Australian Journal of Agricultural Economics, Vol. 29, No. 1 (April, 1985), pp. 63-83.

THE IMPACT OF QUOTAS ON THE SOUTHERN BLUEFIN TUNA FISHERY

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Recent increases in the harvests of southern bluefin tuna, particularly by Australian fishermen, have led to the recognition that the fishery is overexploited. A model is developed to examine the effects that quotas on Australian and Japanese harvesting would have on economic welfare and on stock levels. Recursive quadratic programming is used to simulate harvesting decisions through time, with and without the imposition of quotas.

Stocks of southern bluefin tuna are an example of what Munro (1982) has termed a transboundary renewable resource. Stocks are fished primarily by Australian and Japanese fishermen. Australian fishermen mainly catch juveniles aged between one and seven years within the Australian Fishing Zone. The Japanese fishermen catch some juveniles but mostly mature fish between 7 and 13 years of age. In recent years, Japanese fishermen have taken about 10 per cent of their total catch from within the Australian Fishing Zone. The rest of the catch has been caught south of latitude 30°S in areas stretching from South Africa to New Zealand. The transboundary nature of the fishery means that management initiatives taken by one country have subsequent effects on the fish stocks fished by the other country.

In the early 1970s, the annual Japanese harvest was about 40 000 tonnes, whilst that of Australia was about 10 000 tonnes. By the 1982-83 season, the annual Japanese harvest had fallen to about 17 000 tonnes, whilst that of Australia had risen to over 20 000 tonnes. The increased Australian catch largely consisted of young fish caught off Western Australia and South Australia. Fisheries scientists studying these developments concluded that unless constraints were placed on Australian and Japanese fishing, the parental biomass was likely to fall so low as to risk recruitment failure.[1]

The Australian government responded to this concern by introducing an interim management program for the 1983-84 season. The program was a stopgap measure which prevented Australian harvests rising above the previous record harvests. At the same time, the government commissioned the Industries Assistance Commission to report on, *inter alia*, the management program which would ensure the efficient development of the industry.

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[1] Recruitment refers to the entry of young fish into the age group which is fished. Recruitment failure occurs in a year if the level of recruitment is greatly reduced in that year.

The main purpose of this article is to investigate the welfare effects for Australia and Japan of the introduction of quotas on Australian harvests, of varying degrees of severity. Experiments are conducted with a recursive quadratic programming model which is used to simulate harvesting by Australian and Japanese fishermen. A subsidiary purpose is to find to what extent a sudden increase in harvesting levels, such as that recently achieved by Australian fishermen, leads to subsequent feedback effects which reduce harvesting levels. The model described here has also formed the basis of a dynamic programming model of the fishery. The dynamic programming model was used to find optimal harvesting levels through time assuming various objective functions (Kennedy and Watkins 1986), and to answer some questions posed by the Industries Assistance Commission in its inquiry into the fishery (IAC 1984).

The spawning area and the migration pattern of the fish in relation to the Australian Fishing Zone are shown in Figure 1. All fish start by migrating south off the west coast of Australia from the spawning ground south of Java. One migration path continues east off the south coast of Australia to the waters off New South Wales. Fish on this path are harvested mainly by Australian fishermen.

The biological dynamics of the fishery are fundamental to any management model of the fishery. The following dynamic considerations were taken into account in designing the model: the fish have a lifespan of up to 20 years; the rate of weight gain during the juvenile phase of their lives is very high—100 per cent per annum for example for two to three year olds; besides being subject to mortality through fishing, the fish are subject to natural mortality; the fish are sexually mature at about eight years of age; the precise relationship between recruitment and parental biomass is not known, but recruitment is thought to be insensitive to levels of parental biomass above some low critical level.

Also reflected in the model are the very different marketing opportunities for selling the Australian as against the Japanese catches, and the different harvesting technologies used by Australian as against Japanese fishermen. Harvesting costs are assumed to be a negative function of stocks of fish. Because Australian and Japanese fishermen jointly exploit the stocks of some age groups, allowance has been made for the harvesting levels of one country's fishermen to affect the harvesting costs of the other country's fishermen.

The Recursive Quadratic Programming Model

In the absence of quotas, the fish stock is assumed to be harvested at the level at which average cost equals average revenue. The level is shown as h^0 in Figure 2 which depicts linear average cost, marginal cost and average revenue schedules for the fishery. Thus the traditional assumption is made that without quotas the fish stock is treated as a common property resource and that economic rent is driven to zero (see Munro 1982). The finding by the Bureau of Agricultural Economics (BAE 1983) that returns to capital in the southern bluefin tuna fishery before the introduction of quotas were low or negative suggests the assumption is reasonable. If a quota is imposed which restricts harvesting to say h^1 in Figure 2, it is assumed that the quota is enforced efficiently. For example, enforcement might be by way of a tax of JK levied on each fish caught, or by the sale of harvesting quotas with a price of JK.

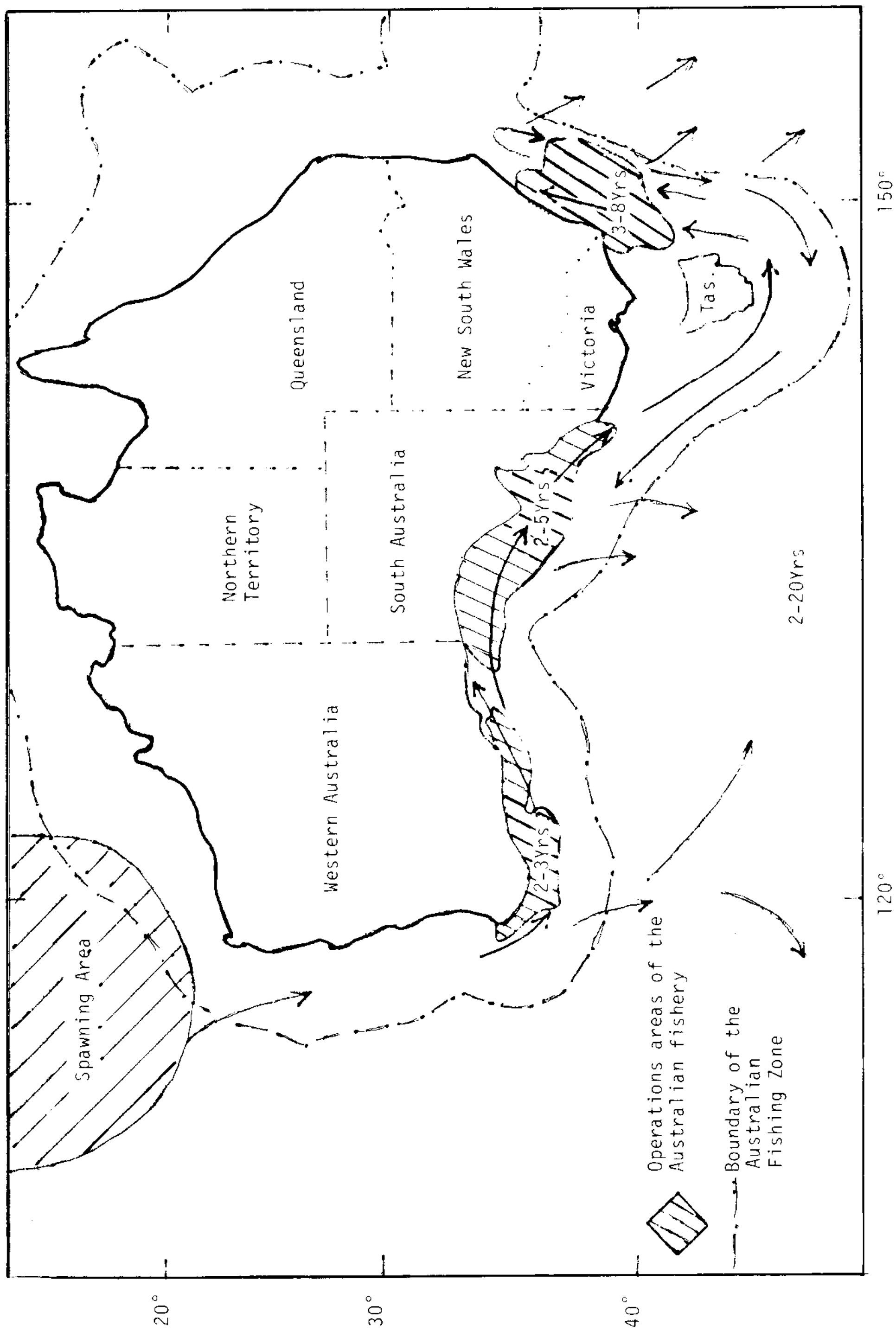


FIGURE 1—Migration Flows of Southern Bluefin Tuna Juveniles.

The modelling method used is recursive programming (Day 1963). The technique has been used to model agricultural sectors by simulating sequential decision making by farmers under uncertainty. The technique involves 'myopic suboptimisation' period by period rather than 'complex intertemporal optimisation' (Day 1977, p. 83). The decision maker is assumed to discount the future because of uncertainty and choose actions which maximise returns over the current period only. The resources available at the beginning of the next period are calculated assuming the implementation of these actions. A plan for the next period is then determined, based on the updated level of resources.

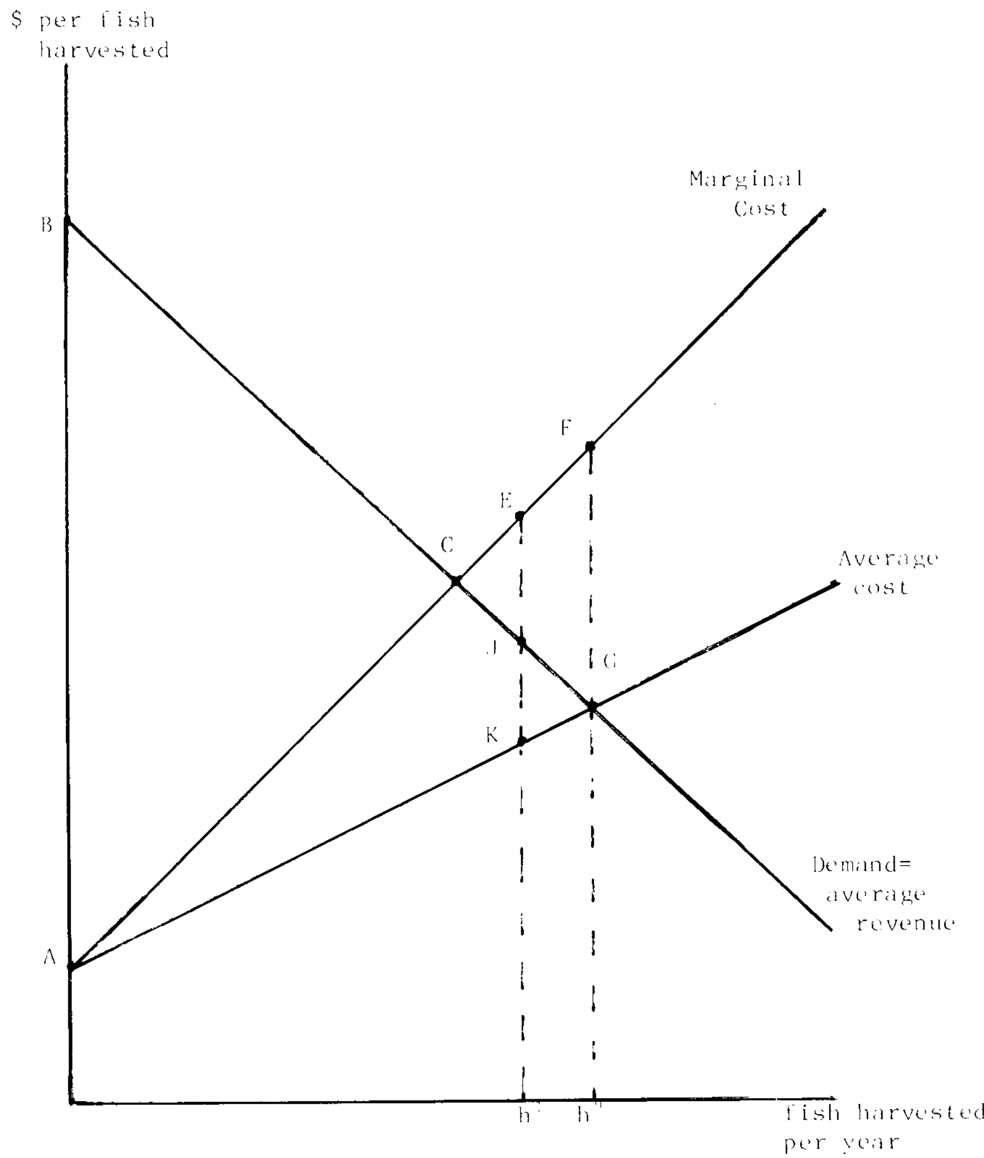


FIGURE 2—Harvesting Levels under Open Access and under Quotas.

The method is particularly appropriate for modelling an open-access fishery, although to the authors' knowledge this has not been done before. Not only are fisheries subject to uncertainty regarding prices, harvesting costs and stock abundance, but also the nature of an open-access fishery makes it rational for fishermen to pursue myopic decision making. Because fishermen do not have property rights in the fishery, there is no incentive for them to moderate current harvesting levels in the interests of higher returns to future harvesting.

In the present model the objective function for each period is quadratic rather than linear.[2] Stock levels are updated period by period in line with the modelled levels of fishing effort, migration, natural mortality and recruitment.

Flows of southern bluefin tuna were modelled based on descriptions of the fishery by Murphy and Majkowski (1981) and Shingu (1981). The fish are classified into four age groups G1 to G4 as shown in Figure 3. Those in groups G2 and G3 are further subdivided into a coastal group which is subject to fishing, and an oceanic group which is not. The oceanic group is assumed to escape beyond the range of Australian fishermen, and to swim too close to the surface to be caught by Japanese fishermen. The flows between groups are also shown in Figure 3. The state of the fishery at the beginning of each year t is described by the numbers in each age group subject to fishing (x_{1t} to x_{4t}) and numbers in G2 and G3 which are not subject to fishing (xn_{2t} and xn_{3t}).

The model consists of four components which deal with linear average cost functions, linear demand functions, harvesting levels and the updating of stock numbers. These components are dealt with in turn.

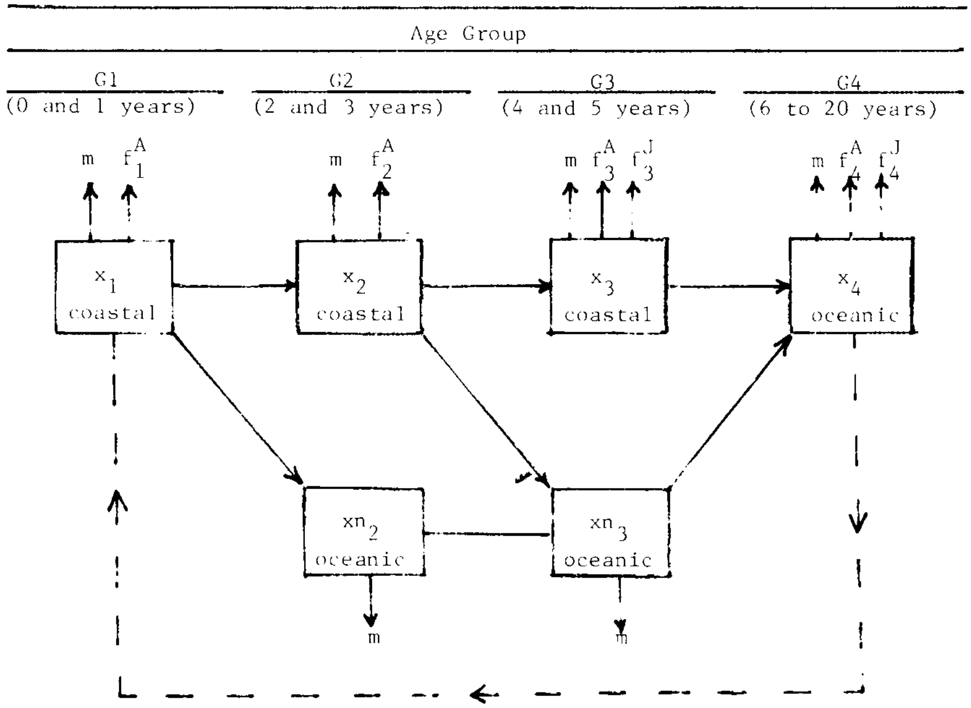
Cost functions

It is usual to assume in fisheries economics that harvesting cost is a function of stock density, or stock numbers, as well as harvest level. The cost functions used in the model relate the annual harvesting cost to the number of fish caught over the year, h, as a proportion, q, of opening stock numbers, x_0. The functions are based on a continuous model of the fishing process. The following four simplifying assumptions are made: fish are subject to a constant instantaneous rate of natural mortality, m; fishing effort results in a proportional instantaneous rate of fishing mortality[3], f; fishing effort is applied at a constant level throughout the year[4]; and total harvesting cost equals kf, where k is the harvesting cost per unit rate of fishing mortality.

[2] Watkins and Kennedy (1982) describe a recursive linear programming model of the fishery which incorporates stepped average revenue and average cost schedules. Watkins (1981) further discusses the appropriateness of recursive linear programming to model the open access fishery.

[3] This is implicit in the production function used in the Schaefer model. Munro (1981) notes that this production function is used extensively in the fisheries economics literature.

[4] In fact, tuna fishing is seasonal. However, allowing for seasonal effort would have complicated the cost equations. Given that $(f+m)$ feature in the equations below, and that m is known only approximately, greater precision in dealing with f does not seem justified.



Legend

x_i	number of fish subject to fishing in age group i
xn_i	number of fish not subject to fishing in age group i
m	rate of natural mortality
f_i^A	rate of fishing mortality due to Australian fishing
f_i^J	rate of fishing mortality due to Japanese fishing
———→	flows of fish
- - - -→	recruitment

FIGURE 3—Modelled Flows of Southern Bluefin Tuna.

It follows that if fish numbers at the start of the year are x_0, fish numbers at any instant t during the year are:

(1) $$x_t = x_0 \exp[(-f-m)t]$$

The number of fish harvested over one year is cumulative fishing mortality:

(2) $$h = x_0 \int_0^1 f \exp[(-f-m)t]dt$$
$$= x_0 [f/(f+m)][1 - \exp(-f-m)]$$

From equation (2) it follows that f and m determine the *proportion* of the initial stock harvested, regardless of what the initial stock may be. That is:

(3) $$q = h/x_0 = [f/(f+m)][1 - \exp(-f-m)]$$

The average cost of harvesting is:

$$kf/h = kf/(x_0 q) = (k/x_0)(f/q) \tag{4}$$

Although it is clear from a plot of (f/q) against q that (f/q) is not a linear function of q, nonetheless, for the range of q likely to be encountered in practice, the linear approximation:

$$f/q = u\{m\} + v\{m\}q \tag{5}$$

is reasonable, where u and v are coefficients dependent on m. For example, for $m = 0.2$ and $0 \leq q \leq 0.6$, a regression fit led to estimates of u and v equal to 1.044 and 1.045 respectively, with $R^2 = 0.975$.

Substituting (f/q) from equation (5) in equation (4) enables the average cost of harvesting to be expressed approximately as the linear function:

$$AC = (k/x_0)(u + vq) \tag{6}$$

Six cost coefficients, k, are required for the model: four for the Australian fleet fishing groups G1 to G4; and two for the Japanese fleet fishing groups G3 and G4. Differences between Australian and Japanese cost coefficients are to be expected because the harvesting technology of the two fleets is quite different. The Australian fleet consists mainly of pole boats and purse seiners, whereas the Japanese fleet consists of longliners. The Japanese vessels cover much greater distances and require facilities for preserving fish on board.

Demand functions

A country's total harvest by weight in year t is:

$$TH_t = \sum_i w_i \, x_{it} \, q_{it} \tag{7}$$

where subscript i refers to the number of the age group fished by the country; w_i is the average weight of fish in group i; x_{it} is the number of fish in group i at the beginning of year t; and q_{it} is the proportion of group i stocks harvested in year t.

For both the Australian and Japanese markets, the prices fishermen received for tuna from processors were assumed to be linear functions of harvests by weight of the form:

$$P_t = r + s(TH_t) \tag{8}$$

where P_t is price or average revenue and r and s are parameters.

Australian and Japanese markets for southern bluefin tuna are quite distinct. Most of the Australian harvest is canned whereas much of the Japanese harvest is specially processed and sold as highly priced sashimi fish. The Japanese price has ranged between 10 and 20 times the Australian price in recent years. So far, Australia has sold very little on the Japanese sashimi market, partly because of the difficulty in meeting the stringent quality conditions required by the Japanese. For these reasons the Australian and Japanese demand schedules used in the model are assumed to be independent.

Unlike the Japanese market, the Australian market is open. The percentage of the Australian harvest exported, mainly to Italy, grew from 19 in 1978-79 to 56 in 1982-83 (IAC 1984 pp.15-16). The Australian price does not appear to be sensitive to the level of Australian harvests. It is heavily dependent upon world demand and supply for tuna fish in general. The demand schedule for the Australian catch was therefore assumed to be horizontal, though this assumption was subjected to sensitivity analysis.

Elasticity estimates of Japanese demand for tuna could not be found from other studies. It was estimated to be roughly -1, using data on monthly landed catch and ex-vessel prices at the major Japanese tuna market of Yaizu from July 1978 to September 1980 (United States Department of Commerce 1979 to 1981). In the absence of an adequate price index for all Japanese southern bluefin tuna landings, it was assumed that the elasticity for the Yaizu fish market (which handled 39 per cent of the Japanese 1978-1980 catch) held for Japanese demand as a whole. Experiments were also conducted with Japanese demand elasticities of -2 and -0.5.

Harvesting levels

The proportions of opening G1 to G4 stocks harvested by Australia (q^A_{1t} to q^A_{4t}) and of opening G3 and G4 stocks harvested by Japan (q^J_{3t} and q^J_{4t}) are simulated for each year t. The proportions are determined such that fishing rents are competed away to zero if fishing effort is unrestricted. This is achieved by finding the proportions for which y_t, equal to the sum of the relevant areas below the two demand schedules and above the six average cost schedules for year t, is maximised subject to constraints. For linear average revenue and cost schedules, the problem is the following quadratic programming problem:

$$(9) \qquad \underset{q^A_{it},\, q^J_{jt}}{\text{maximise}}\, y_t = R^A\left\{\sum_{i=1}^{4} q^A_{it}\right\} + R^J\left\{\sum_{j=3}^{4} q^J_{jt}\right\} - \sum_{i=1}^{2} C^A_i\{q^A_{it}\} - \sum_{i=3}^{4}\left[C^A_i\{q^A_{it}, q^J_{it}\} + C^J_i\{q^J_{it}, q^A_{it}\}\right]$$

subject to:

$$(10) \qquad 0 \leq q^A_{it} \leq Q^A_{it} \quad i = 1, \ldots, 4$$

$$(11) \qquad 0 \leq q^J_{jt} \leq Q^J_{jt} \qquad j = 3,4$$

$$(12) \qquad q^A_{jt} + q^J_{jt} \leq 1 \qquad j = 3,4$$

where

$$(13) \qquad R\{\sum_i q_{it}\} = r(\sum_i w_i\, x_{it}\, q_{it}) + s(\sum_i w_i\, x_{it}\, q_{it})^2/2$$

$$(14) \qquad C^A_i\{q_{it}\} = k^A_i(u_i q^A_{it} + v_i(q^A_{it})^2/2) \quad i = 1,2$$

$$(15) \qquad C^A_i\{q^A_{it}, q^J_{it}\} = k^A_i[u_i\{q^J_{it}\}q^A_{it} + v_i\{q^J_{it}\}(q^A_{it})^2/2] \qquad i = 3,4$$

$$(16) \qquad C^J_i\{q^J_{it}, q^A_{it}\} = k^J_i[u_i\{q^A_{it}\}q^J_{it} + v_i\{q^A_{it}\}(q^J_{it})^2/2] \qquad i = 3,4$$

Curly brackets indicate functional dependence. Functions R denote the areas under the relevant demand schedules (based on equation (8)), and functions C the areas under the relevant average cost schedules (based on equation (6)). Constraints (10) and (11) ensure that proportions of opening stock harvested are non-negative, and less than any imposed quota on the proportion of initial stock harvested, Q_{it}. If a quota is binding for any age group and either fleet, average revenue exceeds average cost for that age group and fleet and, thus, a rent is earned. An upper limit of Q^A_{1t} and $Q^A_{2t}=1$ in the absence of quotas prevents harvesting of more than the entire opening stock of G1 and G2. Constraint (12) ensures the same for age groups G3 and G4 jointly fished by Australia and Japan.

As is shown in equations (9), (15) and (16), in the cases of G3 and G4 the harvest level of one country affects the harvesting cost of the other country. An iterative procedure ensured that all of the u_i and v_i parameters in equations (15) and (16) were consistent with the final solution values of q^A_{it} and q^J_{jt}. Because the same procedure applies for $i=3$ and $i=4$, and for all t, subscripts i and t are dropped in the following explanation to simplify notation. Let the rate of fishing mortality at the k-th iteration be denoted by f^A_k and f^J_k for Australia and Japan respectively. At the k-th iteration, Australian fishermen are assumed to perceive the rate of mortality outside their control as $m+f^J_{k-1}$, and likewise Japanese fishermen as $m+f^A_{k-1}$. Given values of q^A_k and q^J_k determined in the k-th quadratic programming solution, f^A_k and f^J_k can be estimated from equation (5) using rates of uncontrollable mortality of $m+f^J_{k-1}$ and $m+f^A_{k-1}$ respectively. For the $(k+l)$-th quadratic programming problem, all of the u_i and v_i parameters in equations (15) and (16) are revised to be consistent with rates of uncontrollable mortality in the k-th iteration. The values f^A_0 and f^J_0 used in the first iteration are set equal to zero. About five iterations are required until none of the six q values in the quadratic programming solutions differ significantly between iterations.

Stock updating

Stock numbers are updated at yearly intervals in a way which approximates the change in stock numbers given by $x_{t+1}=x_t \exp(-f_t-m)$. Since in equation (3) q_t is a one-to-one function of f_t, so f_t is a one-to-one function of q_t. Consequently:

$$(17) \qquad x_{t+1}=x_t\, d\{q_t,\, m\}$$

where $d\{q_t, m\}$ is a well-defined function of q_t for fixed m. Although it is clear from a plot of this function that d is not a linear function of q_t, nonetheless the linear approximation:

$$(18) \qquad x_{t+1}=x_t\,(b_1+b_2\, q_t)$$

is reasonable. For example, for $m=0.2$ and $0\leq q\leq 0.6$, regression coefficients $b_1=0.817$ and $b_2=-0.889$ were determined with $R^2=0.999$.

One system of updating stock numbers would have involved keeping track of numbers of stock in all age categories spanning ages of one year, and then aggregating to obtain values of the state variables, x_1 to x_4, and xn_2, xn_3. This would have meant accounting for 24 state variables. Because the model was to be further developed to obtain optimal multiperiod results for which the number of state variables had to be as few as possible, updating was instead approximated by a system based on just the six aggregate state variables. This required assuming that for any year, the proportion, a, of stock belonging to the first year of each category spanning two years was a constant. In fact the proportion depends on m and previous harvesting levels. Based on calculations presented in the Appendix a value of $a=0.6$ is used in standard runs of the model.

As shown in Figure 2, allowance is made for a proportion of the stock outflow from coastal G1 and G2 to be diverted to oceanic G2 and G3. The proportion, g, depends on the instantaneous rate of outmigration, previous harvesting levels and m. It was found that g was not very sensitive to values of previous harvesting levels. For reasons explained in the Appendix, g was set equal to 0.28 in standard runs of the model.

The following equations summarise the updating process:

$$(20) \quad x_{1,t+1} = R_{t+1} + x_{1,t}(b_1 + b_2 q^A_{1,t})a$$

$$(21) \quad x_{2,t+1} = x_{1,t}(b_1 + b_2 q^A_{1,t})(1-a)(1-g) + x_{2,t}(b_1 + b_2 q^A_{2,t})a$$

$$(22) \quad x_{3,t+1} = x_{2,t}(b_1 + b_2 q^A_{2,t})(1-a)(1-g) + x_{3,t}[b_1 + b_2(q^A_{3,t} + q^J_{3,t})]a$$

$$(23) \quad x_{4,t+1} = x_{3,t}[b_1 + b_2(q^A_{3,t} + q^J_{3,t})](1-a) + x_{4,t}[b_1 + b_2(q^A_{4,t} + q^J_{4,t})] + xn_{3,t}\, b_1(1-a)$$

$$(24) \quad xn_{2,t+1} = x_{1,t}(b_1 + b_2 q^A_{1,t})(1-a)g + xn_{2,t} b_1 a$$

$$(25) \quad xn_{3,t+1} = x_{2,t}(b_1 + b_2 q^A_{2,t})(1-a)g + xn_{2,t} b_1(1-a) + xn_{3,t} b_1 a$$

It is shown in equation (20) that G1 stock numbers in $t+1$ depend on recruitment, R_{t+1}. Because the determinants of recruitment are uncertain, experiments with the model were conducted with two deterministic functions based on two stochastic functions used by Hampton and Majkowski (1983), rescaled consistent with recruitment at age 0 instead of age 1. Under the first recruitment function, RF1, R_{t+1} is independent of parental stock numbers, and is equal to 6.43 million. Recruitment is dependent on parental stock numbers in the second recruitment function, RF2. It consists of the following linear segments which are an approximation to the continuous function used by Hampton and Majkowski:

$$(26) \quad R_{t+1} = \begin{cases} 1.72 x_{4,t} & x_{4,t} \leq 3.43 \\ 4.03 + 0.545 x_{4,t} & x_{4,t} > 3.43 \end{cases}$$

where $x_{4,t}$ is in millions of fish.

Welfare measure

The social surplus, z_t, generated for a country from fishing in year t is measured by the area below the processors' demand schedule less the areas below the marginal cost schedules (derived from equation (6)), to the level of aggregate harvest.[5] For example, social surplus for Japan is:

$$(27) \quad z^J_t = R^J\{\sum_{i=3}^{4} q^J_{it}\} - \sum_{i=3}^{4} k^J_i\,[u_i q^J_{it} - v_i (q^J_{it})^2]$$

[5] In the context of Figure 2, the annual social surplus accruing to a harvest level h[1] is the area ABC less the area CEJ. This contrasts with the value of the objective function used in the behavioural model, which would be represented by the area ABJK.

Equivalently, z_t^J is the sum of fishing rents and the area under processors' demand schedule and above the price line. The latter area equals the consumers' surplus accruing to final consumers of fish if markets in the vertical chain from processor to consumer are perfectly competitive and if input supply schedules in these markets are perfectly elastic (Just, Hueth and Schmitz 1982, pp.186-8).

A similar social surplus measure, z_t^A, is used for Australia. Note that under open access conditions without quotas, if the demand for the Australian harvest is infinitely elastic, z_t^A equals zero. Neither fishing rent nor consumers' surplus is generated.

Economic welfare associated with fishing over a five-year period is the present value of the stream of social surplus. For example, Japanese welfare is:

$$W^J = \sum_{t=1}^{5} z_t^J/(1.1)^t \tag{28}$$

assuming a real rate of discount of 10 per cent per annum, a rate which the Australian Treasury recommends for public sector project analysis (Australian Treasury 1981, p.42). The Treasury argument is based on making the discount rate equal to the social opportunity cost of capital. Other approaches take account of the (lower) social rate of time preference, as well as the social opportunity cost of capital, which generally lead to a lower rate of discount. It should be borne in mind that use of a high rate of discount leads to a conservative estimate of optimal quota levels to the extent that less weight is placed on the future benefits of quotas. The short time horizon of five years was chosen in order to again err on the side of undervaluing quotas because of the uncertainty attached to economic and biological variables.

Parameter settings

From 1975 to 1980 there was no discernible trend in the Australian and Japanese catches by weight. The breeding stock is judged to have been stable and to have produced 'satisfactory and stable recruitment over this period' (IAC 1984, p.106). By 1979 Australian and Japanese scientists were convinced that the southern bluefin tuna stock was fully exploited in the sense that 'increasing the fishing effort would not result in substantially increased catches' (Murphy and Majkowski 1981, p.29). Nevertheless, as indicated in Table 1, Australian harvests increased during the 1980-82 fishing seasons.

For modelling purposes, it was assumed that the average 1978-80 harvest was sustainable. Stock levels x_1 to x_4 and xn_2 and xn_3 were calculated which would sustain indefinitely the average 1978-80 harvest shown in Table 2 using the stock updating equations (20) to (25) and recruitment function RF1. The stock levels are shown in Table 2, and were the stock levels assumed to hold at the beginning of year 1 of the model runs.

One purpose of using the model was to determine the feedback effects on subsequent harvest levels via changes in stocks if Australian harvests increased markedly in the way they did from 1980 to 1982. For model runs it was assumed that the increased harvests had resulted from expectations of lower harvesting costs, based on the introduction of poling machines and more sophisticated fish detection systems (Australian Department of Primary Industry 1980, pp.3-5). The six cost coefficients

k_i were calculated which would result in the year-1 harvests equal to the average 1980-82 harvest levels, and were assumed to hold for all five years. The cost coefficients are shown in Table 2.

Other parameter settings used in standard runs of the model are shown in Tables 2 and 3. The demand parameters r and s in equation (8) were calculated assuming the elasticities shown in Table 3 applied at the average 1980-82 prices and harvest levels. These were A$880 and A$9 930 per tonne for Australian and Japanese prices, and 16 200 and 23 700 tonnes for Australian and Japanese harvests. The standard rate of natural mortality of 0.2 per annum is that determined by Murphy and Majkowski (1981).

TABLE 1

Average Annual Harvests (thousand tonnes) by Age Group

Years	Fleet	Age group				Total
		G1	G2	G3	G4	
1978-80	Australian	0.5	7.5	3.7	0.8	12.5
	Japanese	—	—	2.6	23.8	26.4
		0.5	7.5	6.3	24.6	38.9
1980-82	Australian	0.7	9.3	4.8	1.4	16.2
	Japanese	—	—	2.6	21.1	23.7
		0.7	9.3	7.4	22.5	39.9

Source: Compiled from records of numbers of fish harvested by age category (Department of Primary Industry, personal communication) and data on fish weights by age category (Hampton and Majkowski 1983, Table 3).

TABLE 2

Fish Weight, Opening Stocks and Cost Coefficients for Standard Run

	Age group			
	G1	G2	G3	G4
Ages at beginning of each year	0,1	2,3	4,5	6, . . ., 20
Average mid-year weight[a] (kg) (w_i)	0.98	7.84	21.72	56.93
Stocks at beginning of year 1 (millions)				
subject to fishing (x_{i1})	12.08	4.32	1.21	2.92
not subject to fishing (xn_{i1})	—	2.07	1.92	—
	12.08	6.39	3.13	2.92
Cost coefficients (A$m per unit of f)				
Australia (k^A)	8.60	20.05	17.51	130.18
Japan (k^J)			203.01	1395.14

[a] Weighted average using an age distribution factor = 0.6.

TABLE 3
Parameter Settings Used in the Model

Parameter	Standard	Alternative
Australian demand elasticity	$-\infty$	-10; -3
Japanese demand elasticity	-1	-0.5; -2
Rate of natural mortality (m)	0.2	0.1; 0.25
Age distribution factor (a)	0.6	0.55; 0.65
Rate of outmigration (ψ)	0.2	0.0; 0.3
Recruitment function	RF1	RF2

Each result obtained from a standard run of the model was compared with the results from a further 11 runs of the model, each run with a change in a different parameter. The alternative settings of parameters for sensitivity analysis are shown in Table 3. All the other parameters were set at the standard value, unless they were directly related to the changed parameter. For example, changing the rate of natural mortality required revisions to the age distribution factor, the average weights of fish by age group, the opening stock numbers and the cost coefficients.

Results

No-quota results

Simulated harvest levels and prices over five years in the absence of quotas and for standard parameter settings are shown in Table 4. The year-1 harvest levels are the average 1980-82 harvest levels. In subsequent years, Australian harvests are lower overall than year-1 harvests with significant proportional reductions in the G1 to G3 harvests and a slight increase in the G4 harvest. The total Japanese harvest changes little over the five years, a reduction in G3 harvests balanced by a rise in G4 harvests.

Other results show that the relatively high year-1 harvest levels lead to an initial reduction in stock levels in year 2, after which they remain fairly stable with only a slight downward drift discernible.

These results indicate the extent to which harvest increases occasioned by reductions in harvesting costs would be reversed in the face of falling stocks, even in the absence of any restrictions on harvesting. The same picture emerges when alternative values are substituted for standard parameter values except when recruitment function 2 is used in the model. The harvest levels for RF2 are shown in Table 5. Recruitment to G1 is much reduced. The lower G1 stock levels result in no harvesting of G1 stock from year 2 onwards. The overall Australian harvest falls significantly year by year. Stock levels by the end of year 5 are reduced from year 1 levels of 12.08 and 6.39 to 9.91 and 5.74 million for G1 and G2 respectively. However, further results show that by the end of year 10, G1 and G2 stock levels are only marginally reduced from the end-of-year 5 levels. G3 and G4 stock levels are marginally reduced from year 1 levels. Thus it appears that if RF2 applies, intervention to restrict harvesting would be required if a continuous fall in younger-age stocks over the initial five-year period is to be prevented.

TABLE 4

Harvest Levels and Prices Given No Quotas and Recruitment Function RF1

Year	Fleet[a]	Harvest (thousand tonnes) by age group					Price (A$ per tonne)	
		G1	G2	G3	G4	Total	Australian	Japanese
1	A	0.70	9.30	4.80	1.40	16.20	880	
	J	–	–	2.60	21.10	23.70		9 930
		0.70	9.30	7.40	22.50	39.90		
2	A	0.60	7.40	3.20	1.83	13.03	880	
	J	–	–	1.54	22.14	23.68		9 938
		0.60	7.40	4.74	23.97	36.71		
3	A	0.60	7.88	4.04	1.94	14.46	880	
	J	–	–	2.06	21.65	23.71		9 924
		0.60	7.88	6.10	23.59	38.17		
4	A	0.60	7.77	3.69	1.50	13.56	880	
	J	–	–	1.91	21.76	23.67		9 942
		0.60	7.77	5.60	23.26	37.23		
5	A	0.60	7.79	3.78	1.46	13.63	880	
	J	–	–	1.98	21.69	23.67		9 942
		0.60	7.79	5.76	23.15	37.30		

[a] A stands for Australian and J for Japanese.

Quotas on Australian harvests

The effect over five years on Australian welfare of imposing uniform percentage reductions in Australian harvests across all age groups can be seen in Figure 4. It is assumed that a harvest quota imposed on an age group is made effective by allocating to boat owners entitlements to shares in the quota. No quotas apply to Japanese harvesting. The uniform reduction which maximises Australian welfare at A$3.88 million is a reduction to 50 per cent of the average 1980-82 harvest level, the quota referred to as QA1 in Table 6. Australian welfare can be further increased to A$4.35 million by eliminating harvesting of G1 and transferring the 350 tonnes quota for G1 to the remaining age groups, the quota referred to as QA2 in Table 6. It is worthwhile to postpone harvesting the tuna when they are young because the rate of weight gain is high relative to the rate of natural mortality, and because the higher stock densities which result for G2 to G4 lead to lower harvesting costs. Harvest levels in each year equal the quota levels. There is no tendency for harvest levels to fall below quotas in later years because stocks gradually rise, resulting in reduced harvesting costs.

The results from imposing QA1 and QA2 were much the same when the model was run with alternative parameter values. Australian welfare was greatest under QA2 even when zero outmigration was assumed, when the rate of natural mortality was increased form 0.20 to 0.25 and when recruitment function RF2 applied. The only parameter for which different conclusions were obtained was the demand elasticity for the Australian catch. For an elasticity of -3 instead of $-\infty$, the optimal uniform quotas were 60 per cent instead of 50 per cent of the average 1980-82 harvest level[6], as shown in Figure 4. Again Australian welfare is further increased for the same overall limit on the harvest by eliminating fishing G1 and increasing quotas on the remaining age groups. The quota profile is shown as QA3 in Table 6.

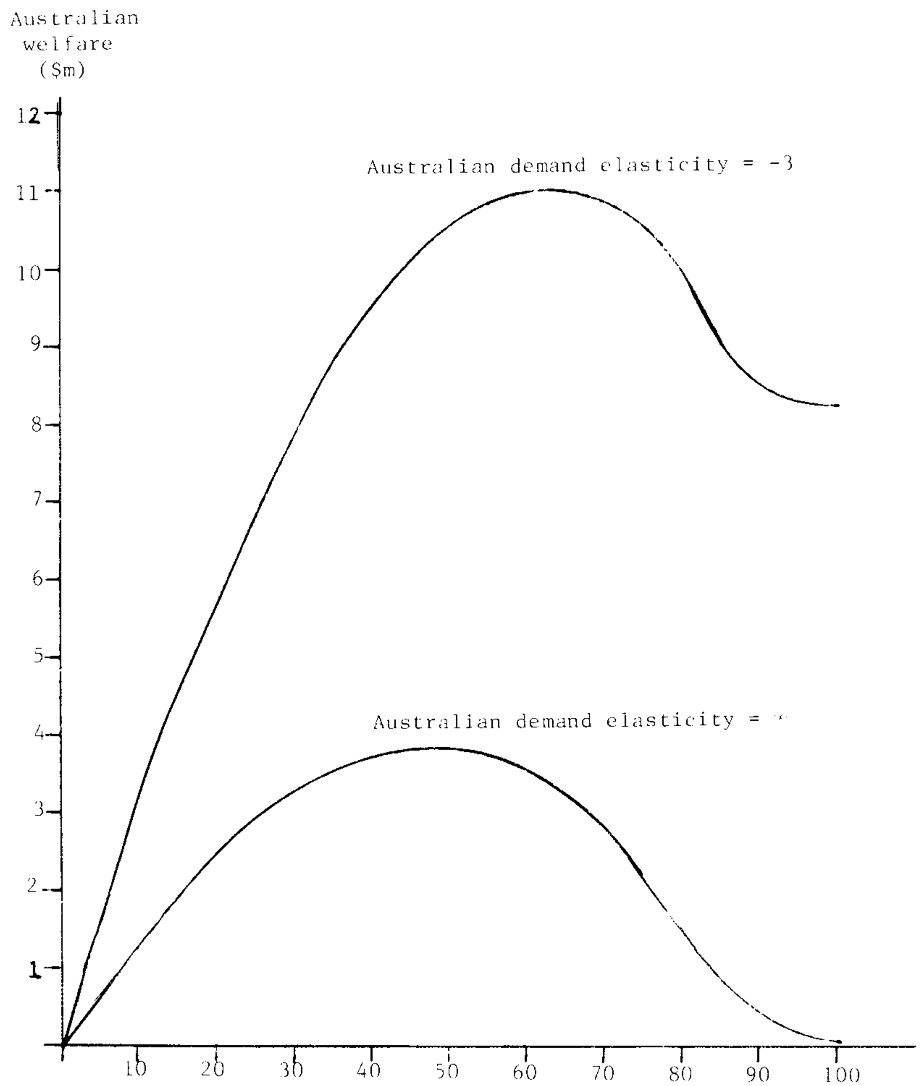


FIGURE 4—The Welfare Impact of Quotas on Australian Harvesting.

[6] For an elasticity of -3 it is assumed that over the range of quotas investigated, none of the Australian catch is exported. This means that total consumers' surplus is the same as Australian consumers' surplus, and that all of z_t^A accrues to Australia. The assumption is consistent with an infinitely elastic world demand schedule with world price below A$880 per tonne.

TABLE 5

Harvest Levels and Prices Given No Quotas and Recruitment Function RF2

Year	Fleet[a]	Harvest (thousand tonnes) by age group					Price (A$ per tonne)	
		G1	G2	G3	G4	Total	Australian	Japanese
1	A	0.70	9.30	4.80	1.40	16.20	880	
	J	–	–	2.60	21.10	23.70		9 930
		0.70	9.30	7.40	22.50	39.90		
2	A	–	7.40	3.20	1.84	12.44	880	
	J	–	–	1.54	22.14	23.68		9 939
		–	7.40	4.74	23.98	36.12		
3	A	–	6.06	4.05	1.96	12.07	880	
	J	–	–	2.06	21.65	23.71		9 925
		–	0.06	6.11	23.61	35.78		
4	A	–	5.55	4.04	1.60	11.19	880	
	J	–	–	2.12	21.57	23.69		9 936
		–	5.55	6.16	23.17	34.88		
5	A	–	5.26	4.08	1.22	10.56	880	
	J	–	–	2.21	21.45	23.66		9 947
		–	5.26	6.29	22.67	34.22		

[a] A stands for Australian and J for Japanese.

TABLE 6

Summary of Quota Level Options[a]

Harvesting	Quota level (thousand tonnes) by age group			
	G1	G2	G3	G4
For Australia				
QA1	0.35	4.65	2.40	0.70
	(50)	(50)	(50)	(50)
QA2	0.00	4.70	2.55	0.85
	(0.0)	(50.5)	(53.1)	(60.7)
QA3	0.00	5.64	3.06	1.02
	(0.0)	(60.6)	(63.8)	(72.9)
For Japan				
QJ1			1.95	20.05
			(75)	(95)
QJ2			1.30	18.99
			(50)	(90)

[a] Figures in parentheses below harvest levels are the harvest levels expressed as a percentage of the average 1980-82 harvest levels.

Japanese welfare is increased as a result of reductions in Australian harvest. This is because G3 and G4 stock densities are increased which leads to reduced Japanese harvesting costs. Over five years Japanese welfare increases from A$446 million to A$502 million if the quota QA2 is applied, and to A$565 million if Australian harvesting is eliminated altogether.

Quotas on Japanese harvests

It is assumed that 50 per cent of the Japanese G3 harvest and 10 per cent of the Japanese G4 harvest are caught within the Australian Fishing Zone. The model is not set up to deal directly with the imposition of quotas on Japanese harvesting of G3 and G4 within the Zone. It is only possible to impose restrictions on *total* G3 and G4 Japanese harvests, whether within or outside the Zone. However, for experimental purposes, quotas on Japanese harvesting, QJ1 and QJ2 in Table 6, are used as an approximate representation of halving and eliminating respectively access to the Zone. These quotas would only effectively reflect restrictions on Japanese access to the Zone if there were no offsetting increase in Japanese G3 and G4 harvesting outside the Zone. Because the Japanese are likely to react by increasing their fishing effort outside the Zone, only the effects on Australian welfare were investigated.

The effect on Australia's welfare of quotas on Japanese harvests depends on the level of restrictions on Australian harvesting. Because Australia's welfare is always zero if there are no quotas on Australian harvesting, quotas on Japanese harvesting can only lead to increases in Australia's welfare if there are quotas on Australian harvesting. If there are restrictions on harvesting, and if the Japanese do not pay a fee for access to the Austalian Fishing Zone, increasing restrictions on Japanese harvesting increases Australian welfare. For example, if the quota QA2 is imposed on Australian harvests, Australia's welfare increases from A$4.35 million to A$5.70 million with the quota QJ1 imposed, and to A$5.84 million with the quota QJ2 imposed.

In fact, since 1979 the Japanese have been required to pay an access fee at the beginning of each year equal to 5 per cent of the revenue that Japanese fishermen are expected to earn from catching southern bluefin tuna in the Zone during the year. For the average 1980-82 Japanese harvests this increases Australian welfare by about A$5.70 million. Assuming the access fee is reduced to zero under QJ2, Australia's welfare would be greatest without quotas on Japanese harvests, at A$10.05 million. Similar conclusions were reached for the other parameter values used in sensitivity analysis.

Conclusion

The results indicate that, if (a) the average 1978-80 harvest levels were sustainable and (b) the recent increase in harvests resulted from a fall in harvesting costs, the negative feedback effects on harvesting incentives of falling stocks are sufficient to prevent a stock collapse in the immediate future. Without quotas, stocks of juvenile southern bluefin tuna do fall over the first four years, but not significantly thereafter. The extent of the fall in stocks depends upon whether recruitment falls as parental stocks decrease.

Although quotas may not be necessary to avoid stock collapse, they can be used to increase Australian and Japanese economic welfare. Given the particular welfare criterion used, reductions in the Australian harvest to around 50 to 60 per cent of the average 1980-82 harvest would appear to be beneficial. This suggests a quota on the total Australian harvest of about 8 to 10 thousand tonnes.

In interpreting the results of the model, the limitations of the model must be borne in mind. No account has been taken of additional income some tuna fishermen earn from catching other species of fish. Such income may make larger harvests of tuna economic. A second limitation is that many stochastic relationships are treated as deterministic in the model. A biological simulation model incorporating stochastic relationships has been developed by Hampton and Majkowski (1983) and used for examining the likelihood of a stock collapse. The results are less sanguine than those presented here. The fact that fishermen do not know stocks and harvesting cost with certainty means that there is plenty of scope for experimenting with alternative expectations hypotheses in the behavioural model.

Another limitation of the model which is evident when it is run without quotas is the lack of restrictions on the rate of change of fishing effort. There may be reasons why effort may not be reduced as fast as the model suggests in the face of increasing harvesting costs resulting from falling stocks. Once investments have been made in vessels, equipment and know-how, limited alternative uses for them may trap them in the industry despite unfavourable economic conditions. This type of effect has been simulated in other recursive programming models by incorporating flexibility constraints. Another possibility would be to disaggregate the modelling of harvesting costs from the fleet level to the vessel level. Allowance could be made for fixed and variable costs, and for changes each year in the number of vessels in the fishery dependent on rents earned in previous years.

In the experiments reported here, the model has been used as a behavioural simulation model for testing the impact of alternative management programs. The model has also been incorporated within a dynamic programming framework for finding the harvests which would maximise economic welfare (Kennedy and Watkins 1986). The same structural equations were used in both versions of the model so that results could be compared. However, because many of the equations in the optimising model had to be linear and the number of state variables kept to a minimum, the structural equations have been simplified to a greater degree than is necessary for a simulation model. As a consequence, the model described here could be extended to incorporate more complex and, hence, more realistic biological relationships.

Postscript

In line with recommendations of the Industries Assistance Commission (IAC 1984), a program of individual transferable quotas was introduced from 1 October 1984. The individual transferable quotas have been allocated to vessel owners dependent on their highest historical catch and their investment in the fishery. They entitle the owner to a specified share of the national quota set annually by the Minister for Primary Industry. Quotas have not been imposed on particular size or age groups of fish following arguments accepted by the Industries Assistance Commission that these would be costly to implement and would lead to the wasteful dumping of fish caught illegally.

The national quota for the 1984-85 season has been set at 14 500 tonnes. Although this represents a substantial reduction from the record catch of 21 000 tonnes in the 1982-83 season, the quota is about 90 per cent of the average 1980-82 harvest. If the assumptions underlying the model are correct, it is clear from Figure 4 that the benefits to Australia of the 90 per cent quota are minimal in the case of an infinitely elastic Australian demand schedule.

APPENDIX

The determination of the age distribution factor, a, and the proportion of fish leaving an age category which outmigrate, g, is explained in this appendix. These coefficients are used in the stock updating equations.

Age Distribution Factor, a

Assume for simplicity that the instantaneous rate of fishing mortality, f, is constant. If the number of fish aged n years were z, then by equation (1) the number of fish aged $n+1$ years is $z\exp(-f-m)$ where m is the instantaneous rate of natural mortality. The proportion of $n+1$ year olds out of the total of n and $n+1$ year olds is therefore

$$a=[\exp(-f-m)]/[1+\exp(-f-m)]$$

Values of a for corresponding values of f and $m=0.2$ per annum are shown in Table A.1.

TABLE A.1

Age distribution factor, a

f	0.0	0.1	0.2	0.3	0.4
a	0.55	0.57	0.60	0.62	0.65

To encompass the range of likely a values, a was set equal to 0.60 for standard runs, and to 0.55 and 0.65 during sensitivity analysis.

Proportion of stock outflow diverted to oceanic stocks, g

Suppose a group of fish consists of z which are n years old and $z\exp(-f-m)$ which are $n+1$ years old. Fishing occurs at the fixed rate f. The proportion of the total numbers at the beginning of the year which survive to leave the group at the end of the year is $\exp[-2(m+f)]/[1+\exp(-m-f)]$. If however fish continuously leave the main coastal migration path by migrating at the rate ψ, the proportion which survives to move to the next group on the main migration path is reduced to $\exp[-2(m+f+\psi)]/[1+\exp(-m-f-\psi)]$. A factor

$$(1-g)=\frac{\exp(-2(m+f+\psi))(1+\exp(-m-f))}{\exp(-2(m+f))(1+\exp(-m-f-\psi))}$$

may therefore be applied to the proportion of total numbers leaving the group, to give the proportion reaching the next group on the main migration path.

Values of g for a range of rates of fishing mortality and outmigration, and $m = 0.2$ per annum, are presented in Table A.2.

TABLE A.2

Proportion of stock outflow diverted to oceanic stocks, g

Rate of outmigration ψ	Rate of fishing mortality, f				
	0.0	0.1	0.2	0.3	0.4
0.0	0.00	0.00	0.00	0.00	0.00
0.1	0.15	0.15	0.15	0.15	0.15
0.2	0.27	0.27	0.28	0.28	0.28
0.3	0.38	0.38	0.39	0.39	0.39
0.4	0.47	0.48	0.48	0.48	0.49

From Table A.2 it is clear that g is insensitive to values of f over the range $f = 0.0$ to 0.4. The actual rate of outmigration, ψ, is still not known with certainty (IAC 1984, p.108). Murphy and Majkowski (1981, p.23) estimated the rate to be about 0.4. This rate is a residual after estimating the apparent rate of mortality from tagging experiments, and making assumptions about rates of natural and fishing mortality. As shown in Table A.2, a value of $\psi = 0.4$ implies a value of g of about 0.48. However, it was not possible to use $g = 0.48$ in the stock-updating equations (20) to (25) to find steady-state stocks which would sustain the average 1978-80 harvest indefinitely. In view of the uncertainty of the rate, ψ was set equal to 0.2 in standard runs of the model, and 0.3 and zero in sensitivity analysis. Accordingly, g was 0.28, 0.39 and zero respectively in equations (21), (22), (24)and (25). As noted in the results section, the best quota options were found to be insensitive to values of g.

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