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A Computable Game Theoretic Approach to Modelling Competitive Fishing

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Abstract *A fishery is considered in which the young are harvested by one nation, and the adults by another. The harvests are sold on separate markets. Finding the optimal strategies of the two nations is treated as a problem in dynamic non-cooperative game theory. While in most other models players make decisions simultaneously at each stage, in this model each player makes his decision separately in time, knowing the action of the previous player. The model is applied to the southern bluefin tuna fishery which is jointly exploited by Australia and Japan. The results of non-cooperative and cooperative strategies are compared.*

Introduction

A government which has declared an exclusive fishing zone may be able to maximize the nation's social return from fish stocks within the zone by exercising control over fishing effort. It may be able to determine the optimal catch for each year, and enforce this through a system such as individual transferable quotas. However, if the fleets of other nations have access to fish stocks which are directly related to the fish stocks within the exclusive fishing zone, the nation's socially optimal catch is no longer obvious. Fish stocks within the zone may be directly related to stocks outside the zone because the stock straddles the boundary, because the fish are within the zone for only part of their life cycle, or because the population of one species of fish within the zone affects the population of another species of fish outside the zone through predator or prey relationships.

Fishing effort outside the zone may affect the nation's optimal catch for various reasons. Outside fishing effort may influence the price obtained; it may affect the future size of fish stocks within the zone; and it may affect the cost of harvesting through a stock effect. Similarly, the nation's catch may affect the optimal catch of foreign fleets.

The interdependencies apparent in such fisheries, variously referred to as transboundary (Munro 1979), sequential (Charles and Reed 1985), and divided (Kaitala 1986), mean that nations face game situations in deciding how best to set their own national catches each year. Charles and Reed (1985, p. 953) have pointed out that "the optimal management of sequential fisheries has received scant attention to date, at least within the context of bioeconomic analysis." They consider the problem of inshore and offshore fleets maximizing joint returns from fishing different age classes of the same stock. As the fleets belong to the same nation, joint maximization is a reasonable objective. However, between nations there may be problems in determining how joint returns should be shared. If the nations have different estimates of fishing costs, fish prices or discount rates, it may still be rational for the nations to cooperate by agreeing on suitable side payments (Munro 1979). On the other hand, nationalistic pride on the part of governments or fishermen may lead to nations adopting non-cooperative strategies instead.

Although non-cooperative behavior is probably more common than cooperative behavior, modelling non-cooperative harvesting strategies for sequential fisheries is even more underdeveloped. The modelling task is clearly complex, not only because of the difficulty in making reasonable assumptions about how each nation views the goals of the other nations, but also because of the dynamic interdependencies already mentioned.

The classic model of non-cooperative oligopoly is the Cournot model of firm behavior. It has been criticized on two grounds. The assumption of zero conjectural variations is seen to be unrealistic. For example, in the case of two firms, A and B, it seems implausible that A sets output dependent on B's output, without A supposing that B will set output dependent on A's output decision.

A second criticism is the static nature of the model. The output decisions for the Cournot equilibrium are not dependent on the number of subsequent periods in which output decisions must be made, or on the cost and demand parameters, and discount rates, in those subsequent periods. Cyert and DeGroot (1970) analyze a multiperiod Cournot process and show that typically the reaction functions ". . . are the trivial functions which specify that the outputs of the firm in each period must be equal to equilibrium values" (pp. 414–5). They sum up the reason for this result in stating: "The trivial and static nature of these reaction functions is a result of the fact that the firms are selecting their outputs simultaneously in every period" (p. 415).

Levhari and Mirman (1980) have developed a multiperiod Cournot model of two nations harvesting a common stock of fish, and have determined reaction functions which are not so trivial. Each nation's harvesting is limited by the stock of fish and the other nation's harvesting level. The novel feature in their model is the introduction of stock dynamics. They determine optimal reaction functions for each period using dynamic programming. However, they retain the assumption that the participants make decisions simultaneously, and with zero conjectural variations within each period. Kamien et al. (1985) allow conceptually for non-zero conjectural variations in a dynamic Cournot model of the fishery. However, they do not discuss how optimal or consistent conjectural variations might be determined.

Kennedy (1986, Ch. 4) suggests using dynamic programming to solve game theory problems in which participants make decisions alternately rather than simultaneously. Cyert and DeGroot (1970), in making the same suggestion, point out that many attempts have been made to improve on the static Cournot model by positing different conjectural variation terms, but that none of these attempts has resulted in a general model. They make the strong claim that, by modelling decision making as occurring alternately and by employing recursive induction, they present a general solution to the duopoly problem originally posed by Cournot.

In Cyert and DeGroot's model there is no technical linkage between periods such as stock dynamics. The returns to participants in each period depend only on the output decisions of the two participants. The particular return functions examined are quadratic. In the model suggested by Levhari and Mirman the period return to each participant depends only on the harvesting decision made by the participant. Although the previous decisions of the participants affect the current stock level, which in turn restricts the current harvesting level of each participant, there is no stock effect in the period returns.

The aim of this paper is to outline a multiperiod model of two nations alternately harvesting from different life stages of a common fish stock, allowing for stock effects in the cost-of-harvesting functions. The model is closely related to, but not the same as, the feedback Nash type of model described by Basar and Olsder (1982) and applied by Levhari and Mirman (1980) to a fishery. It could be described as a feedback Stackleberg model with participants taking turns at being the leader. This type of model does not appear to have received much attention in the game theory literature since the work of Cyert and De Groot (1970). No mention is made of such a model in a recent review of game theory models of fisheries by Kaitala (1986).

Numerical solutions are obtained for the model applied to the southern bluefin tuna fishery, although it must be emphasized that the model is mainly illustrative. The solutions are compared with those from a model in which joint returns are maximized. The relevance of the game theory approach to actual decision making is discussed after the presentation of the results. Of particular interest is the way in which the returns of the two nations involved, Australia and Japan, are differentially affected by playing non-cooperative instead of cooperative strategies.*

The Duopoly Model of Alternating Harvesting Decisions

State Variables

For modelling purposes, a fish stock is partitioned by age into two sets. All fish below a certain age are assumed to exist within the exclusive fishing zone of Nation 1. All older fish are assumed to exist outside the zone and to be harvested by Nation 2. The state of the system at any stage is given by the biomasses x_1 and x_2 of the fish within and outside the zone.

Decision Process

Nation 1's harvesting season starts at the beginning of each year and lasts for six months. Nation 2 harvests throughout the second half of each year. Each nation sets a harvesting quota at the start of its harvesting season. If the number of years to the modelling horizon is T years, the number of decision stages is $n = 2T$.

* There has been previous discussion of modelling the southern bluefin tuna fishery in a gaming framework. Tisdell (1983) shows how a static equilibrium solution might be obtained using a zero-sum threat payoff table and a Pareto-efficient frontier. Kennedy and Watkins (1986) and Kennedy (1986, Ch. 10) recognize the game situation in attempting to find optimal harvesting policies for Australia, but sidestep the complexities of gaming by keeping Japanese effort level fixed for all years at a base level.

Stage Return Functions

The objective of each nation is to maximize the present value of stage returns to the nation, subject to the other nation following an optimal policy. The k-th nation's stage return is a function of its fishing effort, u_k, and the biomass level, x_k. Let the weight of fish harvested be denoted by $h_k\{x_k, u_k\}$. Each nation sells its harvest on its own market, and obtains a price $p_k\{h_k\}$. The cost of fishing effort is assumed to be directly proportional to fishing effort. Then the return from each season's harvesting in terms of economic surplus is:

$$\Pi_k\{x_k, u_k\} = \int_0^{h_k} p_k\{q_k\}dq_k - c_k u_k \tag{1}$$

where c_k is the constant average cost of fishing effort.

Stock Dynamics

The stocks of each nation are updated at six-month intervals in line with harvesting and population dynamics. Nation 1's stock increases with recruitment dependent on Nation 2's stock six months earlier, and decreases with natural mortality, diffusion to Nation 2's stock, and its own harvesting effort. Nation 2's stock increases with diffusion from Nation 1's stock, and decreases with natural mortality, and its own harvesting effort. Thus the stock dynamics can be expressed as

$$x_{k,i+1} = g_k\{x_{k,i}, x_{\mathit{k},i}, u_{k,i}, u_{\mathit{k},i}\} \begin{matrix} \mathrm{k} \\ \mathit{k} \end{matrix} = \begin{matrix} 1 \\ 2 \end{matrix}, \begin{matrix} 2 \\ 1 \end{matrix} \tag{2}$$

where $x_{k,i}$ denotes nation k's stock level at the beginning of the i-th period. For i odd, $h_{\mathit{k},i} = 0$, and i even, $h_{k,i} = 0$.

National Objectives

The problem facing Nation 1 is:

$$\mathrm{Max} \sum_{i=1}^{n} \alpha_1^{i-1}\, \Pi_{1,i}\{x_{1,i}, u_{1,i}\}$$

with respect to

$$u_{1,1}, u_{1,3}, \ldots, u_{1,n-1}$$

subject to

$$u^*_{2,2}, u^*_{2,4}, \ldots, u^*_{2,n}$$

$x_{1,1}$ and $x_{2,1}$ given, and (2)

where α_1 is the six-month discount factor for Nation 1; and $u^*_{2,2}$, $u^*_{2,4}$, . . . are the solution levels of Nation 2's fishing effort for Nation 2's problem. Note that because $u_{1,i} = 0$ for i even, $\Pi_{1,i}\{x_{1,i}, u_{1,i}\} = 0$ for i even, also.

Nation 2 faces an exactly analogous problem.

Solution Procedure

The two problems can be solved by dynamic programming using the appropriate recursive equations. The recursive equation for Nation 2 is:

$$V_{2,i}\{x_{1,i}, x_{2,i}\} = \max_{u_{2,i}} [\Pi_2\{x_{2,i}, u_{2,i}\} + \alpha_2^2 V_{2,i+2}\{x_{1,i+2}, x_{2,i+2}\}] \quad (i = n, n-2, \ldots, 2) \tag{3}$$

with

$$\begin{aligned} x_{1,i+2} &= t_{1,2}\{x_{1,i}, x_{2,i}, u^*_{1,i+1}, u_{2,i}\} \\ x_{2,i+2} &= t_{2,2}\{x_{1,i}, x_{2,i}, u^*_{1,i+1}, u_{2,i}\} \end{aligned} \tag{4}$$

$$V_{2,n+2}\{x_{1,n+2}, x_{2,n+2}\} = 0 \tag{5}$$

where $V_{2,i}\{x_{1,i}, x_{2,i}\}$ is the value to Nation 2 of stock levels $x_{1,i}$ and $x_{2,i}$ if both nations pursue optimal policies at each stage from Stage i to Stage n. The state transformation functions, Equation 4, follow from the stock-dynamics functions, Equation 2. Included in the arguments of the transformation functions is $u^*_{1,i+1}$, which is the optimal effort level of Nation 1, given stock levels $x_{1,i+1}$, $x_{2,i+1}$ dependent on $x_{1,i}$, $x_{2,i}$ and $u_{2,i}$.

The equivalent recursive equation for Nation 1 is:

$$V_{1,i}\{x_{1,i}, x_{2,i}\} = \operatorname*{Max}_{u_{1,i}} [\Pi_1\{x_{1,i}, u_{1,i}\} + \alpha_1^2 V_{1,i+2}\{x_{1,i+2}, x_{2,i+2}\}] \quad (i = n-1, n-3, \ldots, 1) \tag{6}$$

$$\begin{aligned} x_{1,i+2} &= t_{1,1}\{x_{1,i}, x_{2,i}, u^*_{2,i+1}, u_{1,i}\} \\ x_{2,i+2} &= t_{2,1}\{x_{1,i}, x_{2,i}, u^*_{2,i+1}, u_{1,i}\} \end{aligned} \tag{7}$$

$$V_{1,n+1}\{x_{1,n+1}, x_{2,n+1}\} = 0 \tag{8}$$

The solution procedure starts by solving Nation 2's problem for $i = n$, given in Equation 3. Because this is the final decision stage, the problem is a single-period problem, not affected by a subsequent decision by Nation 1. That is, Equation 5 applies. It is therefore possible to find $u^*_{2,n}\{x_{1,n}, x_{2,n}\}$. In similar fashion it is possible to find $u^*_{1,n-1}\{x_{1,n-1}, x_{2,n-1}\}$, using Equations 6 for $i = n - 1$, and 8. Equation 3 can now be solved for $i = n - 2$, because $V_{2,n}\{\cdot\}$ in Equation 3, and $u^*_{1,n-1}\{\cdot\}$ in Equation 4, have been calculated. This allows Equation 6 to be solved for $i = n - 3$, given $V_{1,n-1}\{\cdot\}$ and $u^*_{2,n-2}\{\cdot\}$. Equations 3 and 6 continue to be solved alternately for decreasing i until $i = 1$.

Note that the solution procedure described so far applies for simplicity to a deterministic formulation of the problem faced by each nation. It would be more realistic to recognize various sources of uncertainty. For example, the stock dynamics function would be better formulated as stochastic. One of the features of a dynamic programming approach is that it can be readily extended to solve stochastic problems. For example, recursive Equation 3 would be altered by placing an expectation operator before $V_{2,i+2}\{\cdot\}$ on the RHS, and $V_{2,i}\{\cdot\}$ would be the expected present value of the fish stocks. Methods of stochastic dynamic programming are expounded in Hastings (1973) and Kennedy (1986).

The Joint-maximization Model of Alternating Harvesting Decisions

Both nations could obtain a greater combined economic surplus if they cooperated to maximize the sum of the present values of their economic surpluses. Both nations would be able to agree on their harvesting levels at the beginning of each year, although Nation 2's decision would still not be implemented until half-way through the year. The recursive equation for the joint-maximization problem is:

$$V_i\{x_{1,i}, x_{2,i}\} = \max_{u_{1,i},\, u_{2,i+1}} [\Pi_{1,i}\{x_{1,i}, u_{1,i}\} + \alpha\Pi_{2,i+1}\{x_{2,i+1}, u_{2,i+1}\} + \alpha^2 V_{i+2}\{x_{1,i+2}, x_{2,i+2}\}] \quad (i = n-1, n-3, \ldots, 1) \tag{9}$$

with

$$V_{n+1}\{x_{1,n+1}, x_{2,n+1}\} = 0 \text{ and } (2) \tag{10}$$

where $V_i\{x_{1,i}, x_{2,i}\}$ is the value to both nations of stock levels $x_{1,i}$ and $x_{2,i}$ if both nations pursue an optimal cooperative policy from Stage i onwards.

As before, the solution procedure starts by solving Equation 9 for $i = n - 1$. The solution to this problem gives V_{n-1}, which then permits the solution of Equation 9 for $i = n - 3$. The process continues until $i = 1$.

An Application to the Southern Bluefin Tuna Fishery

To illustrate and compare the working of the duopoly and joint-maximization models, the models are applied to the southern bluefin tuna fishery. The fish are primarily exploited by Australia, corresponding to Nation 1, and Japan, corresponding to Nation 2. As a broad generalization, Australia harvests young fish within the Australian Fishing Zone (AFZ), and Japan harvests adult fish. Most of the Japanese catch is obtained outside the AFZ. About 10% is obtained within the AFZ on a fee-for-access basis.

By 1983 both Australian and Japanese scientists agreed that the fishery was overexploited, and that its future biological viability was threatened. The parental biomass had reached such a low level that there was the risk of recruitment being severely attenuated.

The Australian government reacted by introducing a preliminary quota on the Australian catch of 21.0 thousand tons for the 1983–84 season, and after a government inquiry by the Industries Assistance Commission, a more restrictive quota of 14.5 thousand tons for the 1984–85 season. Before introducing the latter quota the Australian government made it clear that, in setting a restrictive quota on the Australian catch, it expected the Japanese harvest to be restricted as well, or at least not increased. The report of the Industries Assistance Commission (1984, 38) into the fishery stated: "If no agreement could be reached with the Japanese and the Japanese catch increases, while the Australian quota may need to decline to protect parental biomass, strategically it may be in Australia's interest to increase the Australian quota." Subsequently, the Australian government did decide that the Japanese catch was not curtailed sufficiently, and retaliated by effectively banning Japanese harvesting within the AFZ during the 1984–85 season. The Japanese fleet was readmitted for the 1985–86 season after a resolution of the disagreement between the two countries. The incident highlights the game situation the Australian government is involved in now that it is attempting to control the exploitation of southern bluefin tuna within the AFZ.

Model Description

The model simulates harvesting over a twenty-year period, starting with the 1982–83 season. Stock level x_A is the biomass of young fish under 8 years old harvested by Australia and x_J is the parental biomass (8 years and older) harvested by Japan. The initial levels are 198 and 224 thousand tons, consistent with the data on the population age structure for 1983 estimated by Hampton and Majkowski (1986, Table 3).

The stage return functions, based on Equation 1, depend on the harvest, price, and cost-of-fishing-effort functions. The harvesting equations are:

$$h_A = 0.108u_A^{0.8}x_A$$

$$h_J = 0.0759u_J^{0.8}x_J$$

where h is harvest in thousands of tons per year, u is fishing effort level standardized equal to 1.00 for 1982–83 levels, and x is the stock level in thousands of tons. The catchability coefficients 0.108 and 0.0759 were calculated for 1982–83 stocks, and 1982–83 harvest levels of 21.3 and 17.0 thousand tons. The effort exponents were set at 0.8 to reflect diminishing returns to effort. Clark (1985) has argued that for pelagic species there are good reasons for positing an exponent on stock level of 1.0 or greater. The exponents in the model results described here are kept at 1.0. Results for exponents of 1.2 show little different.

The Australian and Japanese catches have traditionally been sold on separate markets. The demand for the Australian catch, which is mainly either canned or exported to Europe, is reasonably taken to be infinitely elastic because it substitutes for the much larger world catches of other types of tuna. The demand for the Japanese catch which is sold as sashimi fish after processing is assumed to be unit elastic. The average wholesale prices of southern bluefin tuna recorded for 1982–83 (Industries Assistance Commission 1984, 14) are A$700/ton for Australia and A\$14,000/ton for Japan. Synthetic inverse demand equations corresponding to Equation 2 and centered on 1982–83 price and harvest observations were:

$$p_A = 700$$

$$p_J = 28000 - 0.824h_J$$

where p is in thousands of Australian dollars per ton.

Constant average cost coefficients in Equation 1 were estimated to be c_A = A\$14.7 million and C_J = A\$238 million per unit of effort, assuming open access conditions prevailed in 1982–83 prior to the introduction of controls. That is, the total cost of harvesting in 1982–83 was assumed equal to the total revenue obtained from selling the harvest.

The stock updating equations, corresponding to Equation 2, can only be approximate because only total fish numbers in the Australian and Japanese stocks are specified as state variables. A more realistic model would record numbers in each of the seven-year classes in the Australian stock, and in each of the twelve-year classes in the Japanese stock. Only two state variables were used for computational feasibility, though this meant sacrificing modelling the effect of changes in harvest levels on the age distribution of each nation's stocks. In determining the equations, the age distribution is assumed to be that estimated by Hampton and Majkowski (1986, Table 3) for 1982–83. The annual rate of mortality for both stocks was assumed to be 0.2, based on Hampton and Majkowski (1986, Table 2). The equations are:

$$s_{A,i+1} = R_{i+1} + 0.875s_{A,i} - f_{A,i} \tag{11}$$

$$s_{J,i+1} = 0.894s_{J,i} + 0.0174s_{A,i} - f_{J,i} \tag{12}$$

$$R_{i+1} = 1.52s_A/(1 + (2.53 \times 10^{-7} \times s_A)^{1.5}) \tag{13}$$

where s is stock numbers, R is recruitment, and f is the harvest in fish numbers. The recruitment equation is based on one used by Hampton and Majkowski (1986) for annual updating. Equation 13 is a modification of their equation in that half the annual recruitment occurs at six-month intervals. In calculating stock and harvest biomasses, the average weights of fish in the Australian and Japanese stocks were taken to be 12.1 and 87.4 kilograms respectively, consistent with Table 3 in Hampton and Majkowski (1986).

Solution Procedure

The basic solution procedure using dynamic programming has already been outlined. Solutions were obtained numerically, which meant that the range of continuous values of x_A, x_J, u_A, and u_J had to be replaced by a limited grid of values. Because the problem consists of two state variables and two decision variables, the number of grid points which must be allowed to represent the possible stock combinations for a reasonable range of effort levels is potentially very large. However, the problem was solved for relatively few stock combinations by using linear interpolation to approximate stock combinations between grid points. The grid points of stocks consisted of the 49 combinations of x_A and x_J from the sets

$$x_A \in 180, 195, \ldots, 270 \text{ thousand tons}$$

$$x_J \in 180, 195, \ldots, 270 \text{ thousand tons}$$

The range of stock levels was set so as to include the initial stock level, and adjusted as necessary in line with model results. The seven grid points of effort levels consisted of u_A and $u_J \in 0.00, 0.15, \ldots, 0.90$ alternately in the duopoly model, and of the 49 combinations of u_A and u_J simultaneously in the joint-maximization model. The grid of effort levels was also refined in successive runs of the model.

The duopoly problem was solved by determining $V_{A,i}\{x_{A,i}, x_{J,i}\}$ and $V_{J,i}\{x_{A,i}, x_{J,i}\}$ at the 49 $x_{A,i}/x_{J,i}$ grid points recursively using Equations 3 and 6. Estimates of $V_{A,i+2}\{\cdot\}$ and $V_{J,i+2}\{\cdot\}$ on the right-hand sides of Equations 3 and 6 for $x_{A,i+2}$ and $x_{J,i+2}$ which did not fall on grid points were estimated by linearly interpolating between the $V_{A,i+2}\{\cdot\}$ and $V_{J,i+2}\{\cdot\}$ values for adjacent grid points. The joint-maximization problem was solved in the same way with Equation 9. Lewis (1975, 1977) used the method of linear interpolation in a dynamic programming problem applied to the Eastern Pacific yellowfin tuna fishery with fish stock as the single state variable.

The solution procedure resulted in $u^*_{A,i}\{\cdot\}$ and $u^*_{J,i}\{\cdot\}$ for each of the 49 x_A/x_J grid points. The objective functions of the two models were assumed to be the present value of returns over infinite harvesting seasons. The infinite-stage $u^*_A\{\cdot\}$ and $u^*_J\{\cdot\}$ were estimated as equal to $u^*_{A,1}\{\cdot\}$ and $u^*_{J,1}\{\cdot\}$ for $n = n^*$. The value of n^* was sufficiently large that $u^*_{A,1}\{\cdot\}$ and $u^*_{J,1}\{\cdot\}$ did not change for $n > n^*$. For a discount rate of 10% per annum n^* was less than 20, but greater than 20 for a zero discount rate.

The optimal harvesting sequence for the two nations starting with the base year stocks $x_A = 198$ and $x_J = 224$ thousand tons was obtained by a process of forward tracking using $u^*_A\{\cdot\}$ and $u^*_J\{\cdot\}$. Optimal effort levels for $x_{A,i}$ and $x_{J,i}$ which did not coincide with grid points were estimated by linearly interpolating between optimal effort levels for adjacent grid points.

Results

Optimal infinite-stage effort levels for a discount rate of 10% per annum at selected stock grid points are shown in Table 1 for both the duopoly and joint-maximization models. Under joint maximization, it is optimal for Australia to leave harvesting completely to Japan, whatever the stock levels of the two countries. This is not surprising given the high average weight of fish in the Japanese stock, and the high Japanese market return. The result is in agreement with the findings of a previous model with more detailed stock dynamics (Kennedy and Watkins 1986).

Australian and Japanese annual harvests resulting from the implementation of the duopoly and joint-maximization policies over a 20-year period are shown in Figure 1. Corresponding stock levels are shown in Figure 2. Japan's strategy is much the same under duopoly as under joint maximization. Australia, however, fishes under duopoly, though at modest levels by historical standards.

Harvest levels of both nations do not change markedly from year to year under

Table 1
Effort Policies (discount rate = 10% per annum).

Stocks (thousand tons)		Effort (1982–83 level = 1.00)			
		Duopoly		Joint Maximization	
x_A	x_J	u_A	u_J	u_A	u_J
180	180	0.15	0.60	0.00	0.60
180	225	0.15	0.60	0.00	0.60
180	270	0.15	0.60	0.00	0.60
225	180	0.30	0.45	0.00	0.45
225	225	0.30	0.60	0.00	0.60
225	270	0.30	0.60	0.00	0.60
270	180	0.75	0.45	0.00	0.60
270	225	0.75	0.60	0.00	0.60
270	270	0.75	0.60	0.00	0.60

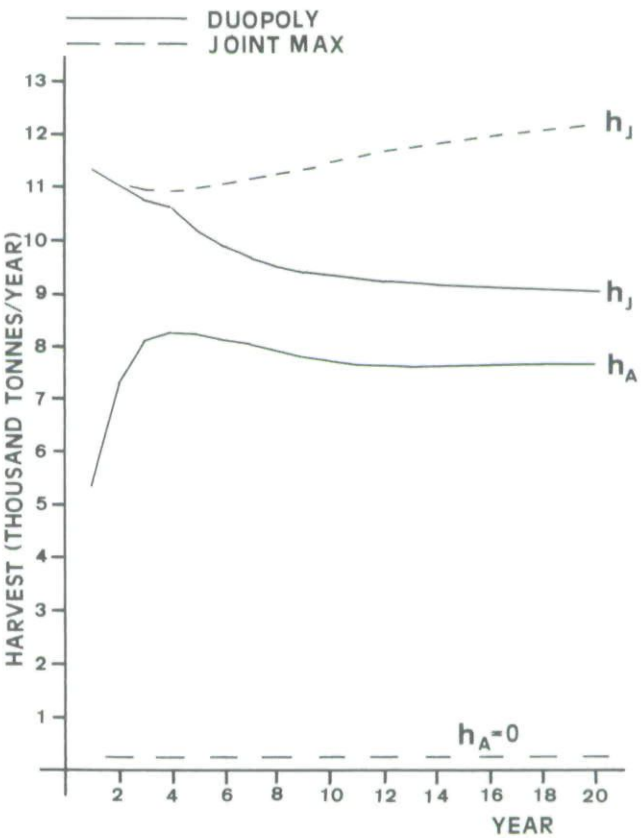

Figure 1. Annual harvests for Australia (h_A) and Japan (h_J) (discount rate = 10% per annum).

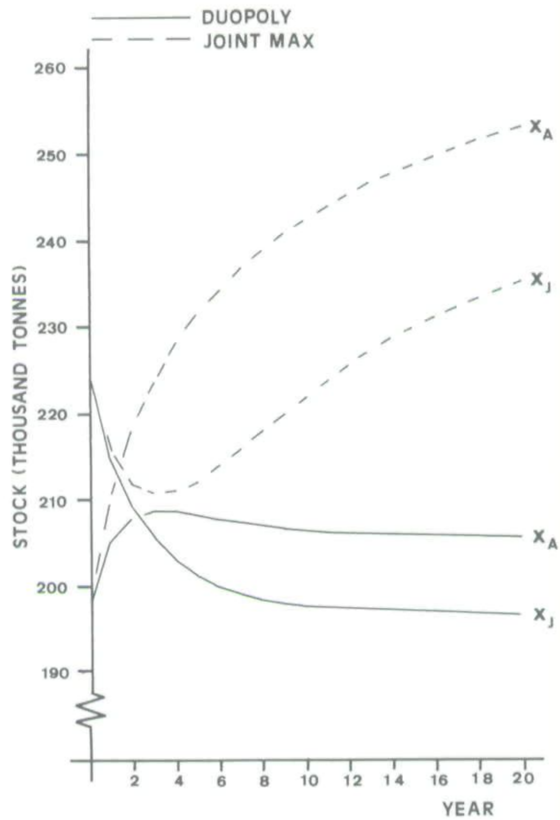

Figure 2. Stocks for Australia (x_A) and Japan (x_J) (discount rate = 10% per annum).

either duopoly or joint maximization. Under joint maximization, Japan harvests 11 to 12 thousand tons per year, while Australian harvets are zero for all years. Australian stocks rise sharply in early years, from 198 to reach 253 thousand tons by year 20, while Japanese stocks rise from 224 to 235 thousand tons by year 20 after an initial dip. Japan's harvest and both stock levels continue to increase slightly at year 20.

Under duopoly, Japan maintains a harvest of 9 to 11 thousand tons per year, and Australia 5 to 8 thousand tons per year. Although the combined catch rate is higher than under joint maximization (17.3 as opposed to 11.5 thousand tons per year), it is still significantly below the actual 1982–83 catch rate (38 thousand tons per year). Harvests and stocks reach virtually steady states by about year 14.

Table 2 shows that Australia obtains a present value of social return equal to A$14 million under duopoly. This compares with Australia's zero contribution to total social return under joint maximization. The present value of social return is lower for Japan under duopoly at A$937 million compared with A$1084 million under joint maximization. These results would enable Australia to argue for at least a A$14 million share of joint social return in response to Australia acting cooperatively to harvest the tuna.

The lower the discount rate used by a nation, the greater is the impact of future harvesting, both by that nation and the opponent nation, on the present value of net returns from the current harvesting decision. To see the effects of a lower

Table 2
Total Harvests and Returns (discount rate = 10% per annum).

	Duopoly		Joint Maximization	
	Australia	Japan	Australia	Japan
Total harvest over 20 years (thousand tons)	152	193	0	230
Present value of social return (million Australian dollars)	14	937	0	1084
Present value of combined social return (million Australian dollars)	951		1084	

Table 3
Effort Policies (zero rate of discount).

Stocks (thousand tons)		Effort (1982–83 level = 1.00)			
		Duopoly		Joint Maximization	
x_A	x_J	u_A	u_J	u_A	u_J
180	180	0.15	0.60	0.00	0.60
180	225	0.15	0.45	0.00	0.45
180	270	0.15	0.45	0.00	0.45
225	180	0.15	0.30	0.00	0.30
225	225	0.30	0.45	0.00	0.45
225	270	0.30	0.60	0.00	0.60
270	180	0.45	0.30	0.00	0.45
270	225	0.60	0.45	0.00	0.45
270	270	0.60	0.60	0.00	0.60

discount rate, the models were also run for a zero rate of discount. Optimal infinite-stage effort levels are shown in Table 3.

In contrast to the policy under a 10% discount rate, optimal effort levels by one nation are not only sensitive to the stocks of that nation, but also to the stock levels of the other nation. This can be explained by the increasing importance of strategic behavior as the discount rate is reduced. Total harvests over 20 years were reduced to about 85% of the levels shown in Table 2 under both duopoly and joint maximization.

Conclusions

In the game theory example of Cyert and DeGroot (1970), the returns of one player were affected by the output decision of the other player because both players sold the same product on one market. In the model of the southern bluefin tuna fishery, the players sell on separate markets, but the returns of one player are affected by the harvesting decision of the other through harvesting depleting stocks and harvesting costs being a function of stock.

A feature distinguishing this model from others is that each player makes successive decisions alternating with the decisions of the other player, instead of each player making successive decisions simultaneously. The solution procedure is relatively straightforward. The question arises as to which type of model is more realistic in practice. While cooperative decisions must be made simultaneously, non-cooperative decisions are perhaps more likely to be made alternately. Alternate decisions in a fishery are facilitated if each nation sets a quota at the beginning of each of its seasons. Without quotas, the decision sequence may be more complex due to delays before each nation is able to discover the harvest of the other nation.

Results obtained for the southern bluefin tuna fishery show that the gains from the duopoly behavior compared with joint maximization are not symmetric for the two nations. Australia obtains a net benefit and Japan a net loss from adopting strategic behavior. One use of this type of model is in determining the bargaining positions of the two nations should they cooperate in the annual setting of quotas on Australian and Japanese catches.

An important limitation of the model is that it is deterministic, and both nations are assumed to have full information. Typically the level of current stocks is uncertain, and the stock level which will result from exploitation of a known initial stock level is also uncertain. Besides these biological uncertainties, and the economic uncertainties of harvesting costs and returns, in a game situation there is also likely to be uncertainty about the strategic behavior of the other fishing nations. However, as already mentioned, it would not be difficult to extend the models to treat any of these sources of uncertainty stochastically. The system of approximation based on linear interpolation could be extended by using probabilities as weights to form linear combinations of grid points in value-of-stock space. Lewis (1975, 1977) has demonstrated how this may be effected in the case of biological and price uncertainties. It would also be possible to allow for each nation to formulate a probability distribution of the other nation's next harvesting decision, centered on the other nation's optimal decision.

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