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A cooperative solution for the three nation problem of exploitation of the southern bluefin tuna

Jacek B. Krawczyk*

and Boleslaw Tolwinski**

* Quantitative Studies Group
Faculty of Commerce and Administration
Victoria University of Wellington

** Colorado School of Mines, Golden, Colorado

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A Cooperative Solution for the Three-Nation Problem of Exploitation of the Southern Bluefin Tuna

Jacek B. Krawczyk
Victoria University of Wellington, New Zealand

Boleslaw Tolwinski
Colorado School of Mines, Golden, Colorado, USA

Abstract

This paper is concerned with the problem of management of fisheries of the Southern Bluefin Tuna (*SBT*). The problem involves three countries exploiting the fisheries, namely Australia, Japan, and New Zealand. Each country faces different economic conditions and may pursue different policies concerning their fishing efforts, catch quotas, etc., to achieve their specific goals. To avoid overexploitation of the fisheries, the three countries set up a Trilateral Commission that provides framework for negotiations on catch quotas. The ultimate goal of this study is to help to provide answers what the level of quotas should be. As a first step in that direction we consider a solution that maximizes the sum of benefit functions of the parties involved.

In particular, we report that higher *SBT* quotas than the current ones can be allocated to the interested parties provided that the stock has achieved a better demographic structure, which consists of having more older fish than at present.

Keywords: *cooperative equilibrium, fisheries management, perturbation method.*

1 Introduction

This paper reports on some preliminary research concerned with management of fisheries of the Southern Bluefin Tuna (*SBT*)[1]. The problem involves three countries exploiting the fisheries, namely Australia, Japan, and New Zealand. Each country faces different economic conditions and may pursue different policies concerning the sizes of their respective fishing fleets (fishing efforts), catch quotas, etc., to achieve their specific goals. To avoid overexploitation of the fisheries the three countries set up a Trilateral Commission that provides framework for negotiations on catch quotas. The ultimate goal of this study is to help to provide answers what such quotas should be. As a first step in that direction we consider a solution that maximizes the sum of benefit functions of the parties involved. That solution is the so-called *balanced Pareto-optimal solution* and is a particular one in the set of all non-dominated solutions, in that the players have equal weights. It is a natural candidate for a cooperative solution, see [Haurie, Krawczyk, Roche, 1992].

The dynamics of the fish population can be expressed in terms of a so-called multicohort model that divides the population into several age groups and describes the evolution of the population over time in terms of a system of differential or difference equations. A realistic model of the *SBT* population has to consider at least four age groups leading to a system of four state equations. Each country can influence the system through its fishing effort in each age group, implying that each country has up to four control variables. In addition, every country has a different benefit function that it would like to maximise. From the mathematical point of view, the problem at hand is a dynamic game with three players (each with up to four independent controls) over a fourth order dynamical system. Since the players can and are willing to cooperate, a natural solution concept for this game is the *cooperative equilibrium* of the type considered in [Tolwinski, 1982], [Haurie & Tolwinski, 1984], [Hämäläinen *et al.*, 1985], [Haurie, Krawczyk, Roche, 1992].

The task of determining such an equilibrium is complex. It usually consists of the three following steps (see [Haurie & Tolwinski, 1984], [Haurie, Krawczyk, Roche, 1992]):

1. find a solution which can be considered by the players as their best outcome if they agree to cooperate (that solution is not an equilibrium to the extent that any player can cheat);
2. find Nash-feedback equilibrium solution which would be the game outcome if the players did not cooperate;
3. design a monitoring-and-punishment mechanism that will define an equilibrium which will dominate the Nash-feedback equilibrium.

In this paper, we address the first issue, *i.e.* that of finding a Pareto optimal solution that could be considered by the players as an acceptable outcome of the game.

In other words, here we solve an infinite horizon optimal control problem with four state and nine control variables. In view of the fact that we are mostly interested in the determination of an optimal steady state of the system and optimal feedback control laws in the neighbourhood of that steady state, we use *the perturbation method* developed in [Horwood & Whittle, 1986a] as the solution technique for the optimal control problem at hand.

Since the paper of [Clark, 1980], in which he introduced a rigorous analytical framework for the discussion of problems of common-property fisheries, there have been a number of works dedicated to the management of fisheries. Their complexity and (often) relevance of the solution

[1] This paper is a revised version of [Krawczyk & Tolwinski, 1991] which was presented at the 15th IFIP Conference on System Modelling and Optimization. The revision was done while the first author was on leave at La Trobe University, Melbourne.

to the underlying real-life problem can be judged using different criteria. We will specify some of them here and briefly explain for which problems they are important. The criteria are:

- *The number of state variables*; if the underlying problem is of a species which has a multicohort population the model has to have a sufficiently high number of state variables.
- *The number of control variables*; if fishing efforts in the different age-groups of the species population are independent of each other then the controls should also be independent rather then modelled through *the catchability coefficients* as parts of the same fishing effort.
- *Is the problem formulated as a dynamic game or an optimal control problem*; if controls are not only independent but also belong to different agents the game-theoretic model affords one a better understanding of the underlying process.
- *Is the proposed solution open-loop or feedback*; in an uncertain natural environment a feedback solution has clear advantages even if the stochastic factors are not explicitly included in the model.
- *Is the problem formulated as stochastic or as deterministic*; in an uncertain environment a solution which allows for stochastic factors is better suited to be applied in the real world.

Most of the papers devoted to the problem of fishery management address at least some of the above issues. In particular, [Horwood & Whittle, 1986b] (also, [Horwood, 1991]) work with a multi-cohort model and find a feedback solution which is *certainty equivalent*[2], [Dockner *et al.*, 1989] use the game theoretic approach, [Kennedy & Watkins, 1986] formulate a two-agent problem and consider multidimensional population dynamics, [Kennedy & Pasternak, 1991] compare a cooperative solution with an open-loop duopoly equilibrium for a multicohort model. The cited papers whilst successfully fulfilling some of the criteria of the relevance of their models fail to score well on some other criteria. *E.g.* [Horwood & Whittle, 1986b] work with one control variable, [Dockner *et al.*, 1989] have no multi-cohort model, [Kennedy & Watkins, 1986] and [Kennedy & Pasternak, 1991] settled for an open-loop solution.

Our ultimate goal is to create a model which will be as relevant as possible to the underlying *SBT* management problem *i.e.* which will score well on all the criteria. In the meantime, this paper considers certainty-equivalent feedback solutions to a fourth order joint-maximisation optimal control problem with nine control variables (individually and jointly constrained). These solutions, as said before, are a first step in the computation of a game-theoretic feedback solution. Moreover, the joint maximisation solution is of interest for indicating the maximum possible returns form the fishery which can be used as a yardstick for evaluating any other management plan involving the three players.

This paper is closest to the work by [Kennedy & Watkins, 1986] who considered a cooperative solution for the *SBT* management problem modelled as a two-agent, fourth order optimal control problem with linear dynamics, and to [Horwood, 1990] who (to the authors' knowledge) is first in the fisheries literature, to successfully obtain a feedback (local-optimal) solution for *two* independent controls while the other feedback approaches were dealing with *one* control and fixed catchability coefficients for each age class.

It should be emphasized that the players in the game are unequal in several ways. In particular,

- the price of *SBT* in Japan is very sensitive to the fish supply, while the Australian price is quite insensitive, see [Kennedy & Watkins, 1986], (the sensitivity of the price to supply in New Zealand is somewhere in between);

[2] *I.e.* one which is optimal for the deterministic stock model as well as for that containing the additive white noise.

- the countries' fleets differ in type and size (*e.g.*, Australia and New Zealand fish predominantly on their territorial waters while Japan fishes far from home) and, consequently, their harvesting costs vary considerably;
- the 1988-89 Australia to Japan to New Zealand catch ratio was approximately 6 to 9 to 0.5 (*thousands of tones*).

The paper is organised as follows. Section 2 presents a population model for the Southern Bluefin Tuna. Section 3 formulates a three-nation *SBT* management problem. Section 4 explains briefly the method used to compute the solution. Section 5 discusses solutions corresponding to different sets of economic parameters. Finally, Section 6 provides some concluding remarks.

2 The Southern Bluefin Tuna Multi-cohort Model

As *SBT* lives for twenty or more years, matures at about eight years and substantially changes in size and weight during its life-span (to reach up to more than 100kg) its dynamics model clearly has to be multi-cohort.

The *SBT* stock will be aggregated into four age groups as follows:

1. spanning years 0 to 1+;
2. spanning years 2 to 3+;
3. spanning years 4 to 5+;
4. spanning years 6 + (to 20 and over).

Underlying that aggregation is the 'technology' which is applied to catch the different sizes of *SBT* , see [Kennedy & Watkins, 1986]. Broadly speaking, that means that, *e.g.* to the Japanese fleet the stock 6 years and over is accessible while the Australian fleet has traditionally concentrated on the first three age groups. Last, but not least for the model, is that the fishing costs are available for this particular aggregation, see [Kennedy & Watkins, 1986].

The model used in this paper will be similar to that of [Kennedy & Watkins, 1986] with two exceptions: no linearisation in the stock updating equations will be made; moreover, instead of the linear, or piece-wise linear, recruitment function utilised in [Kennedy & Watkins, 1986], the nonlinear Shepherd function (see *e.g.* [Kirkwood *et al.*, 1989]) will be applied.

The stock updating equations are:

$$\begin{aligned} x_1(t+1) &= \frac{\alpha p w_s x_4(t)}{1+(\frac{p w_s x_4(t)}{\kappa})^\beta} + \\ &\quad a\exp[-f_{A,1}(t)-m]x_1(t) \end{aligned} \tag{1}$$

$$\begin{aligned} x_2(t+1) &= (1-a)\exp[-f_{A,1}(t)-m]x_1(t) + \\ &\quad a\exp[-f_{A,2}(t)-f_{N,2}(t)-m]x_2(t) \end{aligned} \tag{2}$$

$$\begin{aligned} x_3(t+1) &= (1-a)\exp[-f_{A,2}(t)-f_{N,2}(t)-m]x_2(t) + \\ &\quad a\exp[-f_{A,3}(t)-f_{N,3}(t)-f_{J,3}(t)-m]x_3(t) \end{aligned} \tag{3}$$

$$\begin{aligned} x_4(t+1) &= (1-a)\exp[-f_{A,3}(t)-f_{N,3}(t)-f_{J,3}(t)-m]x_3(t) + \\ &\quad \exp[-f_{A,4}(t)-f_{N,4}(t)-f_{J,4}(t)-m]x_4(t) \end{aligned} \tag{4}$$

where $x_i(t)$ is the stock of fish at time t in the i- th age category, $f_{c,i}(t)$ represents the fishing mortality at time t proportional to the fishing effort of country c in the i-th age category ($c = A$ — *Australia*, $c = N$ — *New Zealand*, $c = J$ — *Japan*), and m is the rate of the natural mortality. For each age group $a/(1-a)$ is the ratio of fish aged n years to those aged $n+1$, where a is a constant. We will assume, after [Kennedy & Watkins, 1986] $a = .6$; experiments with different values of a there conducted indicated lack of sensitivity of the model to a. This lack of sensitivity justifies the proposed approach. On the other hand, introduction of a offers one a model whose size is not detrimental to the computation process of a feedback solution.

The fishing mortalities are the model controls. They are contained between 0 and 1 and have to satisfy the following constraints at any t:

$$f_{A,1}(t) + m \leq 1 \tag{5}$$

$$f_{A,2}(t) + f_{N,2}(t) + m \leq 1 \tag{6}$$

$$f_{A,2}(t) + f_{N,2}(t) + m \leq 1 \tag{7}$$

$$f_{A,3}(t) + f_{N,3}(t) + f_{J,3}(t) + m \leq 1 \tag{8}$$

Parameters α, κ, β are constants of the Shepherd stock-recruitment function; p is proportion of mature fish, w_s is average weight. They were chosen (see [Kirkwood *et al.*, 1989]) as follows: $\alpha = 430.414$, $\kappa = 3200$, $\beta = .69$ (this selection implies ([Kirkwood *et al.*, 1989]) that natural mortality $m = .2$). The parameter $p = .67$ which is the proportion of the parental biomass (8+) within the fourth group, and $w_s = .05693$ *tones* which is an average weight of the fish in the last group. A brief rationale for the choice of the Shepherd function parameters out of many suggested in [Kirkwood *et al.*, 1989] will be provided while the model solutions will be discussed.

For brevity, we will refer to the above system of equations as

$$x(t+1) = \mathcal{A}(x(t), f(t)) \tag{9}$$

where $\mathcal{A}(x(t), u(t))$ represents a vector composed out of the right hand sides of equations: (1), (2), (3), (4); $x(t) = [x_1(t), x_2(t), x_3(t), x_4(t)]^T$ and $f(t)$ is a vector of controllable fishing mortalities.

3 The Dynamic Management Problem

The total cost of harvesting to country c is given by

$$\sum_{i=1}^{4} k_{c,i} f_{c,i}(t) \tag{10}$$

where $k_{c,i}$ represents the harvesting cost per unit of fishing mortality of country c in the ith age category. We adopt a linear cost function and take the values for $k_{c,i}$ for Australia and Japan from [Kennedy & Watkins, 1986]. These values and the corresponding values for New Zealand are given in Table 1. In fact, since New Zealand is still shaping its fishing industry and therefore can consider a variety of options (*e.g.*, hiring a foreign fleet, selling fish on overseas markets, etc.), it is interesting to consider several values of $k_{c,i}$ (see Section 4).

The annual harvest is expressed by (t index dropped for clarity)

$$h_{c,i} = \frac{f_{c,i}}{(f_{c,i} + \mu)}[1 - \exp(-f_{c,i} - \mu)]x_i \tag{11}$$

parameter	age group: I	II	III	IV	units
$k_{i,A}$	9.42	35.59	52.38	130.18	$10^6 AUD$
$k_{i,J}$	0.0	0.0	599.80	1385.14	$10^6 AUD$
$k_{i,N}$	0.0	100.00	300.00	1000.00	$10^6 AUD$

Table 1: Harvesting cost per unit of fishing mortality.

where

$$\mu = m + f_{\cdot,i} \tag{12}$$

with $f_{\cdot,i}$ being the *uncontrollable* mortality composed of the fishing mortality imposed by the other fishing players, and (potentially) of uncertainty about m.

The price of fish is given by a standard linear inverse demand function

$$price_c = r_c - s_c(\sum_{i=1}^{4} h_{c,i} w_i) \tag{13}$$

where w_i is the average weight of fish in the i-th age group. The values of the parameters [Kennedy & Watkins, 1986] are listed in Table 2. However, it is unlikely that the Australian parameters will remain so low in the future and we will vary them in Section 5.

parameter	country: Australia	Japan	NZealand	units
r	.881	18.86	10	$10^3 AUD/ton$
s	.0	.419	.300	AUD/ton

Table 2: Demand function parameters.

The revenue and profit for country c are calculated according to the following formulae:

$$revenue_c = price_c(\sum_{i=1}^{4} h_{c,i} w_i) \tag{14}$$

$$profit_c = revenue_c - \sum_{i=1}^{4} k_{c,i} f_{c,i}. \tag{15}$$

Actually, not all three countries fish in all age groups so the sums extend over the feasible combinations of c, i only. The long term objective of country c is defined as

$$J_c = \sum_{t=0}^{\infty} \delta_c^t profit_c(t) \tag{16}$$

where δ_c is the discount factor of country c.

The instantaneous cooperative objective is therefore

$$g(x(t), f(t)) = \sum_c profit_c =$$

$$\sum_c \left\{ \left(r_c - s_c \sum_{i=1}^{4} h_{c,i} w_i \right) (\sum_{i=1}^{4} h_{c,i} w_i) - \sum_{i=1}^{4} k_{c,i} f_{c,i} \right\} \tag{17}$$

The cooperative solution which is sought in the paper is one which maximises

$$J = \sum_c J_c \tag{18}$$

or, if we assume the same discount rate for all agents

$$J = \sum_{t=0}^{\infty} \delta^t g(x(t), f(t)). \tag{19}$$

4 Computation of the Solution

A convenient method for the solution of the optimal control problem formulated in the previous section is the perturbation technique developed in [Horwood & Whittle, 1986b]), which produces an optimal steady state and a (locally) optimal feedback law in the neighbourhood of that solution. Having a feedback law as opposed to an open-loop control is certainly useful when dealing with a problem that involves as many uncertainties (*e.g.*, food supply, natural disasters, fishing by other parties, etc.) as the management of fisheries. On the other hand, a feedback law can be relevant only when the controllers know the actual values of the state variables, therefore it should be noted that in recent years there have been substantial advances in the 'technology' of fish stock observation (*e.g.*, tagging, photographing), in virtual population analysis as well as in the commitment of the countries involved to do their best to assess the SBT population.

The method of Horwood and Whittle is directly applicable to problems where the control variables are unconstrained, and allows one to obtain an optimal steady state by solving a system of $n+l$ nonlinear equations, where n and l denote the number of states and the number of control variables, respectively. Since in our problem the control variables are constrained to take values between zero and one, and the lower constraint is likely to be active, we solved the problem by using the following obvious procedure. Some of the control variables are set to zero, then the optimal values of the remaining ones are obtained by solving equations (20) and (23), and finally the optimality of the resulting solution is verified.

As noted in Section 3, not all three cooperative players act in all fish age categories. We will assume in particular that New Zealand does not fish in the first category and Japan fishes in the third and fourth only. Let u denote the control vector with nine components:

$$\begin{aligned} u_1 = f_{A,1},\ u_2 = f_{A,2},\ u_3 = f_{A,3},\ u_4 = f_{A,4}; \\ u_5 = f_{N,2},\ u_6 = f_{N,3},\ u_7 = f_{N,4}; \\ u_8 = f_{J,3},\ u_9 = f_{J,4}. \end{aligned}$$

The condition which determines the long-term optimal steady state x^* as a function of control is:

$$x^*(t) = \mathcal{A}(x^*(t), u(t)) \tag{20}$$

The above equation has been solved, producing a mapping[3] of the form:

$$x^* = x^*(u) \tag{21}$$

The optimal control $\hat{u}$ can be found from the Bellman equation:

$$F(x^*) = \max_u [g(x^*, u) + \delta F(\mathcal{A}(x^*, u))]. \tag{22}$$

[Horwood & Whittle, 1986a] demonstrated that the optimal steady-state control $\hat{u}$, if achieved at a stationary point of the bracketed term, can be computed as a solution of the following system of simultaneous equations at $x^*(u)$:

$$g_u + \delta g_x (I - \delta \mathcal{A}_x)^{-1} \mathcal{A}_u = 0 \tag{23}$$

where g_u and g_x denote appropriate gradients of the instantaneous joint reward function $g(x, u)$, and $\mathcal{A}_x$ and $\mathcal{A}_u$ represent the Jacobian matrices for function $\mathcal{A}(x, u)$.

Notice that because of a rather long expression for g (equation (17)) the formulae for the derivatives in (23) become messy and the resulting system of nonlinear equations is difficult to deal with both analytically and numerically. Fortunately, a solution of the undiscounted case, where $\delta = 1$, which leads to the optimal steady-state reward rate, is readily obtained from the maximization of $g(x, u)$ subject to (20) and can serve as a good starting point to compute solutions for cases where $\delta < 1$.

Once an optimal steady state is computed, a locally optimal feedback law can be obtained in the form

$$\eta = K\xi + o(\xi) \tag{24}$$

where K is an $l \times n$ matrix, $\eta = u - \hat{u}$ and $\xi = x - \hat{x}$ (see[Horwood & Whittle, 1986b]). In particular, the matrix K is a product of two matrices of which one is derived from the model parameters and the other involves solving a Riccati matrix equation (*ibid.*). As the experience gathered from [Horwood & Whittle, 1986a], [Horwood, 1990], [Horwood, 1991] indicates there is always a non-empty interval of the discount factor values for which the Riccati equation has a positive definite solution. However, if the positive definite solution is obtained for δ small the matrix K thus yielded may lead to instability of the control based on (24). In such situations, the optimal control would be *pulse* rather than *smooth* (24) (see [Horwood, 1990]). (Alternatively, as the non-optimal smooth control can often be close to the optimal, see [Kennedy, 1989]), one may opt for a sub-optimal stabilisation of the system around the steady-state (21).)

The optimal steady-state stocks can differ substantially from the initial state. The optimal path from the initial state to the optimal one can be computed as a solution of a fixed-end optimal control problem. We will not search for that path in this paper. Instead, we will indicate a demographically feasible path.

[3]That mapping was useful for assessment of the Shepherd function parameters in the following way. We performed a series of experiments with various sets of those parameters. We set all $u_i = 0$ which produced steady-state stocks as if no fishing took place. If the obtained 'virgin' states were too far from the 'biologically' expected the parameters which had produced those states were discarded. In this way we selected the parameters whose corresponding 'virgin' steady-state values were: $10,648, 6,854, 4,412, 7,971 (\times\ 000\ \textit{tones})$. This procedure might solve some controversies around the Shepherd function [Kirkwood *et al.*, 1989].

5 Discussion of Solutions

[Kennedy & Watkins, 1986] obtained cooperative solutions which for some – fairly feasible – combinations of economic parameters guarantee the maximum of J when the Australian harvest is zero. Inclusion of New Zealand, whose current catch is minimal but whose economic parameters are "better" than Australian, into the *SBT* management problem makes the analysis of the parameter values at which countries should "enter the game" interesting and relevant for the bargaining process at the Trilateral Meetings.

The presented solutions define the optimal steady states and the feedback controls which should ensure that those states are maintained.

Tables 3, 4, 5 present the solution corresponding to the parameters given in Tables 1 and 2 and to the discount factor $\delta = 1$ (which is a limit case of the maximisation problem of (19) when $\delta \rightarrow 1$; that solution is called *overtaking optimal*). The joint profit *rate* of the players corresponding to this solution is 144.614 M AUD per year.

country	age group: I	II	III	IV
Australia	0.0	0.0	0.0	0.0
Japan	0.0	0.0	0.0	.0521
NZealand	0.0	0.0	0.0	.0197

Table 3: Optimal fishing mortalities.

age group:	I	II	III	IV
	9,240	5,948	3,829	5,269
	9,055	46,635	83,166	299,983

Table 4: Optimal steady-state stock. First row: number of fish in thousands; second row: corresponding biomass in tones.

country	age group: I	II	III	IV
Australia	0.0	0.0	0.0	0.0
Japan	0.0	0.0	0.0	13,677
NZealand	0.0	0.0	0.0	5,175
total	0.0	0.0	0.0	18,852

Table 5: Harvest in tones.

The optimal solution presented above suggests that higher quotas than the current ones can be allocated to the interested parties, provided that the stock has achieved a better demographic structure, *i.e.*, enough 'parents' to be fished and still to produce sufficient recruitment. The optimal steady-state stock turns out not to be that far from the existing one[4], given by:

$$12'080,000; \;\; 6'390,000; \;\; 3'130,000; \;\; 2'920,000.$$

A (non-optimal) policy of suspending the fishing produces the following levels of stock (Table 6). It seems that four to six years are enough to catch up with the required levels, *i.e.* those for which feedback law (24) could be used.

	age group: I	II	III	IV
initial yr	12,089	6,390	3,130	2,920
1 yr	9,745	7,095	3,630	3,416
2 yrs	8,820	6,777	4,107	3,985
3 yrs	8,594	6,168	4,204	4,608
4 yrs	8,708	5,845	4,085	5,150
5 yrs	8,941	5,723	3,921	5,554
6 yrs	9,179	5,739	3,800	5,831
7 yrs	9,378	5,825	3,746	6,018
target	9,240	5,948	3,829	5,269

Table 6: Projected recovery of the stock under no-fishing policy (in thousands of fish).

The fact that Australia should be eliminated from fishing the *SBT* if Australia and Japan are maximising their joint reward has been known since (at least) the paper of [Kennedy & Watkins, 1986]. Interestingly enough, in the three country environment the elimination of Australia (which incidently catches predominantly the younger fish) is still optimal. However, should the Australian marketing policies change so that it sells more overseas it will be admitted into the set of *active* players contributing to the optimal solution. That situation is presented in Tables 7, 8, 9, after fixing the Australian parameter r_A at the level of 10 000 AUD per ton and s_A at 0.3 AUD per ton. The corresponding cooperative profit *rate* is now 174.119 M AUD per year.

country	age group: I	II	III	IV
Australia	0.0	0.0	0.0	0.0413
Japan	0.0	0.0	0.0	.0520
NZealand	0.0	0.0	0.0	.0118

Table 7: Optimal fishing mortalities ($r_A = 10, \;\; s_A = .3$).

The impact of the discount rate contributed, in general, to an increase in fishing mortalities by a couple of percent. Other experiments (not reported here) with different sets of model parameters were also conducted.

[4]See [Kennedy & Watkins, 1986]. Notice that here older groups are less than in a more recent estimation of the stock [Kennedy & Pasternak, 1991]; that may shorten the time of achieving the steady state.

age group:	I	II	III	IV
	8,757	5,638	3,629	4,519
	8,582	44,198	78,820	257,268

Table 8: Optimal steady-state stock ($r_A = 10,\ s_A = .3$). First row: number of fish in thousands; second row: corresponding biomass in tones.

country	age group: I	II	III	IV
Australia	0.0	0.0	0.0	9,166
Japan	0.0	0.0	0.0	11,521
NZealand	0.0	0.0	0.0	2,625
total	0.0	0.0	0.0	23,312

Table 9: Harvest in tones ($r_A = 10,\ s_A = .3$).

6 Concluding Remarks

Information on steady-state stocks and fishing mortalities obtained in this paper can be incorporated into the catch-quotas negotiation-process between the three countries. The following benefits could be gained:

- the quotas established in that manner will lead to a (model) steady state and therefore the danger of overfishing will be diminished (eliminated, if the model were ideal);
- the upper limit of the joint achievable benefit given from the model will help the countries to see their relative financial positions.

The paper suggests that New Zealand can increase its fishing effort if it is able to shape its economic parameters so that its costs are competitive with Japanese fishing, and if its prices are higher than the Australian. Both targets seem achievable. The first as New Zealand fishes "closer to home", the second through a programme of active marketing. Moreover, solution of the management problem at hand for different sets of model parameters can answer the question as to what are the parameter values for which a player's participation in the game is/ceases to be profitable?

Optimisation of a high-dimensional infinite-horizon control problem is usually a problem in its own right. [Horwood & Whittle, 1986a] showed that the perturbation method can furnish the results if one is interested in an unconstrained-optimum steady state, and in the dynamics about the perturbed optimum, rather then in the global optimisation problem. This paper applies that method to a similar problem whose controls are constrained and of dimensions higher than those in the current fisheries literature.

Finally, a basis for future investigation of the *SBT* management problem in the game-theory framework was established.

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