality set throughout year t in age category i.

w_i = average weight of fish in age category i at spawning or caught.

x_{it} = number of fish in age category i at the beginning of the year t.

h_{nt} = harvest in year t from fishing ground n.

pm_i = proportion of mature fish in age category i.

SSB_t = spawning stock biomass at the start of year t.

$BIOM_{nt}$ = biomass of catchable fish in fishing ground n at the beginning of year t.

fn, un = first and last ages at which fish are eligible to be caught in fishing ground n.

hc_{nt} = harvesting cost for fishing ground n in year t.

α, γ, θ = parameters of the Shepherd recruitment function.

c_n, d_n, s_n, u_n, v_n = parameters of the harvesting cost function for fishing ground n.

a_n, b_n = parameters of the inverse demand function for fishing ground n,
$P_n = a_n + b_n \cdot h_{nt}$.

β_n = crew cost as a proportion of value of catch from ground n.

TABLE A1

Age-specific biological and fishing parameters

Age class i	Initial stock x_{i1} (thousands)	Average weight w_i (kg)	Proportion mature pm_i	Catchability coefficients		
				Ground 1 q_{1i}	Ground 2 q_{2i}	Ground 3 q_{3i}
1+	4,213	1.7	0	0.001	0.001	0.003
2+	3,474	5.0	0	0.001	0.005	0.149
3+	2,849	10.1	0	0.005	0.005	0.840
4+	2,307	17.0	0	0.016	0.191	0.603
5+	1,719	25.0	0	0.021	0.325	0.725
6+	1,119	33.9	0	0.046	0.302	0.211
7+	795	43.4	0	0.066	0.299	0.052
8+	456	53.0	1	0.775	0.369	0.042
9+	290	62.5	1	0.828	0.430	0.005
10+	29	71.8	1	0.650	0.360	0.001
11+	45	80.7	1	0.422	0.422	0.001
12+	72	89.2	1	0.295	0.295	0.000
13+	96	97.1	1	0.215	0.215	0.000
14+	97	104.4	1	0.136	0.136	0.000
15+	90	111.2	1	0.067	0.067	0.000
16+	76	117.3	1	0.043	0.043	0.000
17+	74	122.9	1	0.025	0.025	0.000
18+	47	128.0	1	0.013	0.013	0.000
19+	110	134.1	1	0.007	0.008	0.000

Sources:

Initial stock x_{i1} - estimated for beginning of 1989 from numbers for beginning of 1987 (Geen and Nayar, 1989, Table 14) and catches for 1987 and 1988 (Warashina, 1990, Table 2)

Average weight w_i - middle of year (Geen and Nayar, 1989, Table 15)

Proportion mature pm_i - (Geen and Nayar, 1989, p. 35)

Catchability coefficients:

q_{1i} - Japanese longliners, high seas (based on Geen and Nayar, 1989, Table 12)
q_{2i} - Japanese longliners, off Tasmania
    $i=1, ..., 10$ estimated from reported catches, April to June 1990 (Warashina, 1990, p. 13) and stock estimates x_{i1}
    $i=11, ..., 19$ because small and difficult to estimate, assumed equal to q_{1i}
q_{3i} - Australian purse seiners (based on Geen and Nayar, 1989, Table 12)

TABLE A2

Ground-specific parameters

	Ground n[1]		
	Japanese high seas	Japanese off Tasmania	Australian
	n=1	n=2	n=3
Inverse demand functions[1]			
Intercept - a_n	70.28	46.14	8.00
Slope - b_n	-0.000350	-0.01282	-0.000446
Age limits for biomass in harvesting functions[2]			
Lower - ℓn	8	8	2
Upper - un	19	19	6
Harvesting cost functions[3]			
c_n	14.49	1.39	1.404
d_n	0.1803	0.1803	-
s_n	1.123	9.108	-
u_n	35.55	35.55	
v_n	0.0394	0.0394	0.6
Crew cost as a proportion of value of catch			
β_n	0.00	0.00	0.15

1. $p = a + bq$ where p is in A$/kg; q is in tonnes

2. Used in Equation (A8)

3. Equation (A9) where hc_{nt} is in A$million; and $BIOM_{nt}$ is in tonnes.