An Empirical Analysis of the Net Benefit of Canada-US Cooperation In the Management of the Lake Erie Walleye Fishery

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Abstract

This paper deals with the management of two-country trans-boundary fishery, Walleye in Lake Erie shared by Ontario (Canada) and four surrounding U.S states, namely Michigan, New York, Ohio and Pennsylvania. A standard fishery economic model is employed to simulate the two categories of fishery management games, cooperation and non-cooperation. The steady-state solutions are achieved by the application of maximum principle and game theoretical framework to the analysis of the two-agent fishery model. With the help of empirical data, a comparison between the solutions under non-cooperation and cooperation demonstrates the optimality and inescapability of a cooperative Lake Erie walleye fishery management.

1. Introduction

As the smallest by volume in one of the most important trans-boundary fresh water resources on the earth, Great Lakes System including five lakes, which is shared by Canada vs. the U.S, Lake Erie is shared by one Canada province, Ontario, as well as four surrounding U.S states, namely Michigan, New York, Ohio and Pennsylvania. Lake Erie is known as the most biologically productive of the Great Lakes, which is due to its three properties. Firstly, it is the southernmost of the Great Lakes, which contributes to the warmer temperatures. Secondly, Erie basin is the shallowest of the five lakes, since its average depth is only about 19 meters (62 feet), but the other Great Lakes are all in excess of 750 feet deep. As a result, the lake warms rapidly in the spring and summer. Finally, Lake Erie is also the most sediment-dominated, which allows it to receive more sediment and more nutrients than the other Great

Lakes.

[1]"Walleye capital of the world" is a well-known title of Lake Erie in which there exists the largest walleye population of the earth. In native walleye is a kind of pike-like freshwater perches; hence it is also usually called walleye pike, yellow pickerel or yellow pike. The key reason for the large population of Lake Erie Walleye is genetic diversity, i.e., there are mixed walleye stocks originating from biologically different lakes, which increases walleye's adaptation capacity and survival rate. As the most popular sport and commercial fish in Lake Erie, walleye attracts millions of anglers and companies each year. In 1956, the harvest rate of Lake Erie walleye even reached the level 23.8 million lb (NOAA 1984). Therefore [2]"the walleye is probably the most economically valuable species in Canada's inland waters" (Scott and Crossman 1973).

Sustaining this resource for today and for the future depends on suitable management. It has been challenging for both nations to come up with an appropriate approach for managing this shared resource given its unique nature. After non-cooperative (and independent) management of the Great Lakes for years, [3]"A Joint Strategic Plan for Management of Great Lakes Fisheries was accomplished which resulted in a typical example of trans-boundary cooperation".

The purpose of this paper is to provide a comparison of the behavior and outcomes of

[1] Hartman (2001).
[2] Munro (1991), pp. 95-101.
[3] Great Lakes Fishery Commission (2002a).

a non-cooperative vs. cooperative management of Lake Erie walleye fishery. The goal will be to use mathematical methods to offer an answer to the question, [4]"Is cooperative management between Canada and US of this resource worth the effort?" It is important to note that while this paper will focus on the management of Lake Erie Walleye; this is indeed a general problem for the whole great lakes resource. Therefore Lake Erie could be taken as a model for other great lakes, and, the outcome we gain from this lake can also be applied to the Great Lakes System.

As far as this non-cooperative and cooperative management problem is concerned, many studies have been done, such as Munro's (1991) theoretical results on the optimal management of trans-boundary resources, the main aim of the Law of the Sea is to call for a cooperation between neighboring nations. The Law of the Sea seeks to avoid the famous "prisoner's dilemma," a simultaneous-move game, in which two prisoners make decisions only once and at the same time without any knowledge about each other's rationality. The strictly dominant strategy of a prisoner's dilemma game is an unsatisfactory outcome for both players. As an example of non-cooperative games, "prisoner's dilemma" is directly relevant to the trans-boundary fishery management problem, i.e., non-cooperative management will lead to the over-exploitation of the resource, which is a highly undesirable strategy. The current paper analyzes whether the result deriving from the management of Lake Erie Walleye is consistent with these previous studies.

[4] Great Lakes Fishery Commission (2002b).

The paper is organized as follows: Section 2 gives an overview of the history of the management of Lake Erie Walleye fishery. Section 3 presents the theoretical model and derives the long run optimal solutions. In Section 3.1, the fishery model is formally presented, with assumptions as well as the optimal solution for single agent model. In Section 3.2, the long run equilibrium solutions for each individual country are generated for the two-agent, non-cooperative model. In Section 3.3, the golden rule for the maximization problem of cooperative model is derived as well as the steady state solution is obtained. Section 4 introduces the data. Section 5 carries out the results and provides a comparative analysis of the non-cooperative vs. cooperative game solutions, both numerically and analytically. Section 6 indicates limitations of the model and the data. Section 7 concludes the paper.

2. History of the Management of Lake Erie Walleye fishery

As a trans-boundary resource, Lake Erie Walleye was independently managed for years by the province of Ontario, Canada and the four states of the U.S, namely Michigan, New York, Ohio and Pennsylvania according to the water area boundary. During these periods, the province and states set their own TAC (total allowable catch) in order to manage the lake effectively.

Starting in 1893, both nations started putting efforts to create an international fishery commission for protecting and perpetuating the Great Lakes fisheries. For example, Canada and the U.S. tried to establish a joint board in 1893; in the year of 1908, the

Treaty between the U.S and Great Britain-Fisheries in the U.S and Canada Waters is recommended to be considered; another attempt is the convention between Canada and the U.S for the Development, Protection, and Conservation of the Fisheries of the Great Lakes in1946; the Great Lakes states and Ontario attempt to reach a compact for common conservation of their fisheries. Unfortunately they all couldn't escape the fate of failure since the province of Ontario and U.S. states was unwilling to cede regulation authority to federal government or to any international institution.

But by the early 1950s, the combination factors of sea lamprey and overfishing heavily depleted some species of Great Lakes. This propelled both nations, who feared a collapse of the resource, to put into place a mechanism for a more effective fisheries management, the cooperative management. Finally, Canada and the U.S signed the 1954 Convention on Great Lakes Fisheries in order to facilitate binational fishery management. Subsequently the Great Lakes Fishery Commission (GLFC) was created to become the first institution for coordinate Great Lakes fisheries management between Canada and U.S. [5]"In 1981 A Joint Strategic Plan for Management of Great Lakes Fisheries was signed by state, federal and provincial fish management agencies. Directors restated their commitment in a 1985 review of the Plan and again in the review completed in 1997."

As an important resource of Great Lakes, Lake Erie Walleye is cooperatively

[5] Great Lakes Fishery Commission (2002a).

managed and a joint TAC is set each year by Canada and the U.S since the 1981 Joint Strategic Plan. [6]"This cooperation is achieved via the Lake Erie Committee (LEC), which is comprised of representatives from the state and provincial fisheries management agencies under the auspices of the GLFC. On a rotational basis, Ontario's Lake Erie Manager is either chair or vice-chair of this committee. Lake Erie Management Unit staffs, make a key contribution to all of the LEC Task Groups, which jointly pursue scientific objectives, evaluate international fisheries management strategies, and set harvest levels for the lake."

3. The Model

3.1 Model

We start by outlining a well-known dynamic fishery model, which is associated with Gordon (1954) and Schafer (1957).

Notation, model equations as well as assumptions are described as follows:

Y : harvest rate

X : Population catch biomass or the remaining stock (in this paper, it represents the stock of walleye in Lake Erie)

E : effort

q : catchability coefficient

$F(X)$: net recruitment or natural rate of increase

k : carrying capacity of the environment

[6] Great Lakes Fishery Commission (2002b).

r : population of growth of the intrinsic rate

δ : periodical (instantaneous) social discount rate

TC : social cost of harvesting the stock X

c : constant cost coefficient

p : price

π : instantaneous profit

PV : present value of discounted social profits

<u>Necessary assumption:</u>

Price P, cost coefficient c and the factor of periodic discount δ are positive and constant throughout this paper. Furthermore, TC is a linear function of effort E.

<u>Natural production function</u>

$$F(X) \quad = rX(1-\frac{X}{k})$$

<u>Harvest production function</u>

$$Y = qX(t)E$$

<u>Cost function</u>

$$TC = cE$$

<u>The instantaneous profit function</u>

$$\pi = pY(X) - TC = (pqX - c)E = pY(X) - c\frac{Y(X)}{qX(t)} = \left[p - \frac{c}{qX(t)}\right]Y(X)$$

<u>The discounted social profit from time t to infinite time</u>

$$PV = \int_0^\infty e^{-\delta}(p - \frac{c}{qX(t)})Y(t)dt$$

Here, Y is the representative of the only control variable E applied to the system and X_t is the state variable. Under the control variable representative $Y(t) > 0$, the state evolves according to the following dynamic equation:

$\dot{X} = F(X) - Y, \quad X^*(0) = \overline{X}(0)$

where $\dot{X}$ is state change rate, and initial stock of the optimal time path, $X^*(0)$ is set equal to a constant level $\overline{X}(0)$. The stock-level time path can be determined by this differential equation meaning the stock change between two neighboring periods is equal to the net growth and less catch.

In the single-agent model, it is assumed that the agent in the fisheries economies seek to optimize the present value of discounted social profits:

(1) Max $PV = \int_0^\infty e^{-\delta}(p - \frac{c}{qX(t)})Y(t)dt$

subject to

(2) $\dot{X} = F(X) - Y$ where $F(X) = rX(1 - \frac{X}{k})$

and

(3) X_0 is given, $X(t) \geq 0$ for all $t \geq 0$

The above present value of the stream of profits maximization problem characterized under infinite time horizon is to derive the time path to the optimal stock level X^* and optimal control $E(t) = E^*(t)$ or $Y(t) = Y^*(t)$ subject to the state equation (2).

Application of maximum principle can show that the solution of this problem results in the following equilibrium condition:

$$\delta = F'(X) + \frac{cF(X)}{X(pqX - c)}$$

which characterizes the steady state biomass level (equilibrium), X^*, that is, if $X_0 \neq X^*$, the state variable X(t) converges to X^* from X_0 as quickly as possible.

Another usual equilibrium associated with the fishery management problem is X^{∞}, the bionomic equilibrium, in open-access common-property fishery. X^{∞} happens when a fishery is unregulated and everyone is free to enter this resource at any time. In an open-access fishery, each harvesting agent seeks to maximize his instantaneous net rent but not the present value PV as in the previous equilibrium. Once net economic rent is dissipated to zero, i.e., $\pi = 0$, equilibrium will be established. In other words, there is no entry or exit. Hence, the biomass remains at the bionomic equilibrium $X^{\infty} = c / pq$, and, $X^{*} > X^{\infty}$ when $\delta < \infty$,

3.2 Two-agent, Non-cooperative Model

In this case, each agent i aims to maximize his discounted profits respectively without communication between them:

1 $PV_1 = \int_0^{\infty} (p_1 - \frac{c_1}{q_1 X}) Y_1(t) e^{-\delta t} dt$

2 $PV_2 = \int_0^{\infty} (p_2 - \frac{c_2}{q_2 X}) Y_2(t) e^{-\delta t} dt$

Correspondingly, both agents face a state equation that governs the optimal remaining stock in each region so as to maximize the above profit functions. It is described as the following dynamics:

$\dot{X} = F(X) - Y_1 - Y_2$, X_0 is given, $X(t) \geq 0$ for all $t \geq 0$

[7]After a lot of calculation, the golden-rule is given as:

[7] Regarding the solution procedure, see appendix 1.

$$\delta = F'(X_i^*) + \frac{c_i F(X_i^*)}{X_i^*(p_i q_i X_i^* - c_i)}$$

from which the constant optimal stock level can be solved in a straightforward manner.

We now assume that both agents are rational players, and that agent 2 is at least as efficient agent 1, that is, $X_1^\infty \geq X_2^\infty$. Therefore, the feedback Nash equilibrium solution for this non-cooperative (competitive) game is specified by the following cases (Clark, 1980):

Case I, $X_1^\infty = X_2^\infty = X^\infty$,I.E, $c_1 / q_1 p_1 = c_2 / q_2 p_2$

$X_{NE}^* = X^\infty$ then $PV_1 = PV_2 = 0$

When the bionomic equilibriums for both agents are identical, the fishery equilibrium will converge to the bionomic equilibrium, as well as, their net profits will be dissipated to zero.

Case II, $X_1^\infty > X_2^\infty$

If $X_2^* < X_1^\infty$, $X_{NE}^* = X_2^*$

$PV_1 = 0$

$$PV_2 = \int_0^\infty (p_2 - \frac{c_2}{q_2 X_2^*}) Y_2 e^{-\delta t} dt$$

Where $F(X_2^*) = rX_2^*(1 - X_2^* / k) = Y_2^* + Y_1 = Y_2^*$

Agent 2 will operate at his sole-owner optimal biomass level X_2^* at the equilibrium state; while agent 1 will only get zero net rent.

If $X_2^* > X_1^\infty$, $X_{NE} = X_1^\infty$

$PV_1 = 0$

$$PV_2 = \int_0^{\infty} (p_2 - \frac{c_2}{q_2 X_1^{\infty}}) Y_2 e^{-\delta_t t} dt$$

Where $F(X_1^{\infty}) = rX_1^{\infty}(1 - X_1^{\infty}/k) = Y_2$

Once the biomass is driven down to X_2^{∞}, the equilibrium will be achieved, in which case agent 2 will keep operating at the equilibrium; similarly like the above result, agent 1 will not have any incentive to enter.

3.3 Two-agent, Cooperative Model

The problem of both agents is to jointly maximize their common present value of discounted economic rent, which is stated formally as follows:

(1)Max

$$PV = \beta \int_0^{\infty} \left[(p_1 q_1 X - c_1) \frac{\alpha Y(t)}{q_1 X_t} \right] e^{-\delta_t t} dt + (1-\beta) \int_0^{\infty} \left[(p_1 q_1 X - c_1) \frac{(1-\alpha) Y(t)}{q_1 X_t} \right] e^{-\delta_t t} dt$$

Subject to:

(2) $\dot{X} = F(X) - Y$

and

(3) X_0 is given, $X(t) \geq 0$ for all $t \geq 0$

[8]where α, β are assumed to be agent 1's share of total harvest, and the weight to this agent's management preference, respectively. Notice that the two parameters are also assumed to be constant, as well as, 0< α, β<1.

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[8] Munro (1991), pp. 95-101.

[9]The equilibrium condition is expressed in three cases:

I $\delta_1 < \delta_2$

(14) $\delta_1 = F'(X) + F(X)\frac{c_1}{(p_1 q_1 X - c_1)X}$

II $\delta_1 > \delta_2$

(15) $\delta_2 = F'(X) + F(X)\frac{c_2}{(p_2 q_2 X - c_2)X}$

III $\delta_1 = \delta_2$

(16) $\delta = F'(X) + \frac{c_1 q_2 \alpha\beta + c_2 q_1 (1-\alpha)(1-\beta)}{(p_1 q_1 X - c_1) q_2 \alpha\beta + (p_2 q_2 X - c_2) q_1 (1-\alpha)(1-\beta)} \frac{F(X)}{X}$

(14) indicates that optimal stock in the cooperative case asymptotically convergences to X_1^*, agent 1's sole-owner optimum; in the contrary, optimal stock in (15) converges to X_2^*. The case where two agents have the same discount rate is more complicated and the specific value can only be decided after applying the data.

4. Data

According to records in Turner et al. (2000) and Deriso et al. (1986), the U.S only focuses on sport fishing. In Ontario there are two kinds of fishing, sport fishing and commercial fishing. But because of the very small proportion of sport fishing in total fishing and for ease of the computation, we assume a single commercial fishery in Canada.

The definition of catchability parameter is the share of the total stock being caught by

[9] For the solution procedure, see appendix 2.

per unit fishing effort. In Table 4 and 8 of TURNER ET AL (2000) they list estimated annual abundance as well as annual catch per unit effort for Lake Erie walleye by gear, management unit, and agency, respectively. We can derive mean catchability parameter by using the function $q = \frac{Y/E}{X}$ to get q for each year and then take the average. These calculations are listed in Table I.

The price per pound for walleye by wholesalers are CAN$2.22 per pound in 2002 in Canada (Morencie et al., 2003), U.S$2.3 (CAN$3.24) in the U.S (Summmerfelt, 2000) based on the exchange rate (U.S$: Can$) 1:1.408. The number of fish is the key metric and price measurement is per thousand fish. [I.E., CAN$ per thousand fish=1000* 3.77lb (average weight) * CAN$ per pound, where 3.77lb is obtained by taking the average of the mean round weight from 1991 to 2000 (TURNER ET AL., 2000).] The prices are CAN$8,386/a thousand fish for Canada and CAN$12,230/a thousand fish for U.S.

Cost information is not available. For the purpose of the present paper, it is assumed that total costs equal 60% of total revenues. This value is based on Kelch (2002), although it is acknowledged that this example involves a shrimp fishery, which may have no relevance for Lake Erie walleye. Thus, in accordance to 60%pY=cE, or, c= 60%p*Y/E where Y/E is given in Table 4 of TURNER ET AL., the cost coefficients standing for the cost of labor, investment and management for one year are calculated to be CAN$552 and CAN$805.28 engaging in 1 unit of effort for Canada and U.S, respectively.

The intrinsic growth rate is defined as "How much a population can grow between successive time periods". According to CBR (2003), which estimated the growth parameter for a generic predator including squawfish, smallmouth bass and walleye, the paper sets the intrinsic growth rate approximately equal to 0.075/year for the 30-year return time. It is assumed that the two nations are identical with respect to discount rate in that Canadians and Americans are similar in terms of their rate of time preference, so that the discount rate, δ, is set equal to the value of 5 percent which approximates the long-run average rate of return on government bonds.

Canada's share of the harvest under cooperation, α, is given the value of 43.3%, as recommended in the Turner et al. (2000) (the allocation of harvest is based on water area and Ontario has 43.3%). Hence, this gives the value of 56.7% as the share of U.S, $1-\alpha$.

Due to the fact that [10]"The Lake Erie walleye stock reached its highest density in 1988 with an estimated 80 to 100 million adult walleye," the estimated value of 150 million is set equal to the approximation of carrying capacity (Pristine or the maximum population size an area can support).

[10] Hartman (2001).

Since no absolute data available for direct use, one must select appropriate maximum effort and initial time. The data search process is the following: First of all, it is seen from Table I and II that abundances of stock are clearly greater than equilibrium biomass X^* both under non-cooperation and cooperation. We can assume E_i^{max} cannot bring the stock down to X^* as fast as possible based on Clark (1980). Secondly, the stock values after year 1988 in Table I show a generally declining trend, which in turn implies that the initial year can be selected from the data-available period 1988-1999. Thirdly, it is indicated from Table 2 - 3 and Figure 2 - 4 in TURNER ET AL. (2000) the total catch and effort are growing from 1975 to1988, falling after 1988 and achieve the highest value in 1988. Finally, the above observation shows that the maximum annul effort are obtained in 1988. The initial year is 1988, and the maximum annul effort for Canada and U.S are set equal to the values of 17,067 kilometers of gill net and 15,216 thousands of angler hours. The initial stock is the number of Lake Erie walleye in 1988, 125,416 thousand. This paper aims to make a general comparison between non-cooperative and cooperative Lake Erie Walleye management, not to decide the specific managing plan and specific equilibrium time. Table I lists known stock levels which are above calculated X^*, which guarantees fish harvesting is on the path indicated by the model. The employed maximum efforts and initial stocks should be able to result in conditions, which are mostly consistent with the underlying model.

Table I. Catchability parameters derived from the Report of Lake Erie Walleye Task

Group for walleye for the period from 1984 -1999

		sport fishery (U.S)		Commercial Fishery (Ontario)	
Year	stock	Catch/effort	Catchability q	catch/effort	Catchability q
1984	119,948.5	0.69	5.75247E-06	0.107	8.91966E-07
1985	92,432.6	0.59	6.38303E-06	0.179	1.93784E-06
1986	90,679.8	0.51	5.62419E-06	0.149	1.63851E-06
1987	90,979.1	0.5	5.49577E-06	0.19	2.08806E-06
1988	125,416.5	0.46	3.66778E-06	0.1779	1.41855E-06
1989	100,198.1	0.45	4.4911E-06	0.158	1.57947E-06
1990	83,755.2	0.34	4.05945E-06	0.119	1.43227E-06
1991	65,136.9	0.27	4.14512E-06	0.116	1.78086E-06
1992	65,172.7	0.34	5.21691E-06	0.106	1.63918E-06
1993	70,886.2	0.4	5.64285E-06	0.105	1.49465E-06
1994	50,682.1	0.31	6.11656E-06	0.101	2.00663E-06
1995	55,600.88	0.31	5.57545E-06	0.092	1.6649E-06
1996	65,780.36	0.44	6.68893E-06	0.095	1.45758E-06
1997	44,766.42	0.28	6.25469E-06	0.111	2.49026E-06
1998	65,324.86	0.48	7.34789E-06	0.079	1.21102E-06
1999	57,868.5	0.29	5.01136E-06	0.083	1.44967E-06
Mean	catchability	Parameter q	**5.47E-06**		**1.64E-06**

Sport CPE (catch/effort) = Number/angler hour

Commercial CPE = 1000 fish /kilometer of gill net

Stock= thousands of fish

*The difference in units between Canada and the U.S. reflects the difference in the units of effort.

5. Results

Tables II and III and Figures 1 and 2 present the results, which are obtained by applying data into the model. With the help of EXCEL, the solutions to the dynamic fishery game are simulated for time periods from initial stage to the point when equilibrium is achieved.

Table II lists the equilibrium solutions under sole ownership, non-cooperation and cooperation, respectively. Once the equilibrium solutions are achieved, the system reaches the steady state and the factors such as biomass, harvest rate and effort will no longer change. Clearly for the scenario of cooperation some different values of β must be tried in order to reach a conclusion about the weight given to Canada's management preferences. β is highly related to those solutions and not exactly known. Regarding different values of the bargaining parameter β (0< β<1), the stock level or biomass increases (decreases) when the policy gives Canada more (less) management preference, i.e., β increases (decreases). Furthermore, notice that harvest rate and discounted profit have the same change direction as biomass; while effort changes conversely. In other words, the higher the stock, the higher the catch amount and discounted rent, but the lower the effort agents put into the fishery.

The above results are not surprising and the proof is verified by directly using the model function derivation. By differentiating the natural production function $F(X) = rX(1-\frac{X}{k})$, it turns out that the first derivative of the net recruiment function with respect to the biomass level $F'(X)$>0 for 0< $X < k/2$, in other words the positive relationship between equilibrium harvest rate and stock occurs if and only if X<k/2. It is clear from Tables II that the stock value under different β is absolutely less than k/2, 75000 thousand, which guarantees the positive relationship between X as well as Y. Notice that given $E^* = \frac{r(1-X^*/k)}{q}$ and predetermined constant harvest share, effort is negatively correspondent with X. Furthermore, it is seen from the optimal present value of profit $PV = \int_0^\infty e^{-\delta}(p-\frac{c}{qX^*})F(X^*)dt$ that present value of

discounted profit will be positively correlated to the stock level if harvest rate has a positive relationship with biomass.

In the single-agent case, only one country exploits the fishery as a sole owner, which can be realized negotiation between the two nations, i.e., Canada exits the fishery and obtains a side payment. Table II indicates the highest discounted rent is achieved by putting lowest effort under U.S' sole ownership where the highest stock level and harvest rate are reached. Therefore, an interesting finding is that, Canada gains smallest discounted rent under sole ownership; conversely if both nations manage the fishery jointly, the higher the weight given to Canada's management preference, the higher profit is made. It should be noted that the extreme cases are not considered as a choice for optimal policy in current paper since it is not really realistic to keep only one country operating the fishery.

We commence the comparison between cooperation and non-cooperation by supposing only 0.433 as β value since it is supposed that if Canada and the U.S. can agree on $\alpha = 0.433$, then they would probably also agree on $\beta = 0.433$. In Table II that the equilibrium biomass level under divided management and unified management are 40,136.58 (since X_1^∞ is above X_2^∞, i.e., 40,136.58>12,037.41), and 49,581.37, respectively. Thus the cooperative management between Canada and the U.S. leads to a relatively higher equilibrium stock, while a lower stock is obtained by both nations' operating under non-cooperation.

From Table II we see that once the system reaches equilibrium state the total harvest for two nations under cooperation achieves the highest level, and, non-cooperation is undesirable. At the steady state, Canada has zero harvest rate under non-cooperation and 1,046 thousand walleye under cooperation, while U.S harvests 2,205 and 1,412 under non-cooperation and cooperation, respectively. Notice that by moving from non-cooperation to cooperation, the U.S is worse off, while Canada is better off by harvesting a positive number of fish instead of having no catch. However, Canada's harvesting amount still takes up a smaller proportion of the total equilibrium catch as indicated in other three managements cases. The lower catch share coefficient for Canada is a factor under cooperation resulting in the low catch, but the key reason is its relatively low catchability, i.e., 1.6E-06<5.14E-06. The average annual catch amount per unit effort in Canada is 109.73 thousand fishes, while 450 thousand fishes in U.S., which directly leads to the less efficiency.

The equilibrium effort levels reported in Table II show that in the equilibrium Canada will not continue harvesting in the fishery, i.e., E=0, as well as, the effort is 10042.36 angler hours for U.S under non-cooperation. Under cooperation, Canada and U.S exploit the fishery by putting effort 13,256.48 angler hours and 5,204.512 kilometer of gill net, respectively. It is seen from the above solutions under non-cooperation and cooperation, for Canada cooperation is undoubtedly preferable, as well as, for U.S, the average catch is higher under cooperation than under non-cooperation.

Main observations about discounted profit made from Table II are as follows: If Canada or U.S operates the fishery under non-cooperation in Lake Erie Walleye exploitation, the discounted rent for the former is 0 and CAN$8.48 billion for the latter. Thus the total discounted profits for both nations is CAN$8.48 billion by summing the above two single values. Under cooperative management, Canada and U.S achieve a total discounted profit CAN$8.97 billion, among which the discounted profit for Canada is CAN$1.04 billion, while CAN$7.93 billion for U.S. Comparing discounted rents, it shows that: the cooperative management causes a total discounted economic rent surplus over non-cooperation (5.8% profit improvement). However, Canada gains a payoff substantially well in excess of its non-cooperative benefit, but U.S is worse off.

Table III and Figure 1 and 2 show the time paths of harvest rate and biomass stock, for different management strategies. Notice that harvest rates and effort levels between the two neighboring nations are independent in the two sole owner management cases, but dependent on each other under non-cooperation and cooperation.

The annual catch levels and discounted rents of each country for different management strategies are reported in Table III. It is seen from the table that cooperation causes U.S to be more productive and profitable in the early period of the game, but once the equilibrium under cooperation is reached, it made more profits by producing more harvests under non-cooperation. This situation changes until non-cooperative equilibrium is achieved. On the other hand, Canada produces lower harvests and profits under cooperation before non-cooperative equilibrium is reached in 2003. After this point it quits the fishery with zero catch and no rent under non-cooperation, while CAN$1.04 billion with the catch of 1,077.93 thousands fishes each year under cooperation. Both under non-cooperation and cooperation, U.S harvests more and made more profits than Canada because of the higher catchability.

The time paths of yearly biomass level are given in Figure 1 by programming the population dynamics in EXCEL spreadsheet. In 1997 the equilibrium is achieved under cooperation; while the time to achieve equilibrium for the non-cooperative case is 2003. The two time paths cross together at around year of 1999.5, before which non-cooperation causes higher stocks, but lower stock thereafter.

Figure 2 illustrates graphically the time path of annual total harvest rates in two management cases. The harvest time path under cooperation would coincide with Y under non-cooperation by year of 1996 and around year of 2003. It is indicated from the Figure that the periods between 1996 and 2003 are the only time when non-cooperation produces the highest harvests. After 2003 fishing period, as expected, non-cooperation would keep producing the lower harvest than cooperation.

The intuition of the results is described as follows: When both nations manage the fishery non-cooperatively, they use maximum efforts to harvest every day in that they have a common knowledge, that is, if they cannot catch a fish now, perhaps the fish will be harvested by its competitive partner tomorrow. Conversely, if both nations jointly regulate the resource, especially with the fixed harvest share, they will believe that even if they let fish escape today, their harvest share cannot be changed, which leads to the better conservation and hence the higher benefits.

However, unfortunately a different β actually leads to different conclusion. Basically, cooperation is more desirable with a higher β. For example, when β=20%, it clearly appears that under cooperation not only is the U.S worse off, but also the total discounted rent is lower than under non-cooperation; while when β=70% or above, cooperation causes the net benefits for both nations to increase and hence a higher total discounted rent.

This result is not unexpected because it can be seen from the non-discounted rent values in Table II. Firstly, I shall derive a time difference rule for the comparison of discounted rents in different scenarios, cooperation is better if and only if $\pi^{Coop} * e^{-0.05 * t^{Coop}} > \pi^{NC} * e^{-0.05 * t^{NC}}$, where π denotes the non-discounted annual rent, the subscript t refers to time to achieve the equilibrium, and the superscripts Coop and NC stand for cooperative and non-cooperative, respectively. Therefore, if β =20%, equilibrium time difference should be greater than 6.43 year, in other words, Canada's Lake Erie walleye fishery harvesting reaches the equilibrium at least 6.43

year later than U.S does, which can guarantee the superiority of cooperation over non-cooperation. If β=90%, the difference is only at least 2.11 year, because higher β leads to higher equilibrium biomass and hence shorter time to achieve it.

Does it mean that the conclusion should depend on the value of β? This paper cannot give an absolute answer to this question. First, the size of the initial stock leads to different results. If the stock size estimate for 1999, 57,868 thousand is employed as the initial stock, the equilibrium time difference is changed from 6 to 4 when β =43.3%, and hence even total discounted profit is lower under cooperation than under non-cooperation, which is different from the result above. However, from the theory, no matter what the initial stock is, the system should always follow the same time path and of course lead to the same result. Second, the trends of total catch and effort are not straight downward as expected in the model, but jump and reach the highest level in the mid-periods, while relatively lower in two sides, which coincides with that for the U.S sport fishery. The trends for Canada' commercial fishery are consistent with the model. It seems that the sport fishery analysis does not really fit to the model.

6. Limitations of the model and the data

Although Canada gains a substantial net benefit from cooperation, the results of U.S' discounted rent and total discounted rent are uncertain, which is probably caused by the following limitations of the model as well as the data. The highly stylized model employed in this paper rested upon many restrictive assumptions. (i) The model is autonomous such as, price, harvesting cost coefficient, discount rate, catchability parameter q and the harvest share α are assumed to be at constant levels through time. (ii) Effort is the only control variable, without which the optimization problem would be more complicated and hence the mathematical approach would be more difficult to resolve. [11]For example if α is time variant, it is no longer treated as a parameter but control variable. [12]Investment rate is also possible to be used as a control variable, when the assumption of non-malleable capital is relaxed (capital variable is always eliminated from the model due to this assumption). (iii) Linearity is a simplifying assumption which the model highly rests on, [13]whose realization is by assuming that infinite elastic demand for fish, linear cost function in effort and linear catch function. Relaxing this assumption will undoubtedly increase the complexity of the optimization problem. (iv) So far, multiple equilibria have been ignored, but if $\beta + 2(1-\alpha)(1-2\beta)$ (Munro, 1979), or, $\beta > 0.89$ in this paper, this problem will arise since the assumption, linearity of the model in harvest, Y, no longer holds. (v) Another key assumption of the model is that the agents in the two fisheries economies seek to optimize the present value of discounted social rents, but nations don't always behave this way. As far as Canada is concerned, the fisheries managed by the government and the social and political problems are the real concern of politicians and bureaucrats managing Canada's fisheries. For example in the [14]"1970 Economic

[11] Munro (1990), pp. 416.
[12] Clark and Munro (1975), pp. 92-94.
[13] Clark and Munro (1975).
[14] Brubaker (Winter 1998/99).

Policy for the Fisheries explained that the government's primary objective was to maximize employment". Furthermore, it is also problematic to express U.S.'s object of social utility maximization to be maximizing its discounted rent, since the U.S. walleye fishery is a sport fishery. Anglers harvest fish for fun and take them home rather than selling them. Thus the payoffs made from a sport fishery are no longer the price earned from selling fish in commercial fishery and hence the objective of rent maximization no longer holds. (vi) It is usually assumed that a population was at the carrying capacity before being exploited, but the value couldn't be found, so only an approximation is adopted in terms of the highest density in decades. (vii) The average prices and costs employed here would change since they are computed from small amounts of data. (viii) There are errors around the estimates by TURNER ET AL. (2000) which the paper is primarily based on. (ix) Only commercial fishing in Canada is considered in current paper, but there is both sport and commercial fishing in Canada.

7. Conclusion

In this paper we have studied a trans-boundary resource. The Lake Erie Walleye fishery is an optimal management problem subject to Canada and the U.S joint ownership. The fishery model was employed, and then Nash equilibrium solutions were derived by the application of the maximum principle as well as game theory to this dynamic fishery game.

Reviewing previous discussion of each case and summarizing the comparative analysis of the solutions-given the assumptions set in this model and available data-the following has been obtained: Two management strategies between the co-owners of the fishery were considered, divided management (non-cooperation) and joint management (cooperation). In the single-agent case where the fishery is managed by the U.S as a sole owner, the highest discounted profits are achieved; otherwise, the least discounted profits are obtained in the opposite extreme. Since it is more realistic to keep both nations in exploiting the resource, the single-agent case is ignored. In the non-cooperative case there is no difficulty, where single solution is derived, that is, Canada has no access is denied in equilibrium, but more complicated analysis was presented in cooperative case, where harvest shares are predetermined. Under cooperation, considering different values of the bargaining parameter β, both single discounted profits and total discounted profits increase when the policy gives Canada more management preference, i.e., β increases. Cooperation causes net benefit in excess of the zero economic gain from non-cooperation and hence is undoubtedly a preferable strategy in terms of Canada, but does not always produce higher discounted rent for U.S than under non-cooperation based on different values of β. Among the selected value of β, both U.S' discounted rent and total discounted rent are lower under cooperation if β=20%; 40% and 60% of β still causes the lower discounted profit for U.S, but higher total discounted rent; using the value of 70% and above, cooperation is the optimal policy. However, cooperation definitely has powerful walleye conservation benefits due to the higher equilibrium biomass than under non-cooperation. Therefore, regarding that whether this result is consistent with the findings of previous studies discussed in introduction section, the answer depends on which equilibrium is considered.

The uncertainty of the conclusion is possibly caused from the limitations of the model and data, among which some are hard to solve, such as the errors in TURNER ET AL. (2000), but some can really be reached to improve by further study and possible extensions, so that the results are able to be confirmed with confidence. The greatest scope for further research is that some assumptions should be relaxed, such as the autonomy, linearity of the model, the singularity of control variable, as well as the objective of discounted rent maximization. Secondly, uncertainty should be introduced. Furthermore, consider the case in which the problem of multiple equilibria is confronted. Finally, data collection can be improved such as the carrying capacity and average prices, which should be based on larger amount of data.

Table II. Reports equilibrium solutions to country 1(Cana
and sole ownership

	X	B	Y	Y1	Y2
sole owner Canada	57481.13	100%	2659.045	2659.045	
sole owner U.S	44533.66	0	2348.401	0	2348.4
non-cooperation	40136.58		2204.771	0	2204.7
cooperation	46811.69	20%	2415.21	1045.786	1369.4
	49581.37	43%	2489.447	1077.93	1411.5
	51685.93	60%	2540.727	1100.135	1440.5
	53010.63	70%	2570.734	1113.128	1457.6
	54394.74	80%	2600.212	1125.892	1474.
	55849.17	90%	2629.123	1138.41	1490.7

units of X and Y are thousands of fihshes
unit of E1 is kilometer: of gill net
unit of E2 is thousand of angler hours
unit of PV is billions of Canadian dollars

Table III	Time path rent	of harvest under	rate and different	discounted scenarios
	non-cooperion		cooperation	
Year	Y1	Y2	Y1	Y2
1988	3510.393	10438.61	2673.88	13720.57
1989	3163.111	9405.918	2357.217	12095.66
1990	2869.808	8533.746	2095.562	10753.02
1991	2618.739	7787.158	1875.81	9625.402
1992	2401.38	7140.812	1688.796	8665.636
1993	2211.386	6575.841	1527.787	7839.582
1994	2043.929	6077.887	1387.918	7121.869
1995	1895.267	5635.822	1265.407	6493.224
1996	1762.451	5240.877	1157.346	5938.725
1997	1642.124	4886.042	1077.93	1411.516
1998	1535.379	4565.647	1077.93	1411.516
1999	1437.654	4275.049	1077.93	1411.516
2000	1348.659	4010.411	1077.93	1411.516
2001	1267.317	3768.53	1077.93	1411.516
2002	1192.722	3546.713	1077.93	1411.516
2003	0	2204.77	1077.93	1411.516
2004	0	2204.77	1077.93	1411.516
2005	0	2204.77	1077.93	1411.516
	non-cooperation		cooperation	
Year	PV1	PV2	PV1	PV2
1988	20.02	1.15E+02	15.25	1.51E+02
1989	16.27	97.39	11.98	1.25E+02
1990	13.25	82.99	9.41	1.04E+02
1991	10.79	71.09	7.36	87.01
1992	8.77	61.15	5.72	73.16
1993	7.11	52.78	4.39	61.72
1994	5.72	45.7	3.31	52.21
1995	4.56	39.66	2.42	44.25
1996	3.59	34.49	1.7	37.54
1997	2.78	30.03	1.04	7.93
1998	2.1	26.2	1.04	7.93
1999	1.52	22.87	1.04	7.93
2000	1.04	19.98	1.04	7.93
2001	0.63	17.46	1.04	7.93
2002	0.29	15.26	1.04	7.93
2003	0	8.48	1.04	7.93
2004	0	8.48	1.04	7.93
2005	0	8.48	1.04	7.93

unit of PV is billions of Canadian dollars
unit of Y is thousands of fishes

Figure 1. Total stock time pathes under non-cooperation and cooperation

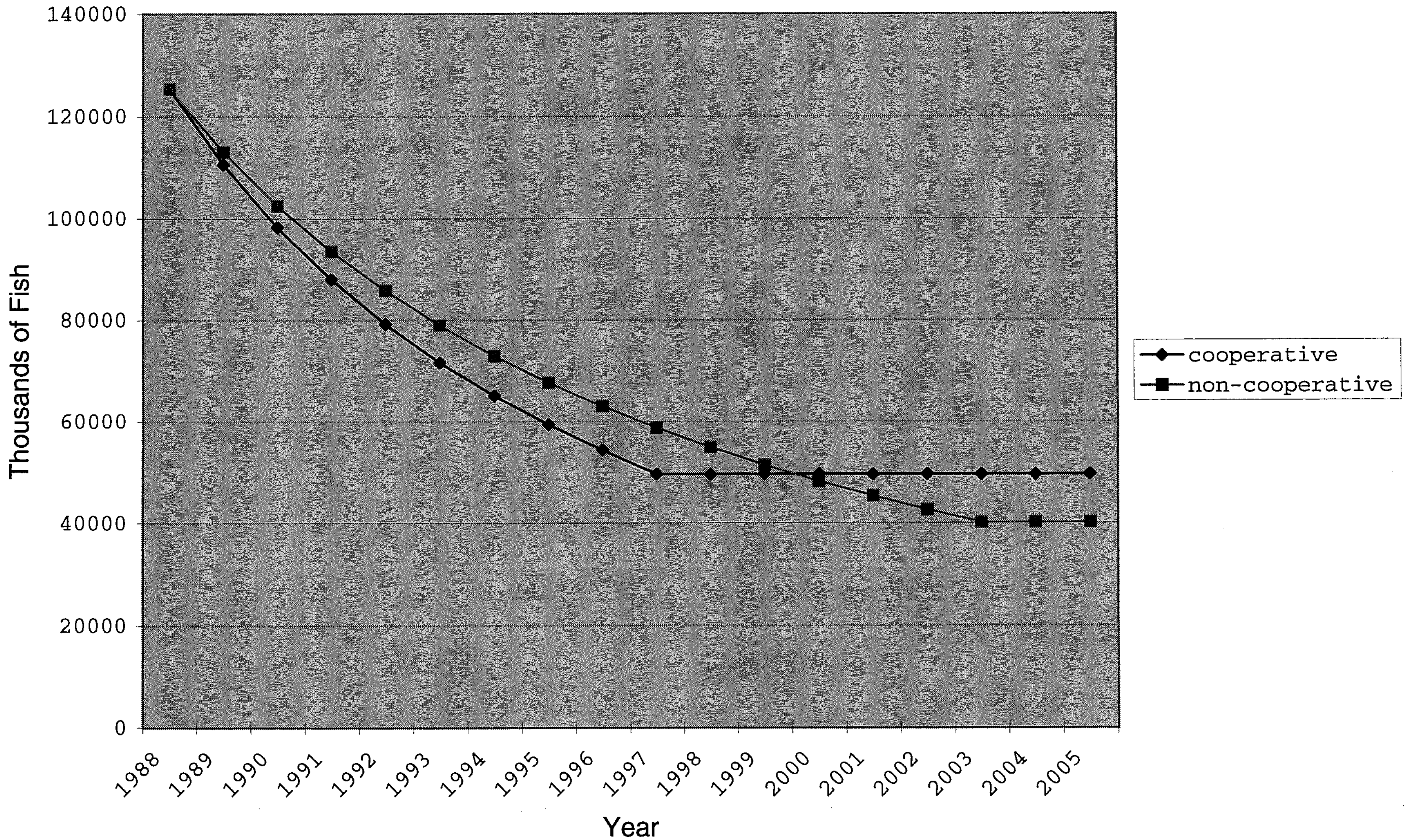
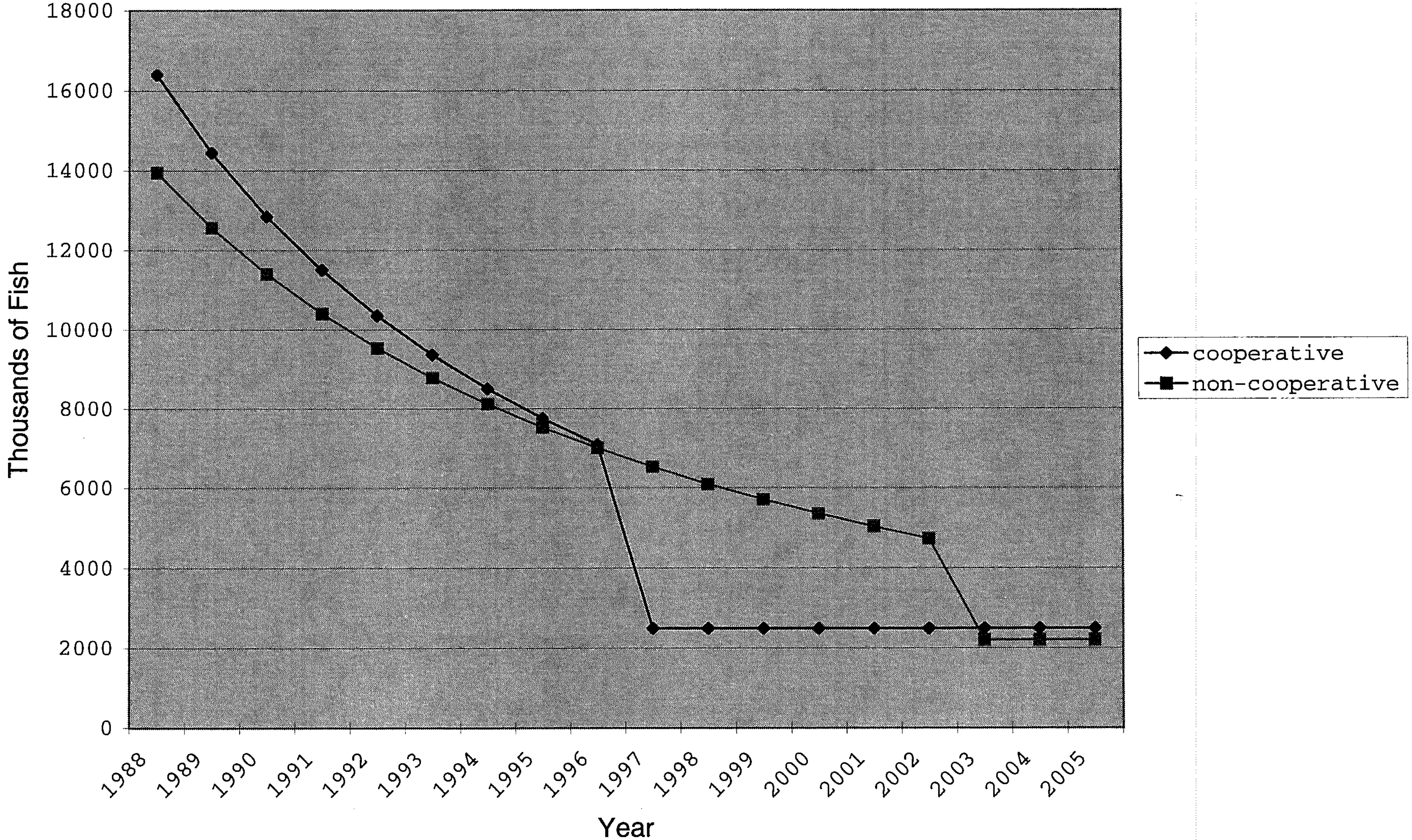


Figure 2. Total harvest time path under non-coopertion and cooperation



Appendix: The Algorithm

1 The problem-specific solution procedure for non-cooperative case

(1) Max $PV_i = \int_0^{\infty} (p_i - \frac{c_i}{q_i X}) Y_i(t) e^{-\delta t} dt$

Subject to

(2) $\dot{X} = F(X(t)) - \sum_{i=1}^{2} Y_i(t)$ where $F(X) = rX(1 - \frac{X}{k})$

and

(3) X_0 is given, $X(t) \geq 0$ for all $t \geq 0$

Applying maximum principle can easily solve it. At each instant, the defined Hamiltonian for player i is as follows:

(4) $H_i = (p_i - \frac{c_i}{q_i X}) Y_i(t) + \mu \left[F(X) - \sum_{i-1}^{2} Y_i \right]$

measuring the daily flow of rents.

Since objective equation (1) is and state function (2) are linear in the control variable $Y_i(t)$, [15]the coefficient of Y is defined as $\sigma(t)$ where $\sigma(t) = p_i - \frac{c_i}{q_i X_i^*} - \mu$. In order to find the singular solution, we must have singular control

(5) $\sigma(t) = 0$

which yields the following expression for costate variable μ

(6) $\mu(t) = p_i - \frac{c_i}{q_i X_i^*(t)}$

μ can also be defined as the shadow price of stock X at time t and along the optimal trajectory. Furthermore the shadow price μ obeys the following adjoint

[15] Clark and Munro (1975).

equation:

(7) $\dot{\mu} - \delta\mu = -\frac{\partial H_i}{\partial X} = -\frac{c_i Y_i}{q_i X^2} - \mu F'(X)$

which is a necessary condition for a long run equilibrium. Next, by differentiating the equation (6), we obtain:

(8) $\dot{\mu} = \frac{c_i}{q_i X_i^{*2}} \dot{X}$

Note we also have the steady-state equation:

(9) $\dot{X} = F(X_i^*) - Y_i(t) = 0$

Using equation (6) (8) and (9) in (7), we obtain:

(10) $\frac{c_i}{q_i X_i^{*2}}\left[F(X_i^*) - Y_i\right] - \delta\left[p_i - \frac{c_i}{q_i X_i^*}\right] = -\frac{c_i Y_i}{q_i X_i^{*2}} - \left[p_i - \frac{c_i}{q_i X_i^*}\right] F'(X_i^*)$

It follows from simplifying (10) that

(11) $\delta = F'(X_i^*) + \frac{c_i F(X_i^*)}{X_i^*(p_i q_i X_i^* - c_i)}$

The last equation is a golden-rule for the non-cooperative game, from which the constant optimal stock level can be solved in a straightforward manner. Hence, we can use equation $Y^* = F(X^*)$ to carry out the optimal harvest rate. Also the optimal control variable E^* can be directly known from its equational expression, $E^* = \frac{r(1 - X/k)}{q}$.

2. The problem-specific solution procedure for cooperative case

We again turn to the optimization process to derive the cooperative golden rule and hence achieve optimal resolutions.

(1) Max

$$PV = \beta\int_0^\infty \left[(p_1 q_1 X - c_1)\frac{\alpha Y(t)}{q_1 X_t}\right] e^{-\delta t} dt + (1-\beta)\int_0^\infty \left[(p_1 q_1 X - c_1)\frac{(1-\alpha)Y(t)}{q_1 X_t}\right] e^{-\delta_2 t} dt$$

<u>Subject to:</u>

(2) $\dot{X} = F(X) - Y$

and

(3) X_0 is given, $X(t) \geq 0$ for all $t \geq 0$

We know at time t the Hamiltonian for the present problem is given as follows:

(4) $H = \alpha\beta e^{-\delta t}(p_1 - \frac{c_1}{q_1 X})Y(t) + (1-\beta)(1-\alpha)e^{-\delta_2 t}(p_2 - \frac{c_2}{q_2 X})Y(t) + \mu[F(X) - Y]$

For the convenience of derivation, we can simplify the above equation by defining:

(5) $M_1(t) = \alpha\beta e^{-\delta t}$ and

$M_2(t) = (1-\beta)(1-\alpha)e^{-\delta_2 t}$

Hence (4) can be rewritten as:

(6) $H = M_1(p_1 - \frac{c_1}{q_1 X})Y(t) + M_2(p_2 - \frac{c_2}{q_2 X})Y(t) + \mu[F(X) - Y]$

The singular control is:

(7) $\sigma(t) = (p_1 - \frac{c_1}{q_1 X})M_1 + (p_2 - \frac{c_2}{q_2 X})M_2 - \mu = 0$

The adjoint equation is as follows:

(8) $\dot{\mu} = -\frac{\partial H}{\partial X} = -\frac{c_1 Y(t)}{q_1 X^2} M_1 - \frac{c_2 Y(t)}{q_2 X^2} M_2 - \mu F'(X)$

From equation (7), the costate variable μ can be obtained as follows:

(9) $\mu(t) = (p_1 - \frac{c_1}{q_1 X(t)})M_1 + (p_2 - \frac{c_2}{q_2 X(t)})M_2$

Differentiating the above function, we obtain:

$$(10)\quad \dot{\mu} = \frac{c_1}{q_1 X^2}\dot{X}M_1 + (p_1 - \frac{c_1}{q_1 X})M_1' + \frac{c_2}{q_2 X^2}\dot{X}M_2 + (p_2 - \frac{c_2}{q_2 X})M'_2$$

Substituting (9) and (10) into adjoint equation (8) and simplifying it, we obtain:

$$(11)\quad -\frac{M_1'(p_1 - \frac{c_1}{q_1 X}) + M_2'(p_2 - \frac{c_2}{q_2 X})}{M_1(p_1 - \frac{c_1}{q_1 X}) + M_2(p_2 - \frac{c_2}{q_2 X})} = F'(X) + \frac{\frac{c_1}{q_1 X^2}M_1 + \frac{c_2}{q_2 X^2}M_2}{M_1(p_1 - \frac{c_1}{q_1 X}) + M_2(p_2 - \frac{c_2}{q_2 X})}F(X)$$

Replacing M with (5) we can rewrite (11) as follows:

$$(12)\quad \frac{\delta_1 e^{-\delta_1 t}\alpha\beta(p_1 - \frac{c_1}{q_1 X}) + \delta_2 e^{-\delta_2 t}(1-\beta)(1-\alpha)(p_2 - \frac{c_2}{q_2 X})}{e^{-\delta_1 t}\alpha\beta(p_1 - \frac{c_1}{q_1 X}) + e^{-\delta_2 t}(1-\beta)(1-\alpha)(p_2 - \frac{c_2}{q_2 X})}$$

$$= F'(X) + \frac{c_1 q_2 \alpha\beta e^{-\delta_1 t} + c_2 q_1 (1-\alpha)(1-\beta)e^{-\delta_2 t}}{(p_1 q_1 X - c_1)q_2 \alpha\beta e^{-\delta_1 t} + (p_2 q_2 X - c_2)q_1(1-\alpha)(1-\beta)e^{-\delta_2 t}}\frac{F(X)}{X}$$

Which is the modified golden rule designed for the two-agent cooperative game. The LHS of (12) can be viewed as a new discount rate δ_3 under cooperation which is [16]"a complicated weight average" of δ_1 and δ_2. Notice that if we can obtain the limit to the above equation when t tends to infinity, optimal stock will be derived easily and hence the equilibrium values of harvest rate as well as effort.

It appears that the above result is different from Munro (1991), which is primarily due to the difference between the model employed in current paper and Munro's – specifically he assumes everything identical between the two countries except for the discount rate.

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[16] Munro (1991), pp. 97.

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