OPTIMAL MANAGEMENT OF A TRANSBOUNDARY FISHERY WITH SPECIFIC REFERENCE TO THE PACIFIC SALMON

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For My Parents

CHAPTER 1

INTRODUCTION

1.1 Introducing the Problem

Managing a common property resource, especially one jointly owned by two nations, is a formidable problem as it involves both incentives to cooperate and incentives to cheat. Often conflicts flare up, followed by efforts of reconciliation, which are interrupted again by new conflicts. A classic example of this is the Pacific salmon fishery, which is jointly harvested by the U.S.A and Canada. To understand the nature of this conflict, and to make policy recommendations, a game-theoretic approach is developed in this thesis. Before doing so, it is essential to describe the nature of the fishing activities and the context in which the disputes arise.

Fishing is a complicated activity involving interactions between naturally produced fish stocks and human beings' fishing effort. It is beset with problems associated with the lack of well-defined property rights. This is caused mainly by the special characteristics of the fishery resource. Unlike other renewable resources, fish growth function are quite often poorly understood. This lack of knowledge makes effective control difficult by human beings. In addition, fish are mobile, leading to problems associated with transboundary resources. In many instances, fish are exploited under conditions of "open access". Under open access, no management regime exists to regulate fishers' activities, therefore, over-exploitation is a likely outcome. This results in the depletion of the stock, if the fish stock has a high commercial value or if the growth rate of the stock is low relative to the harvesting rate.

Exploitation under "open access" generates production externalities: fishers have little incentive to restrain their harvesting activities, since if any individual exercises restraint, the future payoff will accrue to all fishers and not just to himself. They would all take what they could profitably catch before others could do likewise. This results in a smaller stock in the future, which may raise future harvesting cost. In addition to this kind of externality, there is also input inefficiency in harvesting effort under open access situations. Excessive amounts of effort are used to ensure the "first capture", since under open access a fish becomes the property of the first individual who captures it. Moreover, since no fisher has an incentive to preserve the stock, in the long run, it is likely to fall below the level that ensures the maximum sustainable yield[1] . In some extreme cases, the resource stock may become depleted.

Neoclassical economists normally regard the existence of private property rights as the most efficient regime for the allocation of resources[2]. However, to endow a single person or firm with exclusive rights for the exploitation of a fishery resource would result in monopoly. In the case of natural resources, such as fisheries, many people would argue that the creation of such a monopoly would constitute a vio-

[1] The "maximum sustainable yield" stock level is a concept in biology. For economists, this level is not necessarily the long-run optimum, because discounting would tend to favor a smaller stock in the steady state.

[2] This belief is based on the assumption of perfect information and rational decision making.

lation of commonly accepted equity principles. Moreover, because of the special nature of the fish stock, it is hardly possible to trace out each private fish stock before capture. In the case of the Pacific salmon, although Americans and Canadians know the origins (or breeding locations) of various salmon species, because of the intermingling characteristics of the salmon, it is impossible to distinguish a Canadian salmon from an American salmon before they are caught. These important difficulties prevent the private property rights regime from being a main regime in the fisheries.

It has also been shown[3] that even under the private property rights regime resource depletion is still possible. This occurs when the growth rate of the stock is less than the rate of the time preference of the owner who is well informed and manages this resource carefully. While depletion may be privately optimal in some cases, it may be argued that from society's point of view the extinction of a species may bring with it the irreversible loss of potential benefits that society may value over and above the market value of a fish stock.

The international agreement on the 200-mile EEZ (Exclusive Economic Zone) and EFJ (Exclusive Fishery Jurisdiction) changed the exploitation regime of most fishery resources from an open access property rights regime to a state-owned property rights regime. Under this regime, it was believed that several problems could be mitigated: no investment, over-exploitation leading to resource depletion, and production at inefficient level due to no restriction on entry and no regulation

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[3] See, for example, Talbot Page (1977).

on fishing effort, could be eliminated. This is done by developing institutions and rules that regulate harvesting activities. This regime enables government to apply management policies to achieve certain objectives. The governmental agencies[4], according to the "social objectives", set up targets and apply relevant policies to regulate the fishing activities in order to achieve the optimal situation. The objectives usually include MSY[5] or later the OSY[6] . The management policies normally make use of regulatory methods such as:

(1) Closed seasons or areas. In order to protect the stock during a special season, i.e., spawning, or special closing areas.

(2) Gear restrictions. This tends to mitigate against excessive harvesting, by increasing the harvesting cost, artificially generating economic inefficiency, and ensures some escape of the fish stock to restore the species.

(3) Limited entry. This policy is used to avoid the unnecessary economic waste in harvesting effort.

(4) Catch quota. If it is the only measure, every fisher will want to achieve his quota as soon as possible. This will shorten the fishing season and may lead to some coordination failure, such as flooding the fish market with product, influencing the market price and requiring relevant storage facilities thus increasing the fish price,

[4] Under the state-owned property rights regime, the resources may be managed directly by governmental agencies or by some institutions which are responsible to the government.

[5] Maximum sustainable yield is achieved at the population level at which the growth rate of the stock population is maximized. It usually lies between 40% – 60% of the environmental carrying capacity.

[6] Optimal sustainable yield, which depends upon what objective is to be optimized.

etc[7].

Two economic instruments which economists tend to advocate are a landing tax and fishing quota. Though regarded as more rational management policies, they have some unavoidable difficulties because of inadequate information and the high costs of administration and enforcement. If a tax is levied on the harvesting activity, firms will have a strong incentive to avoid this tax by landing their catch away from the taxing range. If the tax is high enough to halt some activities, it will create unemployment, fishing effort will fall and therefore reduce government revenue. In many cases fishing communities have political power which may prevent this policy from being adopted or implemented. If a tax is put on effort, firms will substitute their input factors to avoid this tax, which makes the administration very costly because the administrative agency would have to keep track of every effort change unless all forms of efforts are taxed. By trying to discover every item to be taxed each year, the government may end up spending more than it could collect in tax.

The quota instrument functions as a kind of private property right to a specified amount of fish. If the government is fully informed about the sizes of various stocks and how they will develop over time, the quota could lead to an optimal harvest level. But it can lead to economic inefficiency. If it fails to limit entry to the fishing industry, entry will result in excessive amounts of effort and therefore reduce the economic returns to production.

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[7] Jon M. Conrad,1995, pp. 429.

Resource degradation under state property rights regime would occur when there is: (1) insufficient management by the authority to control the behavior of the users, for example, when there is a lack of knowledge about the optimal use of the resource, such as the lack of biological knowledge, the fish growth function, etc., and (2) lack of strong enforcement, because of a shortage of funds or other reasons, such as a lack of political will.

The EEZ and the EFJ solved many of the problems which occured with the open access regime. In particular, it reduced the conflicts between coastal countries and distant water countries. However, problems still arise with resource degradation and over-exploitation.

The over-exploitation problems are more acute when the fish stocks are shared by two or more countries. Because of the mobile nature of the fish resource, most major stocks migrate between jurisdictions. Many species of fish migrate over long distance, traveling in schools for feeding, spawning, and it is not uncommon that fish eggs are in one nation's jurisdiction area and the adults live in another country's area. When two or more nations are involved in exploiting the same stock, it is widely accepted that "game theory" should be used to understand their behavior. When countries jointly own the same fish stock, they could reach an agreement and behave cooperatively. This jointly owned stock would be managed under a common property rights regime in which the equal right co-owners set up institutions which act as an authority system to regulate its members' behavior. In game theory terms, this is a cooperative game. By means of reaching agreement in the form of a treaty, new institutional organization, the countries involved could be made better off and the fish stock could attain a sustained development level which in turn would benefit all parties. When the joint owners fail to reach an appropriate agreement, conflicts between them, such as disputes on the property rights and the competition on harvesting, will put the stock in danger and cause inefficiency in fishery production. This situation is a classic example of a non-cooperative game. Each of the joint users of the transboundary fish resources would adopt a strategy of attempting to improve their individual payoff by trying to capture as much as their private interest dictates. As a consequence, over-exploitation of the resource is inevitable. In the long run, all the participants will be worse off from this depletion.

It is well recognized that for a jointly owned fish resource, cooperation is the only way to achieve sustainable development from the point of view of the co-owners. Jointly owned fishery resources impose the requirements of setting up a workable institution and management regime which consist of effective policies and acceptable rules. In many instances, common property rights regimes have turned out to be effective in managing resources on a sustained-yield basis. Rules of sharing and effective management can reduce the incentives to deplete the resource for individual gain. Examples include the Alpine grazing land in Switzerland, and underground water pools (Ciriacy and Bishop, 1975).

On the other hand, resource over-exploitation or even depletion under the common property rights regime would occur when the authority system fails to ensure the complete compliance of the co-owners. This can be due to the characteristics of the resource or due to the capability of the authority system. Currently, there is no powerful supra-national body that can definitely design and enforce a fair agreement on exploitation and distribution of gains. This is why disputes often flare up between nations which share a transboundary fish stock. A recent example of this is the dispute between the U.S. and Canada on the Pacific salmon fishery.

Common property rights regimes have an "intrinsic" disadvantage as compared to private property rights regimes. This is because the resource is owned equally by all the members. As a result, this regime is more vulnerable to changes in circumstances than other property rights regimes. When there are changes in environmental or economic factors, such as market prices or people's taste, each of the co-equal owners has more incentive to violate the rules and over-exploit the resource. This is because one party to the agreement may believe that if one does not exploit the resource, other owners will.

While cooperation is difficult, nations do perceive the benefits of cooperation. These benefits include a common interest in ensuring a long term yield of the resource and the realization that the payoffs from a cooperative game (if cooperation is achieved) are greater than payoffs from non-cooperation. They also realize that institutions must be designed in order to rationally manage a jointly owned fish stock. These institutions must develop effective management policies to monitor harvesting activities, punish violations, distribute benefits and achieve the targeted objectives.

In view of the gains from cooperation, and the difficulties of achieving cooperation, economists need to analyse the incentive structure and the behavior pattern of the co-owners of the resource. This will provide insight into the nature of possible conflicts and to make recommendations concerning effective management policies.

1.2 Game Theory and its Applications in the Fishery

Competition for scarce resources creates all the necessary ingredients for an interactive setting, called a "game", in which people have to take their rivals' reactions into account. Moreover, if one accepts the basic assumption of neoclassical economics that in making economic decisions people act rationally, the study of rational interactions (strategic interactions) between groups of people become necessary. Game theory (which was formalized by von Neumann and Morgenstern in 1944) has become an increasingly important approach for analysis in the social sciences, because (1) it provides a unifying framework for economic and political analysis, and (2) it structures the process of modeling economic behavior (Eichberger, 1993). In 1994, the Nobel Prize in Economics was awarded to Nash, Harranyi and Selten for their contributions to game theory. This indicates the widespread recognition of the importance of this theory.

For fishery resources, exploitation behavior often displays strategic interactions at any production level. When it is at the national level, strategic interactions and rational management become all the more crucial. The history of Pacific salmon resources and the development of the Pacific Salmon Treaty between the United States and Canada represents an almost classic game theory case.

1.3 History of The Pacific Salmon Treaty: A case study in applied game theory

The Pacific salmon, a generic name for various salmon species that are commercially harvested along the Pacific northwest coast (see Figure 1.1), is an important biological and economic resource. Because of its special life pattern, this resource is jointly owned by the U.S. and Canada. The U. S. and Canada have been alternatively competitive and cooperative in their management of this valuable natural resource.

The recognition of the need for cooperative exploitation of the Pacific salmon fishery started early this century. The initial attempts at cooperation management focused on the Fraser Rivers salmon species (sockeye and pinks) in 1908. Further attempts at cooperation were made, as the effects of non-cooperation on the fishing resource became severe. In 1930, a treaty, called "Protection, Preservation and Extension of the Sockeye Salmon Fisheries in the Fraser River", was signed.

Under this treaty, the stock was to be managed by an international Pacific Salmon Fisheries Commission in which the U.S. and Canada were to be equally represented. The division of economic returns from this fishery was determined by a seemingly equitable formula: the two countries were to share equally the cost of the management and conservation of the stock, and the allowable harvests were to be divided equally between the two countries.

For the first twenty five years the treaty worked. It worked well as a conservation device and the fish stock increased. Under this treaty, the fishery can be viewed as a simple two player game between Washington/Oregon states (U.S) and

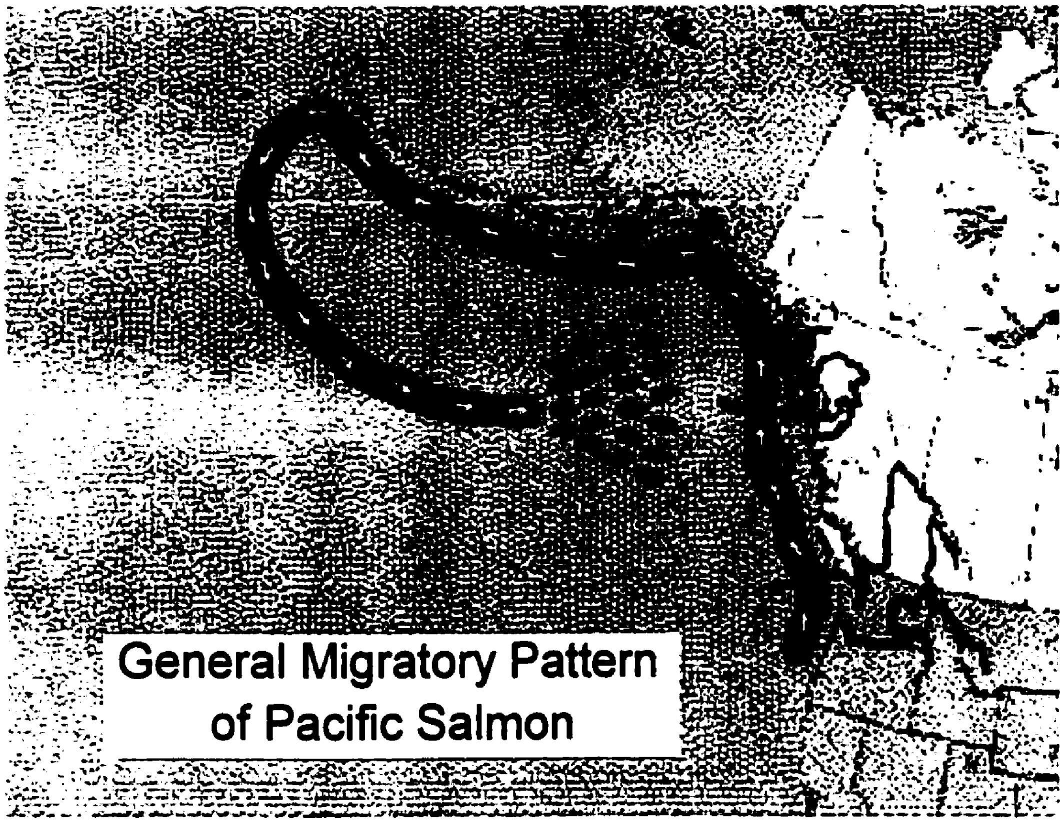

Figure 1.1

Source: Canada (1997), Department of Fisheries and Oceans,
The Pacific Salmon Treaty

British Columbia (Canada). The cooperative surplus was obvious and substantial and each player enjoyed a payoff well in excess of its non-cooperative payoff.

By the early 1960s, British Columbia's fishing industry began to argue that the share of net benefits was unfair because, although the harvest and direct costs of management were shared equally, the indirect costs, such as the foregone power developments were borne solely by the Canadian side. Thess indirect costs were due to dam construction that took into consideration the breeding course of the salmon and the pollution control programs on the rivers in which the salmon resources spawned. Thus, Canada argued that it absorbed more of the cost of salmon management and bargained for a more "equitable" division of the net benefits.

Because salmon species intermingle as they migrate in school across jurisdictions, it is impossible for fishermen to separate them, when harvesting, by country of origin (see Figure 1.2). As a result, interception[8] is inevitable. Thus the "allocation" problem made the negotiations more complicated. Since the 1970s, the two countries' negotiations tried to include all transboundary salmon fishery resources. This has resulted in complex negotiations.

The renewed (common property) management regime has two basic objectives: (1) minimizing interception while at the same time not disrupting "existing" fisheries, and (2) achieving a mutually acceptable division of the benefits[9].

[8] This term means that some fish originating from Canada's rivers will be caught by Americans and that some American fish will be caught by Canadians.

[9] Pacific Salmon Treaty, 1985.

Figure 1.2

Source: Canada (1997), Department of Fisheries and Oceans,
The Pacific Salmon Treaty

The measurement problem turned out to be very difficult to handle but has to be solved before the second objective could be reached. Ongoing disputes have arisen from the interception measurement problem (see Figure 1.3) which threatens the negotiation with collapse (Huppert,1995).

The Treaty signed in 1985 was hailed as "a peace treaty memorializing the end of the Pacific salmon war"(Jensen,1986). It established the Pacific Salmon Commission (PSC). The PSC is supposed to act as a management authority responsible for the conservation of Pacific salmon and the allocation of harvests to the joint owners of this resource. During the first few years, the PSC had several accomplishments, but since 1993, the PSC has been at an impasse and has failed to reach decisions on fishing regulations. As a consequence, each country has applied management rules independently. The increasing tension resulted in a breakdown of negotiations. Disagreements arose because (1) the perception of the "equity" principle changed, and (2) the rough balance, in the form "fish to fish[10] ", was shattered. This rough balance ignores the variations in species values, market prices and fish size. The dispute is a classic example of a cooperative game that degenerates into a non-cooperative game.

Non-cooperation results in inefficient outcomes, typical of the "Prisoner's Dilemma" game. The inefficiencies take two forms:

(1) A "fish war", characterized by deliberate over-exploitation of the stock by one player (at the national level) in order to reduce the other country's harvesting

[10] This means that both countries could count the intercepted fish to ensure that each country get an equal number.

Total Salmon Interceptions

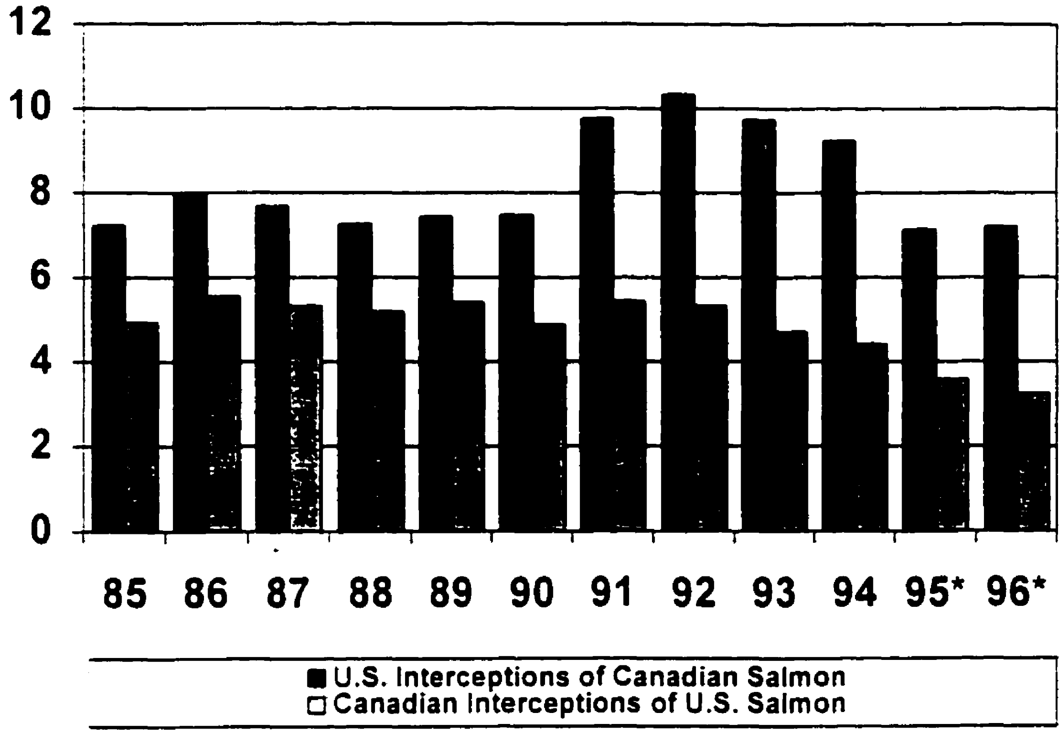

Figure 1.3

Source: Canada (1997), Department of Fisheries and Oceans,
The Pacific Salmon Treaty

opportunities. For example, in the 1970s and 1980s, one of the salmon species, chinook, was severely affected.

(2) "Non-investment". Both players deliberately refrain from implementing investment, such as enhancement facilities for the stock because each party fears that the benefit from this investment would accrue to its rival fishers, rather than its own (Munro and Stokes, 1989).

When Canada found itself in a situation in which its harvest of the stock was falling, the payoffs from the cooperation were declining (both in terms of species value and market prices). In order to cooperate, Canada was required to reduce its harvest even further. While at the same time, the interception by Alaskan fishers was increasing. In 1994, the cooperative behavior of the past reverted into competitive behavior, thereby igniting a "fish war". Canadian fishers fished aggressively in order to prevent the stock from being harvested by American fishers.

In 1997, the negotiation was restarted with the promise of a "breakthrough". However, negotiation broke down again in May and collapsed by June. The impasse in negotiation revolved around the equitable harvest shares of the salmon stock.

The Pacific salmon fishery is a complex game because of the different institutional structures in the two countries. In Canada, the fishery resource is managed solely by the federal government. If the U.S federal government managed the resource, then this would be a relatively simple two player game. But, in the U.S system, the state governments have substantial powers in fishery resource management. In the case of the Pacific salmon fishery, there are two main "players" in the U.S., Washington/Oregon and Alaska. In this game, Alaska has little to gain from cooperation because it faces very limited interception of its salmon while it could intercept significant amounts of salmon from Washington/Oregon and British Columbia. In the Treaty, Alaska was being asked to reduce its interceptions to help rebuild the stock. The benefits from this re-building would accrue to Washington/Oregon and British Columbia fishers.

In fact, the American side may be considered as a coalition, because a consensus must be reached between Washington/Oregon and Alaska before arriving at a consensus with Canada (Miller, 1996; Schmidt, 1996). As a result, the salmon fishery is a complex three-player game.

1.4 Problem Statement

The purpose of this thesis is to provide a theoretical framework for analysing the problems of conflicts and cooperation in the exploitation of a transboundary fish stock. A theoretical model is developed to capture the essential features of strategic interactions in a dynamic context. It is hoped that the model sheds light on the actual conflict concerning the Pacific salmon disputes between U.S. and Canada.

1.5 Objective

This thesis explores some theoretical aspects of cooperation and non-cooperation in the joint exploitation of a transboundary fish resource among three players and applies the theory to the Pacific salmon case. Game theory is applied to a dynamic model to investigate and compare the cooperative and non-cooperative outcomes at first in a game between two players, and then with a game involving three players. In the three-player case, the possibility of a subcoalition formed by two players is also analysed. Numerical analyses are carried out to study the sensitivity of the equilibrium outcomes with respect to changes in the discount rate, the product price, and the cost structures.

1.6 Organization of the Research

A literature review of the theoretical works on the transboundary fishery management is presented in Chapter 2. In Chapter 3, several related models are developed and analysed. At first, the simple two-player game is considered in detail so that the basic intuition of the cooperative and non-cooperative games can be obtained. This is followed by a three-player game model which allows the exploration of more complicated issues such as the formation of a subcoalition. Both theoretical and numerical analyses are performed. In Chapter 4, conclusions are drawn on the usefulness of the models and their applicability to the Pacific salmon dispute. Indications of possible future research are also provided.

CHAPTER 2

LITERATURE REVIEW

This chapter presents a selective survey of game-theoretic models of exploitation of transboundary fish stocks. It begins with a review of the basic elements of game theory, and an exposition of the standard model of the fishery. This is followed by a review of some non-cooperative fishery games, which are essential for understanding the concept of "threat point" in cooperative fishery games. Cooperative games will be discussed in the second part of section 2.

2.1 Basic Elements of Game Theory

Game Theory is concerned with the interactions of individuals in a strategic setting. The interactive individuals are referred to as "players". They are assumed to be rational and to have various "strategies". When they make their policy decisions, they must take into account the impact of such policies upon their rival players and the subsequent reactions of these rival players. The magnitude of the expected return to a player, called his "payoff", depends upon the expected reaction of the other players. When there are more than two players, it is possible that a "coalition" is formed by some subset of players coming together. Transboundary fishery resources are usually exploited by two or more nations or states, so strategic interactions are unavoidable.

There are two broad categories of games:

(1) Cooperative games. In this class of games, it is assumed that while the players are motivated strictly by self-interest, they have incentives to cooperate. The incentive to cooperate arises from the possibility that all players will be better off, as compared with non-cooperation. This often occurs in fishery resource exploitation activities. Each player will bargain hard for as large a share as possible of the total benefits from the cooperation agreement.

A "solution" to a cooperative game must satisfy at least two requirements (Eichberger, 1993):

(i) It must not be possible to find an alternative arrangement that makes one player better off, without harming the others, i.e., the "Pareto Optimal" situation is achieved under cooperation.

(ii) It must not be true that any single player would be better off by refusing to cooperate, i.e., cooperation occurs under an "individual rationality constraint".

The set of potential cooperative agreements in the two player game in which both conditions are met contains all the candidate solutions. It is represented by the segment of $\pi_1\pi_2$ on the "Pareto Frontier", in Figure 2.1. The solution will depend upon the relative bargaining strength of the players.

Suppose that the solution to the cooperative game is the point (π_1^*, π_2^*). Then the global economic benefits arising from cooperation, called the "cooperation surplus", can be expressed simply as: $CS = (\pi_1^* + \pi_2^*) - (\pi_1^0 + \pi_2^0)$. Points π_1^0 and π_2^0 are referred as the "threat point payoff" (non-cooperative payoff) of player 1 and player 2 respectively.

Pareto Frontier

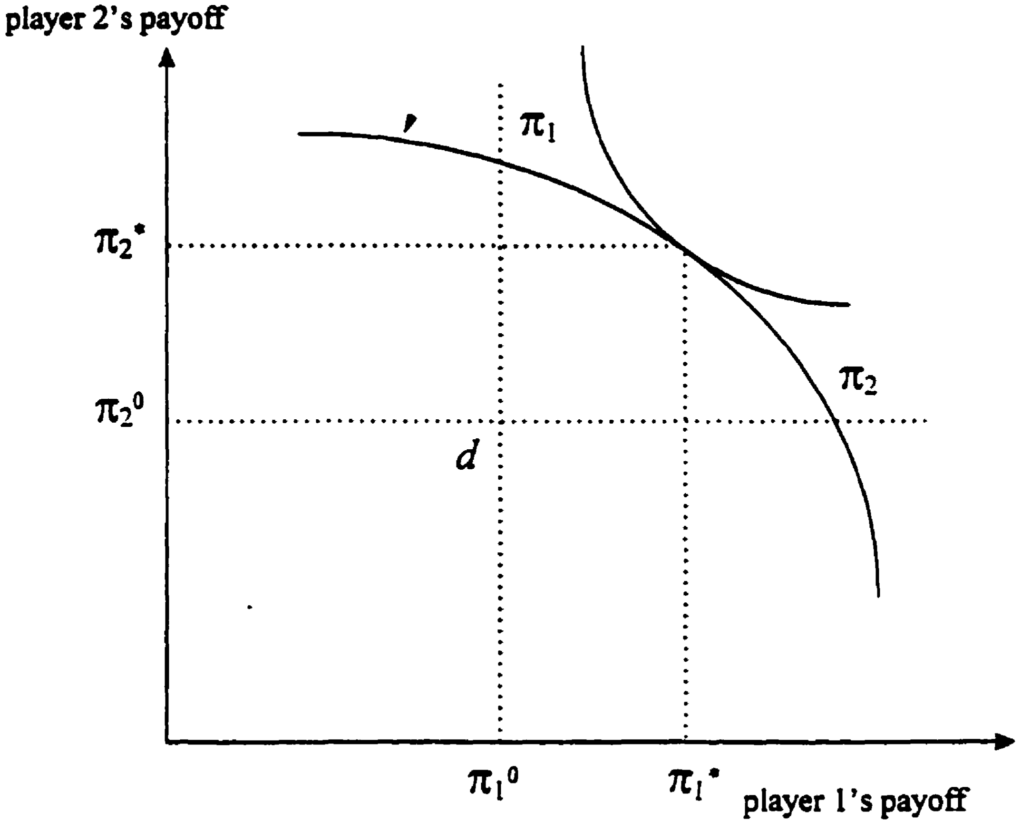

Figure 2.1 Cooperative Agreement: Pareto Frontier with Side Payments

In some cases, it is possible that there exists no point on the "Pareto Frontier" that dominates the disagreement point. For example, with the *status quo,* one player's non-cooperative payoff may be higher than any payoff he could get on the "Pareto Frontier". If a solution does not exist (see Figure 2.2), then attempts at cooperation will fail.

However, if the only reason that the cooperative game will fail is because there is no point on the "Pareto Frontier" which dominates the disagreement point, i.e., which promises both players' payoffs at least equal to their "threat point" payoffs. Then there may exist a way to make cooperation possible. This can be achieved via "side payments" (i.e., a transfer of money or other goods or assets between the players).

If side payments are possible, it may be possible to convert a cooperative game without a solution into one with a solution. In this case, the objective of the players is to maximize the cooperation surplus, and they bargain for a division of the returns. For fisheries, without side payments, the payoffs of each player will depend strictly upon the harvest activities taken by that player. If side payments are possible, the payoffs are not strictly determined (Munro, 1990), in the sense that they depend upon the relative bargaining strength of the players.

Cooperative games between two players are usually solved using the Nash bargaining scheme. When there are several players, one can use a multi-level Nash bargaining approach, or make use of more sophisticated (and more abstract) concepts, such as "Shapley Value" (Eichberger, 1993).

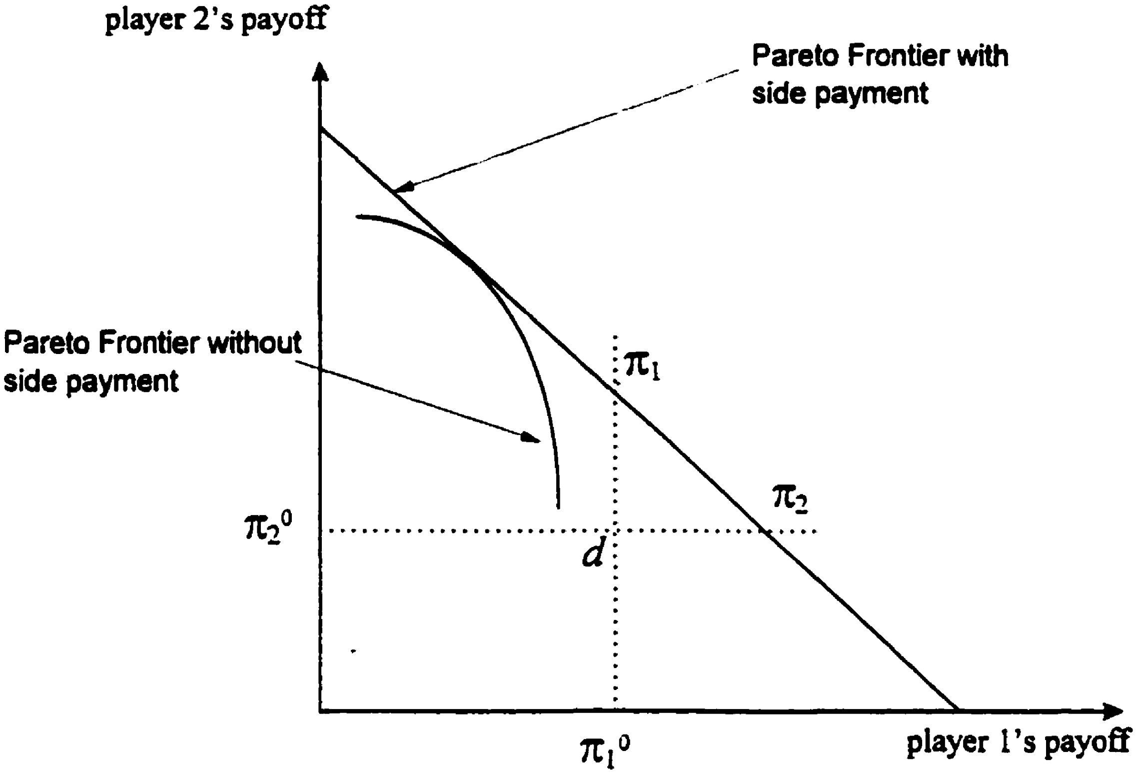

Figure 2.2 Cooperative Agreement: Pareto Frontier without Side Payments

(2) Non-cooperative games. This class of games applies to situations in which individuals can not bargain freely. This can occur when the costs of transactions (bargaining costs) are too high or because of legal or physical constraints.

There are two main points for non-cooperative games:

(i) For a large class of problems, a solution called Nash equilibrium is possible. For two-player games, a solution will be achieved when each of them has no incentive to change his strategy given the strategy of the other player (Eichberger, 1993).

(ii) This game may produce, from the economic standpoint, highly unsatisfactory outcomes. This is most dramatically illustrated by the "Prisoner's Dilemma" game in which the players are driven to adopt strategies which both recognize as being undesirable (Clark, 1980; Levhari and Mirman 1980). In transboundary fisheries, the joint exploiters will be driven to overexploit the resources. The history of the Pacific salmon fishery is a directly relevant illustration of this situation.

2.2 Theoretical Models

Sharing a fish resource is a problem that is amenable to the application of game theory, involving strategic decision making. The modeling[1] is complicated by the fact that fish are biological creatures that have their own growth function, which is affected by human behavior. This requires, therefore, a dynamic analysis that goes beyond the approach taken by authors of texts in pure game theory.

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[1] In what follows, I have used my own symbols (rather than the symbols used in the original articles), in order to keep the survey consistent.

There exists a voluminous literature on fishery economics. Basically, these articles take essentially the same approach: using the standard economic and biological models which are suitable to the fishery problem and combining them with two game-theoretic approaches: cooperative game theory and non-cooperative game theory. The main differences among the papers surveyed below lie in the different emphasis on some key points.

2.2.1 The Basic Model with a Single Owner

Model 1: Stationary Model The origin of fishery models can be traced back to the so called "Gordon-Schaefer Model" in which H. Scott Gordon (1954) developed an economic model of the fishery using static microeconomic analysis, which is based on Schaefer's biological model. This model considered a single-species fishery in which the demand for fish and the supply of fishing effort are both perfectly elastic (i.e., the price p and unit cost of fishing effort a are constant). Then the economic rent from this fishery is the difference between the total revenue $TR = ph$ and total cost $TC = aE$, where h is the fishery production, i.e., harvest. E is the fishing effort level, and $h = qEx$, where x is the stock of fish and q is the catchability coefficient.

The fish stock grows at the rate:

$$\dot{x}(t) = F(x) - h = rx(1 - x/K) - qEx \tag{2.1}$$

where r is the intrinsic growth rate of the stock and K is the carrying capacity of the environment and $F(x)$ is the natural growth function.

At the steady state, $\dot{x}(t) = 0$, or $F(x) = h$.

Solving for h[2]:

$$h = qEK - q^2E^2K/r$$

The optimization problem is to maximize the economic rent :

$$\underset{E}{Max}\ (TR - TC) = \underset{E}{Max}\ \{p\,(qEK - q^2E^2K/r) - aE\} \qquad (2.2)$$

Gordon (1954) obtained two main conclusions:

(1) The optimal size of the fishery is at the point at which the fishing effort level is E_0 where economic rent is maximized, i.e., $MC_E = VMP$ of effort. Any effort that extends beyond E_0 will be called economic overfishing.

(2) There is inefficiency under the open access regime (even though this regime was mistakingly called a "common property"regime). If the fish resource is owned by nobody, then the fishery will end up at E_∞ (which Gordon referred to as the "bionomic equilibrium") at which the economic rent from fishing will be fully dissipated (i.e., $TR - TC = 0$). It means that if a fish resource is commercially valuable but is subject to no control, then the fishery will invariably expand beyond the socially optimal level (see Figure 2.3).

This stationary-state model of the fishery has had an impact on policy makers. For example, the concern over the depletion of fishery resource under open access was a major factor in causing the establishment of the 200-mile EEZ (Brander,

[2] From $h = F(x) = rx(1 - x/K)$ and $h = qEx$, $x = h/qE$, substitute into above equation:

$$h = rh/qE\,(1 - h/qEK)\,, \quad h = qEK - q^2E^2K/r$$

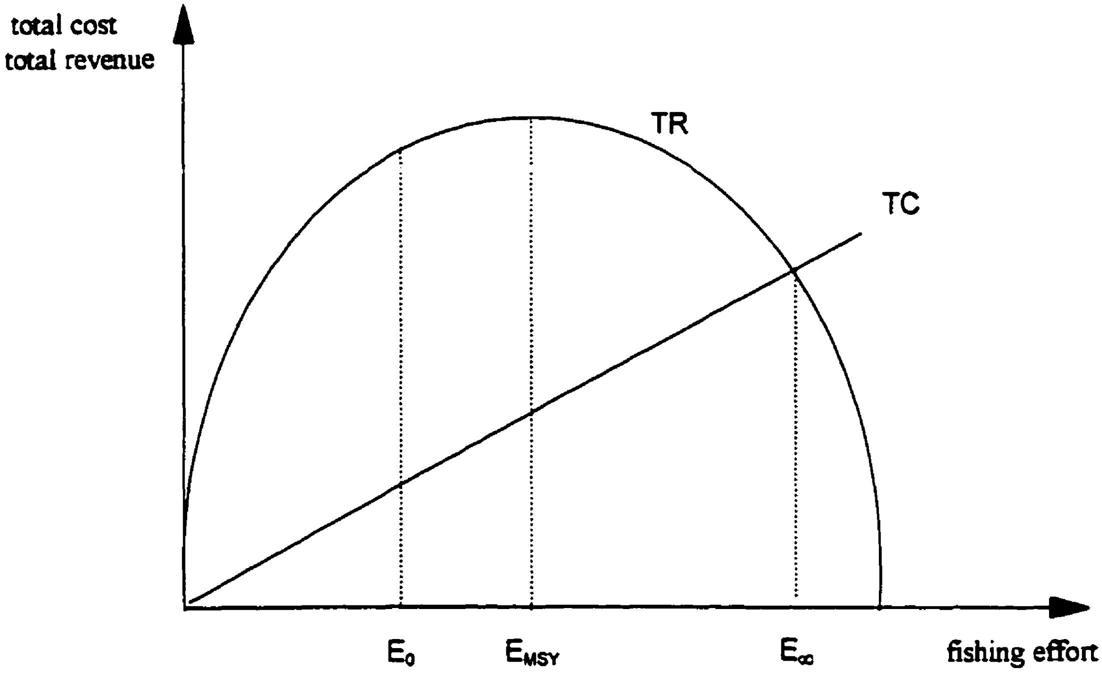

Figure 2.3 Economic Rent Maximization and Dissipation

1978). Governmental agencies seek to reduce fishing effort by increasing harvest cost, by means of traditional management policies, such as closed season, limited entry, etc. However, the model fails to capture the dynamic adjustment of the stock when it is out of the steady state. Fishery management involves the interactions between the production of fish stock and human beings' harvesting efforts. Any adjustment of fishing effort today will affect the stock level and therefore will affect the future harvesting effort level. Therefore, there was a need to develop an appropriate dynamic analysis to capture this major characteristic of fishery activities.

Model 2: Dynamic Model: an Application of Capital Theory In the early 1970's, the development of optimal control theory applied to capital theory made it possible to analyse the dynamic mechanisms in the fisheries. Gordon (1954) acknowledged that the optimal exploitation problem should be defined as a function of time and the achievement of the objective should take into consideration the interaction between the rate of catch, the growth rate of the stock and the economic time preference of the society.

The first attempts to apply control theory to the fisheries were in the 1970's by Quirk and Smith (1970), Plourde (1971). Colin Clark developed an extensive interest in this field, in his famous book: *Mathematical Bioeconomics: The Optimal Management of Renewable Resource* (1976) which is referred to in nearly every article on the fisheries.

The basic dynamic model of stock with harvesting is described by the equation:

$$\dot{x}(t) = F(x(t)) - h(t) \tag{2.3}$$

where $h(t)$ is determined by the production function: $h(t) = qE(t)x(t)$.

Once the functional form for $F(x)$ has been specified, and a given effort level, E, has been determined, then the sustained x level and h level can be obtained at the point where $\dot{x}(t) = 0$[3]. An example of this can be found in Schaefer's model (1954): $F(x) = rx(1 - x/K)$.

The optimal management of the fishery becomes that of maximizing an objective function (its value to the society) subject to the dynamics of the fish stock (biological considerations). Assume that society obtains the net benefit U from the resource which depends upon the production $h(t)$ and the stock itself $x(t)$. Then the optimization problem becomes:

$$Max \int_0^T e^{-\delta t}(h(t), x(t))dt \tag{2.4}$$

such that

$$\dot{x}(t) = F(x(t)) - h(t), \quad x(0) = x_0 \text{ given}$$

It is assumed that $h(t) \leq h_{\max}$ ($h_{\max}$ is the upper bound on the catch rate).

The current value Hamiltonian is:

$$\tilde{H}(x(t), h(t), \psi(t)) = U(x(t), h(t)) + \psi[F(x(t)) - h(t)] \tag{2.5}$$

[3] A different growth function $F(x)$ and or a different production function $H(x, E)$ will give different equilibrium levels of x and h. For example, some authors use the Gompertz growth function:

$$F(x(t)) = rx(t)\ln(K/x(t)).$$

and the Maximum Principle gives the following necessary conditions:

(i) $h(t)$ maximizes $\widetilde{H}\left(x\left(t\right),h\left(t\right),\psi\left(t\right)\right)$ for all t

(ii) $\dot{\psi}\left(t\right)=\delta\psi-\widetilde{H}_{x}$

(iii) $\lim_{t\to\infty}x\left(t\right)\geqslant0,\quad\lim_{t\to\infty}e^{-\delta t}\psi\left(t\right)x(t)=0$

Assume a constant price and utility function: $U\left(x,h\right)=ph-cE\ ,\ \ h=qxE$, then the optimal control problem becomes:

$$h(t)=\begin{cases}h_{\max} & \text{if } x\left(t\right)>x^{*}\\ h(t)=F\left(x^{*}\right) & \text{if } x\left(t\right)=x^{*}\\ 0 & \text{if } x\left(t\right)<x^{*}\end{cases}$$

At the steady state, the stock level x^{*} will be at the point which satisfies the following equation:

$$F'\left(x\right)+\frac{cF\left(x\right)}{x\left(pqx-c\right)}=\delta \tag{2.6}$$

Given the $F\left(x\right)$ function, then a unique solution to this control problem can be obtained and the optimal equilibrium stock level can be determined (Léonard and Long, 1992).

2.2.2 Theoretical Game Models Among the applications of game theory to strategic interaction analyses, there are two streams of literature: applied cooperative game theory and applied non-cooperative game theory. This is reflected in two types of fishery games. Since the cooperative game is motivated by the desire to improve upon the outcome of a corresponding non-cooperative game, non-cooperative models will be reviewed first.

Non-Cooperative Models When the joint owners cannot reach an agreement on the exploitation of a shared fish stock, individual rationality implies that each player in this conflict will apply non-cooperative game strategy to maximize their own objectives. The result is usually unfavorable for all, from a society's point of view.

Levhari and Mirman (1980) develop a discrete time model and show that the non-cooperative equilibrium is inefficient. Two features of the model stand out. First, the strategic aspect, each player takes account of the actions of the other player (Cournot-Nash equilibrium). Second, the underlying population of fish stock is changing over time, so the actions of both players affect the future size and therefore the growth rate of the fish population.

The objective function in this model is that each country maximizes its sum of discounted utilities. The authors assume a two-player game. Each player acts as a Cournot rival and takes the other's policy as given, while trying to maximize his own discounted sum of utilities.

Basic Model (Levhari and Mirman, 1980) :

x_t : quantity of fish, $x_{t+1} = x_t^{\alpha}$ (if there is no harvest)

c_i : present consumption, the utility function is: $U_i(c_i) = \ln c_i$

δ_i : discount rate

Consider first a game with only one-period horizon. For country 1, the maximization problem is as follows:

$$\underset{0 \leqslant c_1 \leqslant x - c_2}{Max} \left[\ln c_1 + \delta_1 \ln 1/2\,(x - c_1 - c_2)^{\alpha}\right] \tag{2.7}$$

The first order condition is:

$$(1+\alpha\delta_1)\,c_1 + c_2 = x \tag{2.8}$$

This is country 1's reaction curve, and similar for country 2:

$$c_1 + (1+\alpha\delta_2)\,c_2 = x \tag{2.9}$$

The Cournot -Nash equilibrium $\left(\bar{c_1}, \bar{c_2}\right)$ is determined by $(2.8)\,,(2.9)$

$$\bar{c_1} = \frac{\alpha\delta_2}{\alpha^2\delta_1\delta_2 + \alpha\delta_1 + \alpha\delta_2}x, \qquad \bar{c_2} = \frac{\alpha\delta_1}{\alpha^2\delta_1\delta_2 + \alpha\delta_1 + \alpha\delta_2}x$$

The remaining fish stock is given by:

$$x - \bar{c_1} - \bar{c_2} = \frac{\alpha^2\delta_1\delta_2}{\alpha^2\delta_1\delta_2 + \alpha\delta_1 + \alpha\delta_2}x \tag{2.10}$$

For the n-period horizon case, when $n \to \infty$, the limiting values are the following:

$$\bar{c_1} = \frac{\alpha\delta_2\,(1-\alpha\delta_1)\,x}{1-(1-\alpha\delta_1)\,(1-\alpha\delta_2)}, \qquad \bar{c_2} = \frac{\alpha\delta_1\,(1-\alpha\delta_2)\,x}{1-(1-\alpha\delta_1)\,(1-\alpha\delta_2)} \tag{2.11}$$

Equation (2.10) is the consumption policies for the two countries. They are independent of time. The resulting net investment in the fish stock is:

$$x - \bar{c_1} - \bar{c_2} = \frac{\alpha^2\delta_1\delta_2 x}{\alpha\delta_1 + \alpha\delta_2 - \alpha^2\delta_1\delta_2} \tag{2.12}$$

Under Cournot-Nash equilibrium, the dynamic equation for the fish stock becomes:

$$x_{t+1} = [x_t - c_1(x_t) - c_2(x_t)]^{\alpha} = \left[\frac{\alpha^2\delta_1\delta_2}{\alpha\delta_1 + \alpha\delta_2 - \alpha^2\delta_1\delta_2}\right]^{s(t)} x_0^{\alpha^t}$$

where $s(t) = \sum_{j=1}^{t} \alpha^j$, hence:

$$\lim_{t\to\infty} \left[\frac{\alpha^2\delta_1\delta_2}{\alpha\delta_1 + \alpha\delta_2 - \alpha^2\delta_1\delta_2}\right]^{\frac{\alpha}{1-\alpha}} = \bar{x} \tag{2.13}$$

Thus the steady state stock is:

$$\bar{x} = \left(\frac{1}{\frac{1}{\alpha\delta_1} + \frac{1}{\alpha\delta_2} - 1}\right)^{\frac{\alpha}{1-\alpha}} \tag{2.14}$$

From (2.14), the higher the discount rate δ_i , the higher is the steady state level of fish stock $\bar{x}$. If both countries have the same δ, then:

$$\bar{x} = \left(\frac{1}{\frac{2}{\alpha\delta} - 1}\right)^{\frac{\alpha}{1-\alpha}} = \left(\frac{\alpha\delta}{2 - \alpha\delta}\right)^{\frac{\alpha}{1-\alpha}} \tag{2.15}$$

Let us compare this steady state with the steady state solution under cooperation:

$$\hat{x} = (\alpha\delta)^{\frac{\alpha}{1-\alpha}} > \left(\frac{\alpha\delta}{2 - \alpha\delta}\right)^{\frac{\alpha}{1-\alpha}} = \bar{x}$$

A Cournot-Nash duopoly implies a smaller steady state quantity of fish, with a lower "permanent" catch and less left for future generations.

The growth function x^α is a reasonable function possessing a natural steady state at $x = 1$ when there is no external interference. However, the possibility of depletion is more easily illustrated using a linear growth function. With this specification, when countries cooperate, the quantity of fish diverges to infinity, while if they do not cooperate, the quantity converges to zero.

$$x_{t+1} = r\left(x_t - c_1(x_t) - c_2(x_t)\right)$$

with $r > 1$.

It can be shown that with an infinite horizon, Cournot-Nash policies are:

$$\bar{c_1} = \frac{\delta_1 (1-\delta_2)}{1-(1-\delta_1)(1-\delta_2)}x, \qquad \bar{c_2} = \frac{\delta_2 (1-\delta_1)}{1-(1-\delta_1)(1-\delta_2)}x$$

and the remaining fish stock is:

$$x - \bar{c_1} - \bar{c_2} = \frac{\delta_1 \delta_2 x}{1-(1-\delta_1)(1-\delta_2)} = \frac{x}{\frac{1}{\delta_1}+\frac{1}{\delta_2}-1}$$

Then the dynamic equation is found to be:

$$x_{t+1} = r\left(\frac{x}{\frac{1}{\delta_1}+\frac{1}{\delta_2}-1}\right) = \frac{r}{\frac{1}{\delta_1}+\frac{1}{\delta_2}-1}x_t$$

For any $x_0 > 0$,

$$\begin{cases} x_t \rightarrow \infty, \text{ if } \frac{r}{\frac{1}{\delta_1}+\frac{1}{\delta_2}-1} > 1, \\ x_t \rightarrow 0, \text{ if } \frac{r}{\frac{1}{\delta_1}+\frac{1}{\delta_2}-1} < 1 \\ x_t = x_0, \text{ if } \frac{r}{\frac{1}{\delta_1}+\frac{1}{\delta_2}-1} = 1 \end{cases} \tag{2.16}$$

If both countries have the same δ , then (2.16) becomes:

$$\begin{cases} x_t \rightarrow \infty \text{ , if } \frac{r\delta}{2-\delta} > 1 \\ x_t \rightarrow 0 \text{ , if } \frac{r\delta}{2-\delta} < 1 \end{cases}$$

Clemhout and Wan (1985) introduce stochastic elements into a differential game among several nations. They consider an N-person, M-species differential game, where equilibrium closed-loop strategies call for harvest rates proportional to resource stocks. Interaction among species and stochastic shocks from nature are the main novelties.

The dynamics of the problem is:

$$dx = F^x(x,t,c)\,dt + F^z(x,t,c)\,dz \tag{2.17}$$

where dz represents random disturbances that have the properties of "Brownian motion"[4].

The admissible strategy space for i, denoted by S_i, is a class of "harvesting rules" that describe harvest rates as functions of the stocks and time. Let ϕ^i be the rule choosen by player i , let $\phi = (\phi^1, ..., \phi^N)$, then the harvests are given by $c(t) = \phi[x(t), t]$

$$dx = F^x(x, t, \phi(x, t))\,dt + F^z(x, t, \phi(x, t))\,dz \tag{2.18}$$

Suppose that (2.18) has a unique solution $x^*(t)$, and $x^*(t_0) = x_0$, then player i's performance index is:

$$J_i(x_0, t_0, \phi) \triangleq E\int_{t_0}^{\infty} e^{-\delta_{ii}t} U_i(x^*(t), t, \phi(x^*(t), t))\,dt$$

The vector of strategies ϕ^* is a Nash equilibrium if for any player i:

$$J_i(x, t, \phi^*) = \sup_{\phi^i \in S_i} J_i\left(x, t, (\phi^i, \phi^{-i*})\right)$$

This means that if player i chooses any other strategy $\phi^i \neq \phi^{i*}$, he will not be better off, given that his opponents chooses ϕ^{-i*}.

To obtain concrete results, Clemhout and Wan (1985) made the following assumptions:

A1. Dynamics. For $j = i, ..., m$,

$$F_j^x(x, t, c) = a_j x_j - x_j \sum_{k=1}^{m} b_{jk} \ln x_k - \sum_{l=1}^{m} c_{lj}, \quad F_j^z(x, t, c) = x_j$$

[4] Or "Wiener process"

A2. Performance Indices. For all players, $\delta_i > \delta_0$, where δ_0 is the largest algebraic value of the real parts of the characteristic values for the matrix $B \triangleq [b_{jk}]$, and

$$U_i(x,t,c) = \sum_{j=1}^{m} \left[J_{ij}^{x} \ln x_j + \sum_{l=1}^{N} J_{ilj}^{c} \ln c_{ij} \right]$$

Then, given certain restrictions on parameter values and on the strategy spaces, the Nash equilibrium strategies can be shown to be:

$$\phi^{i*}(x,t) \triangleq diag\left(J_{ii1}^{c}/v_1^i, ..., J_{iim}^{c}/v_m^i\right)$$

$$v^i \triangleq \left(v_1^i, ..., v_m^i\right) = \left(B' + \delta_i I\right)^{-1} J^i$$

So, the equilibrium is inefficient because of over-exploitation.

Cave (1987) introduces history-dependent strategies to the Levhari and Mirman model. This is a natural extension of history-dependent strategies used in repeated games, where each player's moves depend on the information about the previous history of play.

Let x be the current stock level, and c denote the total current consumption. The stock available is $\xi(x-c)$. Let $U_i(c_i)$ be player i's concave utility function and assume that harvesting strategies are $c_i = c_i(x)$. The optimization problem is:

$$V_i(x) = \underset{c_i}{Max}\ U_i(c_i) + \delta_i V_i \left[\xi \left(x - c_i - \sum_{j \neq i} c_j \right) \right] \tag{2.19}$$

Recall that Levhari and Mirman (1980) assume that player i's utility function is $U_i(c_i) = \ln(c_i)$. If the common discount rate is δ, then the recursive equilibrium strategies are stationary, player i consumes a constant fraction d_i of the stock in each period.

$$x_t = \{[1 - (d_1 + d_2)]\, x_{t-1}\}^{\alpha}$$

Once the equilibrium decision rules for Levhari and Mirman's game are known to be stationary and linear, then :

$$V_i(d, x_0) = \sum_{t=0}^{\infty} \delta^t \ln [d_i x_t (d, x_0)]$$

where

$$x_t(d, x_0) = (1 - D)^{\lambda(t)}\, x_0^{\alpha^t}$$

$$D = d_1 + d_2, \lambda(t) = \alpha \left(1 - \alpha^t\right) / (1 - \alpha)$$

then the discounted present value of equilibrium extraction is a function of x_0 (Cave, 1987):

$$V_i^*(x) = \frac{[(1-\alpha\delta)\ln(1-\alpha\delta) + \alpha\delta \ln \alpha\delta - \ln(2-\alpha\delta) + (1-\delta)\ln(x)]}{[(1-\delta)(1-\alpha\delta)]} \quad (2.20)$$

The equilibrium described by Levhari and Mirman is not "Pareto Optimal". Cave (1987) shows that optimality can be restored if players choose threat strategies. Basically, each player announces that he will cooperate as long as his opponent cooperates, but he will punish his opponent as soon as the latter ceases to cooperate. If the rate of discount is small enough, then there exists threat strategies that achieve Pareto Optimality. History-dependent strategies behavior can be classified as normal behavior and punishment (off path) behavior.

Cooperative Models These models use the Nash bargaining framework. Munro (1979) develops a dynamic model of a two-player cooperative game. He assumes that within each country (player), the fisheries management policy is the responsibility of a single social manager(for example, a government agency), and that the manager's goal is to maximize its country's benefits from the fishery.

The basic model is that there is only a single fish stock. The stock dynamics is described by: $dx/dt = F(x) - h(t)$ and the natural growth function is:

$$F(x) = rx(1 - r/K)$$

The harvest production function is assumed to be identical for both countries: $h(t) = qE(x)x(t)$. Both countries face a world demand for the harvested fish which is infinitely elastic and the effort input supply functions are infinitely elastic.

When two countries jointly own a fish resource and agree to achieve a cooperative exploitation, then given the assumptions of identical effort costs, identical social discount rate, and that side payments are permitted, the optimization problem will be reduced to the sole owner's optimal control problem. The optimization model can then be formulated as follows (Clark, 1976):

$$PV = \int_0^\infty e^{-\delta t} [p - c(x)]\, h(t)dt \tag{2.21}$$

subject to

$$\begin{cases} \dot{x}(t) = F(x) - h(t) \\ 0 \leq h(t) \leq h_{\max} \\ x(t) \geq 0 \end{cases}$$

where $h_{\max}$ indicates the maximum feasible harvest rate, $c(x)h(t)$ is the total cost of harvesting[5].

[5] For example, if $h = qEx$ and the unit cost of E is a, then the total cost is: $aE = ah/qx = (a/qx)\, h = c(x)\, h$

The Hamiltonian equation is:

$$H = e^{-\delta t}\left\{[p - c(x)]\, h(t)\right\} + \lambda\left[F(x) - h(t)\right]$$

From this, the steady state stock level x^*can be determined by the following modified golden rule equation:

$$F'(x) - \frac{c'(x)F(x^*)}{p - c(x)} = \delta \tag{2.22}$$

The left hand side is the marginal sustainable net return divided by the supply price of the resource. It consists of the instantaneous marginal product of the resource and what Clark and Munro refer to as the "marginal stock effect". The equilibrium harvest policy in the steady state is: $h^*(t) = F(x^*)$.

Since the model is linear in the control variable, the optimal approach is the so called "bang-bang" approach:

$$h^*(t) = \begin{cases} h_{\max}, & \text{when } x(t) > x^* \\ 0\ , & \text{when } x(t) < x^* \end{cases}$$

Bargaining will have to take place with respect to the harvest shares and the relative size of shares will have no impact on the optimal management policy.

It is instructive to consider cases where countries are not identical. First, assume that they have different social discount rates with $\delta_1 < \delta_2 < \infty$. Then the management policies will be quite different. Country 1, with a low discount rate, will be more conservationist, i.e., its optimal stock level is greater than that of country 2: $x^*_{\delta_1} > x^*_{\delta_2}$. Country 1 thus has a greater incentive to invest in the resource.

Adopting a method suggested by Hnyilicza and Pindyck (1976), a potential cooperative objective is to maximize a weighted sum of the objectives of the two countries:

$$MaxPV = bPV_1 + (1-b)PV_2 \quad , \; 0 \leq b \leq 1 \qquad (2.23)$$

Where b is a bargaining parameter which permits the establishment of a tradeoff between management preference, i.e., if $b = 1$, then country 1 will be totally dominant.

Using Nash's theory of two-player cooperative games (Nash, 1953), assume that side payments cannot be made between the two countries. The payoffs π_1 and π_2 are present values of the streams of return. By choosing b to maximize (2.23), the Pareto-efficient frontier in the space of payoffs can be obtained.

Nash (1953) introduces the "threat point" to provide a measure of the relative bargaining power of the players. This threat point represents the minimum payoffs under any agreement. Using a number of assumptions, Nash proves that a unique solution can be obtained by maximizing the following:

$$Max(\pi_1 - \pi_1^0)(\pi_2 - \pi_2^0) \qquad (2.24)$$

where (π_1^0, π_2^0) is the pair of payoffs under non-cooperation. Applying Nash's framework to the fishery problems, the objective function under cooperative exploitaion can be expressed as:

$$PV = \int_0^{\infty} \left\{ b\alpha e^{-\delta_1 t} + (1-b)(1-\alpha)e^{-\delta_2 t} \right\} [p - c(x)]\, h(t)dt \qquad (2.25)$$

The Hamiltonian is:

$$H = \left\{b\alpha e^{-\delta_1 t} + (1-b)(1-\alpha)e^{-\delta_2 t}\right\}[p - c(x)]\,h(t) + \psi(t)\,[F(x) - h(t)] \quad (2.26)$$

Applying the golden rule, x^* is no longer independent of time:

$$F'(x^*) - \frac{c'(x)F(x^*)}{p - c(x^*)} = \frac{\delta_1 b\alpha e^{-\delta_1 t} + \delta_2(1-b)(1-\alpha)e^{-\delta_2 t}}{b\alpha e^{-\delta_1 t} + (1-b)(1-\alpha)e^{-\delta_2 t}}$$

Define the right hand side to be δ_3, a weighted average of the two discount rates δ_1, δ_2. The x^* on the left hand side is a function of $\delta_3(t)$: $x^* = x_{\delta_3}(t)$. A possible interpretation is that $x_{\delta_3}(t)$ represents the optimal stock time path resulting from bargaining. The optimal approach path is again the most rapid approach (or "bang-bang" control rule). Thus the nature of the tradeoff is to give the management preference of the more impatient country (country 2), a relatively strong weight in the present, and the other country's preference receives more weight in the future (see Figure 2.4).

It has been assumed that α, the harvest share of country 1, is fixed. If α is allowed to vary over the planning horizon, side payments still not permitted, then α becomes a control variable rather than a parameter. Harvest H must then be maximized with respect to both α and h at each moment:

$$\frac{\partial H}{\partial \alpha} = \left\{be^{-\delta_1 t} + (1-b)e^{-\delta_2 t}\right\}[p - c(x)]\,h(t) \quad (2.27)$$

It can be shown that there exists some critical time $T > 0$, such that the time path of $x^*_{\delta_3}$ coincides with $x^*_{\delta_2}$ up to $t = T$, and with $x^*_{\delta_1}$ thereafter. If side payments are permitted, then the objective will be simplified as

$$MaxPV_1 + PV_2$$

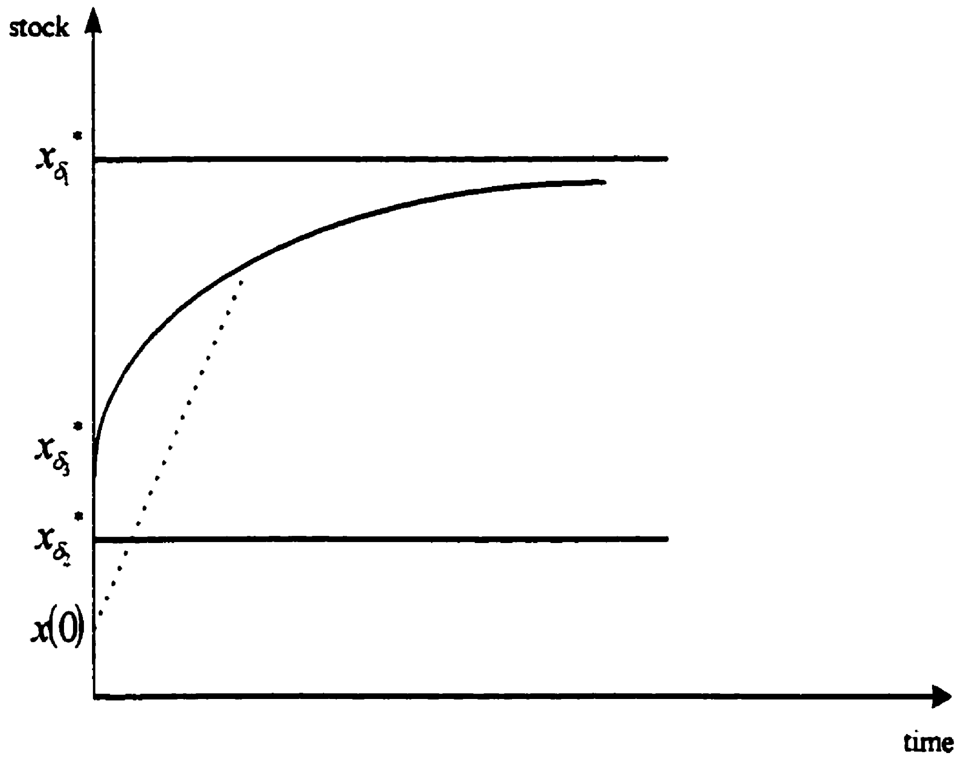

Figure 2.4 Optimal Stock Time Path

and bargaining will define the division of the return from the fishery (Munro, 1979).

The model can be modified to take into account unequal harvest costs. Assume that only harvest costs are different, and they are independent of the effort level, Then:

$$c_1(x) = \frac{a_1}{qx} \qquad c_2(x) = \frac{a_2}{qx}$$

If the harvesting costs are sensitive to the size of the stock level, then the country with higher cost will be more conservationist. The objective function in the cooperative game is:

$$PV = \int_0^{\infty} e^{-\delta t} \left[(\alpha b + (1-\alpha)(1-b))\, p - (\alpha b c_1(x) + (1-\alpha)(1-b)c_2(x))\right] h(t)dt \tag{2.28}$$

Then the golden rule is:

$$F'(x^*) - \frac{[\alpha b c_1'(x^*) + (1-\alpha)(1-b)c_2'(x^*)]\, F(x^*)}{(\alpha b + (1-\alpha)(1-b))\, p - (\alpha b c_1(x^*) + (1-\alpha)(1-b)c_2(x^*))} = \delta \tag{2.29}$$

It follows that the larger is b, the greater will be the "stock effect" on left hand side second term in the (2.29), and the steady state stock will be closer to country 1's optimal biomass level.

The Munro-Clark (1979) formulation has proved to be useful in highlighting some important factors in the cooperative game. However, it relies on very special assumptions, such as linearity in the control variable.

Hämäläinen, Haurie and Kaitala (1984) analyse a cooperative fishing game under an alternative to the Nash bargaining framework, the Kalaï-Smorodinsky bargaining scheme. Since the games of fishery management are dynamic by nature and are played on an infinite time horizon, each player can use threats in order to induce the partner to comply with a negotiated policy.

In a two-country fishery management game, a bargained agreement will usually call for a voluntary reduction of effort in order to let the stock reach a higher level. This also leaves a strong temptation for any player to cheat. By announcing credible threats to be used as retaliation in case of cheating, each partner can reduce or even eliminate the temptation for the other player to deviate from the agreement. The cooperative solution obtained in this bargaining game can thus be viewed as an equilibrium of a non-cooperative game in which players are allowed to use history-dependent strategies.

The bargaining solution can be obtained by using any of several bargaining schemes. This depends upon the axioms chosen for a representation of the rules of fairness accepted by both players. In the Hämäläinen, Haurie and Kaitala (1984) paper, the Kalaï-Smorodinsky scheme was adopted.

Consider a fishery exploited by two countries. The fish population dynamics is:

$$\frac{dx}{dt} = F(x) - h_1 - h_2 \tag{2.30}$$

Over a time interval $[0, \theta]$, the performance of country i is:

$$J_i = \int_0^\theta e^{-\delta_i t} U_i(x, h_i) dt \tag{2.31}$$

Let x^0 be the initial state of the fishery, $A(x^0)$ be the admissible harvest rates. By definition, the pair of $(h_1^*(.), h_2^*(.)) \in A(x^0)$ is an equilibrium if for any other pair $(h_1(.), h(.))$, the following conditions hold:

$$\underset{\theta \to \infty}{Lim} \left\{ J_1\left(x^0; h_1^*(.), h_2^*(.)\right) - J_1\left(x^0; h_1(.), h_2^*(.)\right) \right\} \geqslant 0$$

$$\underset{\theta \to \infty}{Lim} \left\{ J_2\left(x^0; h_1^*(.), h_2^*(.)\right) - J_2\left(x^0; h_1^*(.), h_2(.)\right) \right\} \geqslant 0 \tag{2.32}$$

Two countries sharing a fish stock usually could achieve more under cooperation, as compared to non-cooperation. If there is an independent arbitrator who may enforce an agreement once it has been obtained, it is possible to propose various bargaining schemes depending upon different sets of axioms concerning the behavior of the players. As was noted earlier, the most well-known one is the Nash bargaining scheme. Other schemes have been proposed as well. The Kalaï-Smorodinsky scheme is described as follows (Hämäläinen, Haurie and Kaitala, 1984):

Let $J_i(h_1, h_2), i = 1, 2, h_1 \in S_1, h_2 \in S_2$, be the payoff function of player i, S_i is player i's strategy set. Let $\left(\bar{h}_1, \bar{h}_2\right) \in S_1 * S_2$ be the strategy pair corresponding to the *status quo*, and $\left(\pi_1^0, \pi_2^0\right)$be the pair of payoffs in the *status quo*. Then the best achievable payoff, when negotiating, would be:

$$\pi_i = Max J_i(h_1, h_2) \tag{2.33}$$

such that

$$J_k(h_1, h_2) \geqslant \bar{\pi}_k, k \neq i, h \in S_1, h_2 \in S_2$$

The pair $(\bar{\pi}_1, \bar{\pi}_2)$ is called an "ideal" point which is generally not achievable. Kalaï and Smorodinsky postulate the following axioms under which the bargaining

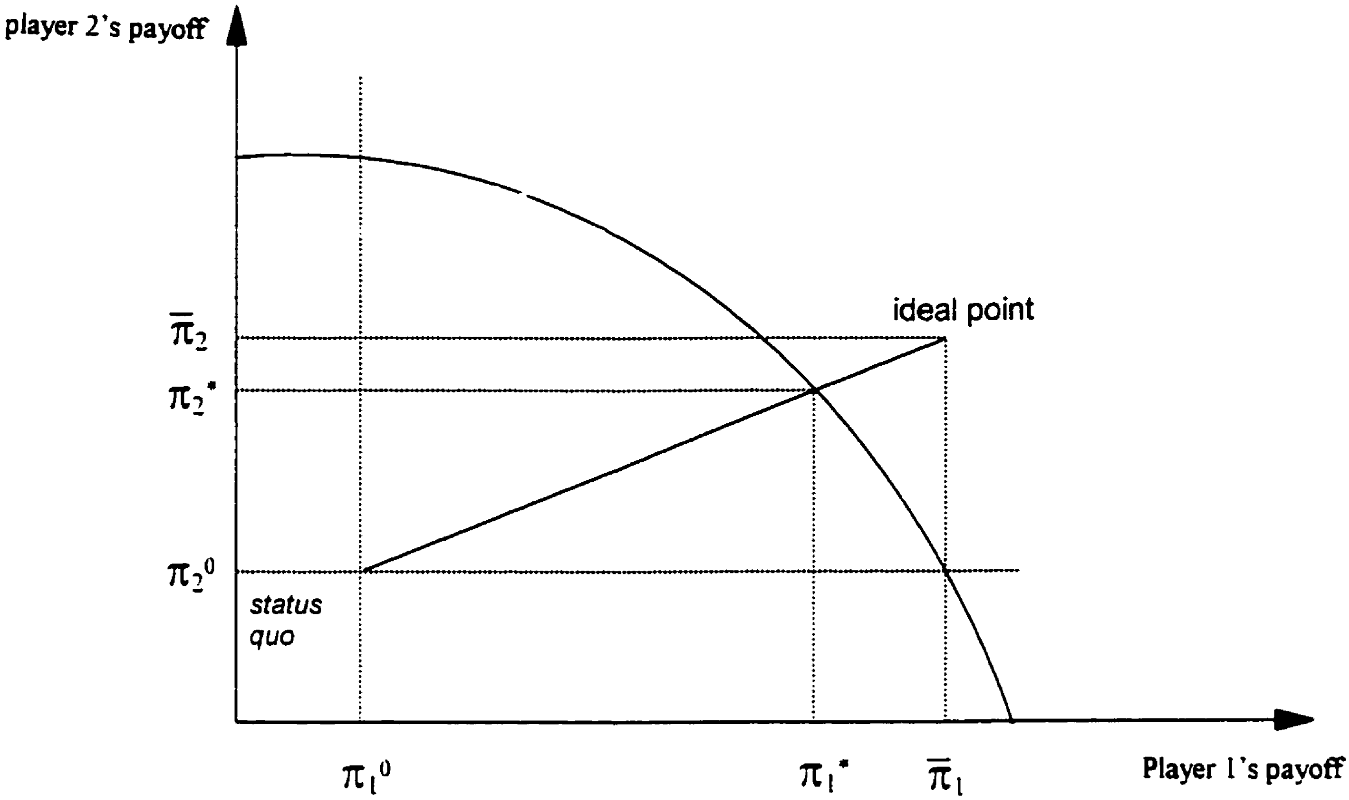

Figure2.5 Kalaï-Smorodinsky Bargaining Solution

solution $\left(\pi_1^*, \pi_2^*\right)$is derived (see Figure 2.5):

(i) $\pi_i^* = J_i\left(h_1^*, h_2^*\right)$ for some $h_i^* \in S_i, i = 1, 2$

(ii) if $\left(h_1, h_2\right) \in S_1 * S_2$ is such that $J_i\left(h_1, h_2\right) \geqslant J_i\left(h_1^*, h_2^*\right)$, for $i = 1, 2$, then $J_i\left(h_1, h_2\right) = J_i\left(h_1^*, h_2^*\right), i.e., \left(h_1^*, h_2^*\right)$ is Pareto optimal.

(iii) $\left(\pi_2^* - \pi_2^0\right) / \left(\pi_1^* - \pi_1^0\right) = \left(\bar{\pi}_2 - \pi_2^0\right) / \left(\bar{\pi}_1 - \pi_1^0\right)$

In negotiations concerning the exploitation of a shared fish stock, there is no powerful arbitrator who could enforce the agreement. It is tempting for one country to deviate from the agreement and optimize its own payoff given the cooperative harvesting strategy adopted by the other country. But since the game is played dynamically, there is a possibility for each player to announce threats which will be used in case of cheating. It may take some time for the non-cheating country to observe the deviation from the agreement. When the threat is applied, it corresponds to a "punishment".

The inclusion of threats in the bargaining strategies can be made precise and general by using a class of memory strategies. The following simple model illustrates the effectiveness of threat strategies in a fishing game (Hämäläinen, Haurie and Kaitala, 1984).

The bargaining solution in a simple game, assume that there is a single species of fish obeying the Gompertz growth equation. Two nations exploit the same fish stock. Let E_i be country i's effort level. The stock dynamics is described by:

$$dx/dt = x\left(\gamma - \mu \ln x - E_1 - E_2\right) \tag{2.34}$$

where γ and μ are positive parameters.

The payoffs for country i is:

$$J_i = \int_0^\infty e^{-\delta t} \ln (xE_i)\, dt \tag{2.35}$$

By changing the variable: $\xi = \ln x$, the model is simplified as follows:

$$\dot{\xi} = \gamma - \mu\xi - E_1 - E_2 \tag{2.36}$$

$$J_i = \int_0^\infty e^{-\delta t} (\xi + \ln E_i)\, dt \tag{2.37}$$

The necessary conditions generate a solution of the state equation (2.36) with $\xi(0) = \xi_0$. The adjoint equations are: $\dot{\psi}_i = -1 + \psi_i (\mu + \delta)$ and the efforts are determined by the necessary condition: $1/E_i - \psi_i = 0$.

The set of outcomes is symmetric, and the bargaining point corresponds to the share $\alpha_i = 1/2$, which is not affected by the initial state ξ_0 at which the bargaining occurs. This feature is due to the special structure of this simple model and will not be observed in more complicated systems.

Consider threats and equilibria in the class of memory strategies. If an arbitrator could enforce the agreement $\left(\pi_1^*, \pi_2^*\right)$ obtained at $(t = 0, \xi_0)$, the two countries would use a fishing effort $E_i^* = \frac{1}{2}(\mu + \delta)$, i.e., half of the fishing effort in the equlibrium solution of the corresponding non-cooperative game.

In the absence of an enforcement mechanism, one player may be tempted to deviate at some time from cooperative behavior. Asssume that if cheating takes place, it will be observed Δ units of time after. Let Z represent the length of punishment period, during which the non-cheating player retaliates by deviating also from the cooperative behavior. Each player may announce a threat corresponding to the control he will use during a certain punishment period if he notices cheating by the other player.

Let's suppose that country 2 announces that if country 1 deviates then it will use a fishing effort $E_2^m \geqslant \beta + \delta$ for a period of length Z as a retaliation. Assume that after $\Delta + Z$ units of time, both countries will revert to the cooperative mode. For country 1, the optimal control problem is (Hämäläinen, Haurie and Kaitala, 1984):

$$C_1\left(t, \xi^*\left(t\right)\right) = \underset{E_1}{Max} \int_t^{t+\Delta+Z} e^{-\delta s} \left[\ln E_1 + \xi\right] ds + e^{-\delta(t+\Delta+Z)} V_1^*\left(\xi\left(t + \Delta + Z\right)\right) \tag{2.38}$$

subject to

$$\dot{\xi}\left(s\right) = \begin{cases} \gamma - \mu\xi\left(s\right) - E_1\left(s\right) - \frac{\beta+\delta}{2}, & \text{if} \quad t \leqslant s \leqslant t + \Delta \\ \gamma - \mu\xi\left(s\right) - E_1\left(s\right) - E_2^m, & \text{if } t + \Delta \leqslant s \leqslant t + \Delta + Z \end{cases}$$

The threat E_2^m and the punishment period Z will be effective at $(t, \xi^*(t))$ if:

$$C_1\left(t, \xi^*\left(t\right)\right) \leqslant e^{-\delta t} V_1^*\left(\xi^*\left(t\right)\right) \tag{2.39}$$

The parameters Δ, Z, and E_2^m must be assigned to ensure that condition (2.39) is achieved. If so, then country 2 will prevent cheating at the point $(t, \xi^*(t))$ by country 1. If (2.39) is not satisfied, then either the threat must be made more powerful or the agreement must be changed.

The Hämäläinen, Haurie and Kaitala (1984) paper does not explore the following issues:

(1) Threat credibility analysis. When a threat is used, it hurts the opponent but also hurts the threatening player. A threat that hurts the punishing player

too much is non-credible, and will not be effective.

(2) Repeated cheating case.

(3) When one country asks for the reopening of negotiations at stock level x^*_{ss} (the bargaining outcome which is based on the initial state x_0), then in general a new bargaining solution will be reached with stock level $x^{*\prime}_{ss}$. Under what condition can the uniqueness of $x^{*\prime}_{ss}$ be asserted.

In a recent paper, Kaitala and Munro (1993) discuss, without systematic analysis, some issues that arise when there are more than two players. Assume that the three players are identical except in terms of harvesting cost. The following issues emerge: First, the obvious threat of non-cooperation exists. Second, during bargaining, should the three be treated as distinct or equal or is there a possibility of some subcoalition between two of them? Could the transfer of membership influence the negotiations within the coalition?

Let the countries be denoted by C, D_1 and D_2 respectively (where C denotes "coastal nation" and D_i denotes "distant water country"). The resource dynamics is:

$$dx/dt = F(x) - xE_c(t) - xE_{D_1} - xE_{D_2} \tag{2.40}$$

Suppose that country C has the lowest cost, $c_C < c_{D_1} < c_{D_2}$, and

$$x^*_{D_1}, x^*_{D_2} > x^*_c > x^\infty_{D_2} > x^\infty_{D_1} > x^\infty_c$$

where x^* indicates the steady state stock level and x^∞ indicates the bionomic equilibrium.

When the nations act independently, the Nash noncooperative equilibrium solution is such that the resource will be harvested in a "most rapid approach" manner until the level $x^{\infty}_{D_1}$ has been reached. i.e.,

$$E_c^N(x) = \begin{cases} E_c^{\max}, & x > x^{\infty}_{D_1} \\ F(x)/x, & x = x^{\infty}_{D_1} \\ 0, & x < x^{\infty}_{D_1} \end{cases} \qquad E_i^N(x) = \begin{cases} E_i^{\max}, & x > x_i^{\infty} \\ 0, & x \le x_i^{\infty} \end{cases}$$

The solution is identical to that of an open access.

Let's turn to the possibility of a cooperative agreement. Assume that there is a binding agreement and side payments are feasible instruments. Player C, with the lowest cost, will dominate the management of the resource, i.e., it would buy out D_1, D_2. The agreement would be focused on the share of the total net returns from the fishery among the three:

$$w_c(x(0)) = w_c^C(x(0)) + w_c^{D_1}(x(0)) + w_c^{D_2}(x(0)) \tag{2.41}$$

where w_c is the total payoffs and the right hand side terms are payoffs to the three individual countries. There are four alternative arrangements:

(1) Non-subcoalition with Non-transferable Membership

A failure to achieve a cooperative agreement will result in a non-cooperative solution. In this case, all three players are against one another. The global net surplus (or net return) under cooperation is:

$$e(x(0)) = w_c(x(0)) - \sum J_i\left(x(0), E_C^N, E_{D_1}^N, E_{D_2}^N\right) \tag{2.42}$$

where J_i is the payoff to country i under non-cooperation. The Nash bargaining scheme is that, given the possibility of side payments, each player receives an equal amount of the net return, i.e., nation i receives : $e(x(0))/3+J_i(x(0), E_C^N, E_{D_1}^N, E_{D_2}^N)$, even when there is a big difference in the costs between the Ds. The reason for equal shares is because if any one of them refuses to cooperate then cooperation breaks down entirely.

(2) Non-subcoalition with Transferable Membership

Let's assume that there is a new entrant, D_3, and if the membership transfer takes place, it must be done before the commencement of the cooperative management program. It is reasonable to also assume that transfer will take place only if the two parties in the transfer can gain from it. If $c_{D_1} < c_{D_3} < c_{D_2}$, then D_2 has an incentive to transfer its membership because the difference in harvesting costs produces an opportunity for the profitable sale of its membership. Under scenario (2), the possibility of transfer will enhance the bargaining power of D_2 in relation to C and D_1.

(3) Subcoalitions with Non-transferable Membership

When the three act independently, a necessary condition for the achievement of a cooperative agreement is that each player receives no less than their threat point payoffs. Therefore, under a cooperative agreement, a subcoalition must receive a payoff at least as large as it would have received under non-cooperation.

If D_1 and D_2 form a subcoalition, and if C refuses to cooperate, D_1 and D_2 will have the option to act independently. In this situation, the resource will be driven down to $x_{D_1}^{\infty}$ and both will be forced out of the fishery. Alternatively, they can form a subcoalition, and the one with lower cost can buy out the other. Ultimately, the resource will still be driven down to $x^{\infty}_{D_1}$.

Another possibility is a coalition between C and D_2. If this occurs, then the resource will be driven down to $x^{\infty}_{D_1}$.

The third possible coalition is between C and D_1. Then it is D_2 that is unable to cooperate with. The resource will stabilize at $x^{\infty}_{D_2}$, the joint payoff to C and D_1 will be considerably greater than without a subcoalition.

(4) Subcoalitions with Transferable Membership

If C and D_1 could form a subcoalition, then D_2's threat to transfer its membershipto D_3 will be weak. C and D_1 could negotiate with D_3, thus reducing the price which would be paid to D_2. D_2 will become passive in the game, in which it could accept or reject D_3's offer.

CHAPTER 3

THE MODEL

In this chapter, a dynamic game-theoretic model is developed to compare the outcome under cooperation and non-cooperation, and to study the benefits of cooperation. The sensitivity of such benefits to changes in important parameters is also investigated. The parameters that are varied include the discount rate, the price of landed fish, and the cost of effort. Another purpose of this model is to examine the possible payoffs of forming a subcoalition between two players in a game in which there are three players. This is an important issue that seems tc have been neglected in the literature on dynamic games of fishery.

The model contains a number of novel features. The harvest function is modelled as a Cobb-Douglas production function, with two inputs: the effort level and the fish stock level. The advantage of this formulation over the traditional approach is that such a function avoids the "bang-bang" controls caused by the linearity of the Hamiltonian with respect to the harvest rate. "Bang-bang" control means that each of the player will either harvest nothing, or harvest at a maximum rate, until a steady state is reached. This feature does not seem to be observed in real world situations. Furthermore, the concept of a maximum harvest rate is somewhat artificial.

Assume that x represents the fish stock level. Its dynamics is: $\dot{x}(t) = F(x(t))$, where $F(x) = rx(1 - x/K)$ is its natural growth function (i.e., without harvesting) and it satisfies the conditions:

$$F(0) = F(x_K) = 0$$

and $F(x) > 0$, for $0 < x < x_K = K$ (where K indicates the environmental carrying capacity).

Let n_i be the fishing effort of player i,

w_i be the unit cost of effort of player i,

p : be the price of landed fish, (here it is assumed that the players face the same market price, for example, they sell the harvested fish in the world market),

δ : be the social discount rate, $\delta \in (0, 1)$,

h_i : be the catch rate.

The production function is:

$$h_i(t) = A\left[x(t)\right]^b \left[n_i(t)\right]^{1-b}$$

where A is a positive constant and $0 < b < 1$. This production function indicates that production depends both on fishing effort and the current stock level. It is assumed that each player has the same production function.

With harvesting, the stock dynamics becomes:

$$\dot{x}(t) = F(x(t)) - \sum_{i=1}^{m} h_i(t)$$

Assume that each player chooses his own time path of fishing effort level, $n_i(t)$, to maximize his objective function. This would be the present value of the flow of net economic return from his fishing activities over an infinite time horizon:

$$Max \int_0^{\infty} e^{-\delta t}\left[ph_i(t) - w_i n_i(t)\right] dt$$

such that

$$\dot{x}(t) = F(x(t)) - \sum_{i=1}^{m} h_i(t)$$

$$x(0) = x_0, \lim_{t\to\infty} x(t) \geqslant 0$$

The properties of the model are explored under a number of cases, begining with the simplest. This serves to show how complexity builds up very quickly, when additional features are introduced. The outcomes under cooperation are compared with the outcomes under non-cooperation.

3.1 Two-player Game in its Simplest Form

This subsection considers the simplest case, where there are two identical players, i.e., $w_1 = w_2$. The following parameter values are selected for simplicity, $A = 2, b = \frac{1}{2}$, and $w_1 = w_2 = 1$, $p = 1$, $r = K = 1$.

3.1.1. Non-cooperative Game: [Case 1a] Each player i takes the time path of effort of his opponent, $n_j(t)$, as given. His problem consists of finding a time path of his own effort, $n_i(t)$, to maximize his objective function:

$$\underset{n_i}{Max} \int_0^{\infty} e^{-\delta t} \left[2x^{\frac{1}{2}}n_i^{\frac{1}{2}} - n_i\right] dt$$

The maximization is subject to the following constraints:

$$\dot{x}(t) = x(1-x) - 2x^{\frac{1}{2}}n_1^{\frac{1}{2}} - 2x^{\frac{1}{2}}n_2^{\frac{1}{2}}$$

$$x(0) = x_0$$

To solve this problem, optimal control theory will be used. The current value

Hamiltonian is:

$$\tilde{H}_i = 2x^{\frac{1}{2}}n_i^{\frac{1}{2}} - n_i + \psi_i\left[x(1-x) - 2x^{\frac{1}{2}}n_1^{\frac{1}{2}} - 2x^{\frac{1}{2}}n_2^{\frac{1}{2}}\right] \tag{3.1}$$

where $\psi_i(t)$ denotes the costate variable. The economic interpretation of this variable is that it is the player's marginal valuation of the state variable (the fish stock). ψ_i is also referred to as player i's "shadow price" of the stock.

Solving this dynamic non-cooperative game (see Appendix 1), it can be shown that the equilibrium harvest policies satisfy the following differential equations:

$$-\frac{1}{2}x^{-\frac{1}{2}}n_1^{-\frac{1}{2}}\dot{n}_1 = \left[1-\left(\frac{n_1}{x}\right)^{1/2}\right]\left[\delta - 1 + 2x + \left(\frac{n_2}{x}\right)^{1/2}\right] - \frac{n_1}{x} - \frac{1}{2}x^{-\frac{3}{2}}n_1^{\frac{1}{2}}\dot{x}$$

$$-\frac{1}{2}x^{-\frac{1}{2}}n_2^{-\frac{1}{2}}\dot{n}_2 = \left[1-\left(\frac{n_2}{x}\right)^{1/2}\right]\left[\delta - 1 + 2x + \left(\frac{n_1}{x}\right)^{1/2}\right] - \frac{n_2}{x} - \frac{1}{2}x^{-\frac{3}{2}}n_2^{\frac{1}{2}}\dot{x}$$

These harvest activities (with suitable initial condition) will bring the stock level to a steady state, x_N^* , which is given by:

$$x_N^* = \left[-(5+\delta) + \sqrt{(5+\delta)^2 + 6(2.5 - 3\delta)}\right]/3 \tag{3.2}$$

This steady state is stable in the saddle point sense. This means that for any initial stock level $x(0)$, there exists a unique pair $(n_1(0), n_2(0))$ of initial effort levels which, when used with the above pair of differential equations, provide a unique solution to the game.

3.1.2. Cooperative Game: [Case 1b] In the cooperative case, it is assumed that the two players agree on a common harvesting plan. Suppose the same weights are given to both players and side payments are permitted, then the objective function of the cooperative problem is simply the maximization of the sum of net profits over the time horizon. There is only one common "shadow price". This is identical to the sole owner's optimization problem:

$$\underset{n_1,n_2}{Max} \int_0^{\infty} e^{-\delta t} \left[2x^{\frac{1}{2}}n_1^{\frac{1}{2}} - n_1 + 2x^{\frac{1}{2}}n_2^{\frac{1}{2}} - n_2\right] dt$$

such that

$$\dot{x}(t) = x(1-x) - 2x^{\frac{1}{2}}n_1^{\frac{1}{2}} - 2x^{\frac{1}{2}}n_2^{\frac{1}{2}}$$

$$x(0) = x_0$$

The current value Hamiltonian is:

$$\tilde{H} = \left[2x^{\frac{1}{2}}n_1^{\frac{1}{2}} - n_1 + 2x^{\frac{1}{2}}n_2^{\frac{1}{2}} - n_2\right] + \psi\left[x(1-x) - 2x^{\frac{1}{2}}n_1^{\frac{1}{2}} - 2x^{\frac{1}{2}}n_2^{\frac{1}{2}}\right] \qquad (3.3)$$

The optimal harvest policy satisfies the following condition (see Appendix 2):

$$-\frac{1}{2}x^{-\frac{1}{2}}n^{-\frac{1}{2}}\dot{n} = \left[1 - \left(\frac{n}{x}\right)^{1/2}\right][\delta - 1 + 2x] - 2\frac{n}{x} - \frac{1}{2}x^{-\frac{3}{2}}n^{\frac{1}{2}}\dot{x}$$

and for any $x(0)$, there exists a corresponding $n(0)$ such that the optimal harvest policy will bring the stock to a steady state, x_C^* which is given by:

$$x_C^* = \left[-(6+\delta) + \sqrt{(6+\delta)^2 + 6(3.5 - 3\delta)}\right]/3 \qquad (3.4)$$

Again, this steady state has the usual saddle point property.

Comparing (3.2) and (3.4), it can be shown that under cooperation, the steady state stock level is higher than the one obtained in the non-cooperative case, $x_C^* > x_N^*$, and therefore each player has a higher steady state harvest rate, $h_C^* > h_N^*$.

Figure 3.1 and Figure 3.2 illustrate the phase diagrams under non-cooperation and cooperation. Both diagrams show that the steady state is unique and stable in the saddle point sense. If the initial stock $x(0)$ is below the steady state level,

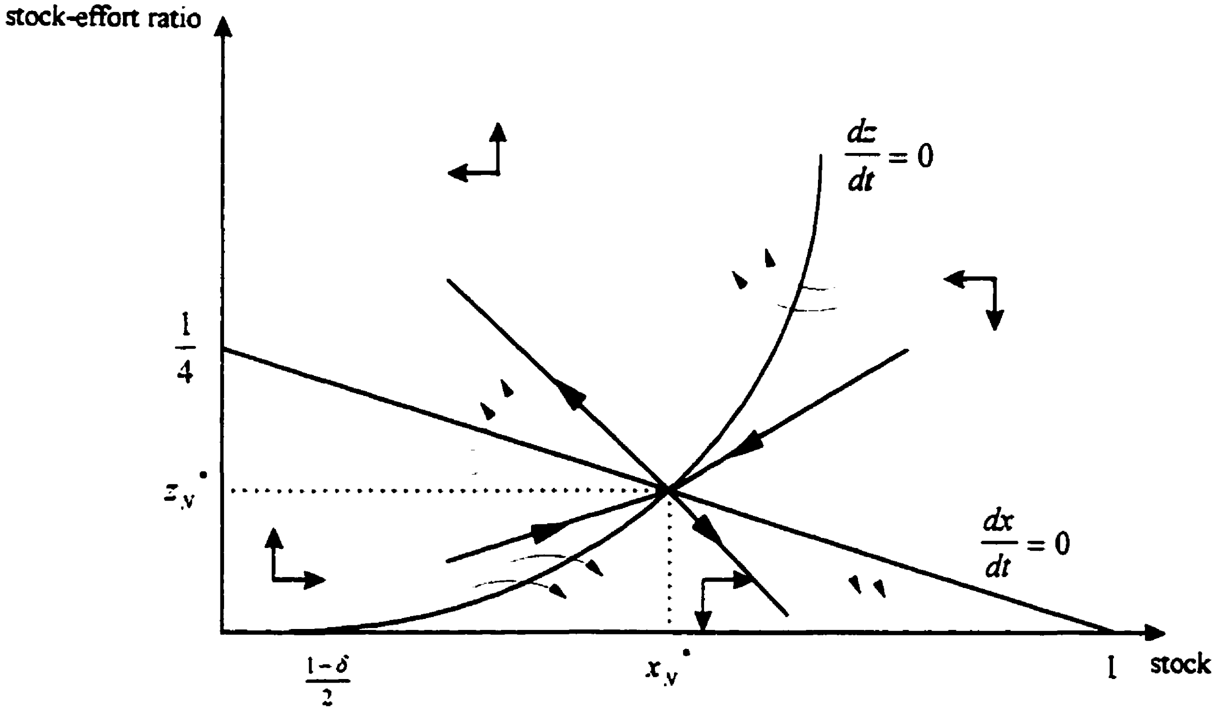

Figure 3.1 Phase Diagram under Non-cooperation

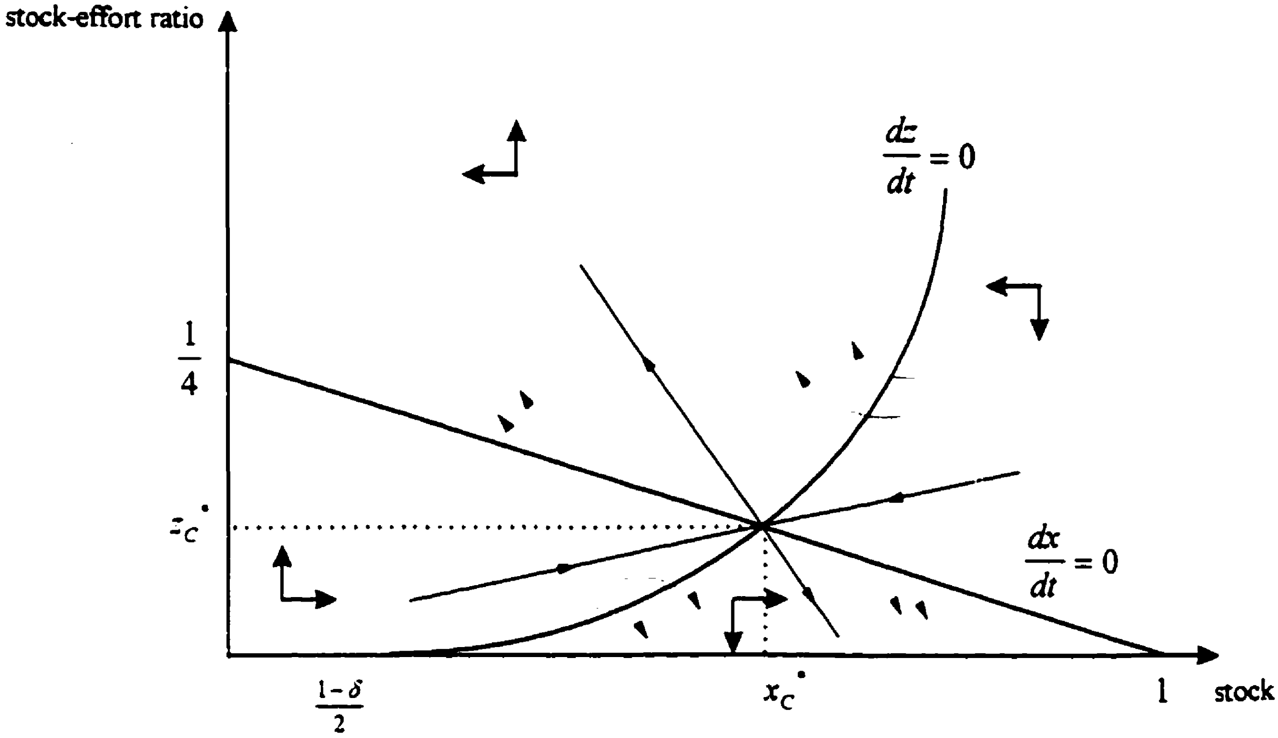

Figure 3.2 Phase Diagram under Cooperation

then the initial rates of effort are low. This allows the fish stock to grow to reach the steady state. Conversely, if $x(0)$ exceeds the steady state fish stock level, then the optimal initial rates of efforts to the stock are high, and this leads to a gradual decrease of the fish stock, until the steady state is reached.

3.2 Generalized Two-player Game Model

The production function is given by: $h_i = Ax^b\, n_i^{1-b}$ with different harvest costs, i.e., $w_1 \neq w_2$.

3.2.1. Non-cooperative Game: [Case 2a]

For player i , the optimization problem is to maximize net profit over the time horizon by choosing n_i, taking into account player j's harvesting strategy. Thus his objective is:

$$Max \int_0^\infty e^{-\delta t} \left[pAx^b n_i^{1-b} - w_i n_i\right] dt$$

subject to

$$\dot{x} = x\,(1-x) - Ax^b n_i^{1-b} - Ax^b n_j^{1-b} \tag{3.5}$$

The current value Hamiltonian for player i is:

$$\tilde{H}_i = \left(pAx^b n_i^{1-b} - w_i n_i\right) + \psi_i \left[x\,(1-x) - Ax^b n_i^{1-b} - Ax^b n_j^{1-b}\right]$$

It can be shown (see Appendix 3) that the equilibrium harvest policies satisfy the following equations:

$$-\frac{bw_1}{A\,(1-b)}\left(\frac{n_1}{x}\right)^b \left[\frac{\dot{n}_1}{n_1} - \frac{\dot{x}}{x}\right] = \left[p - \frac{w_1}{A\,(1-b)}\left(\frac{n_1}{x}\right)^b\right]\Delta_2 - \frac{bw_1}{(1-b)}\left(\frac{n_1}{x}\right) \tag{3.6}$$

where

$$\Delta_2 = \left[\delta - 1 + 2x + Ab\left(\frac{n_2}{x}\right)^{1-b}\right]$$

$$-\frac{bw_2}{A(1-b)}\left(\frac{n_2}{x}\right)^b\left[\frac{\dot{n}_2}{n_2}-\frac{\dot{x}}{x}\right]=\left[p-\frac{w_2}{A(1-b)}\left(\frac{n_2}{x}\right)^b\right]\Delta_1-\frac{bw_2}{(1-b)}\left(\frac{n_2}{x}\right) \quad (3.7)$$

where

$$\Delta_1=\left[\delta-1+2x+Ab\left(\frac{n_1}{x}\right)^{1-b}\right]$$

and these efforts will bring the stock to a steady state, x_N^*.

3.2.2. Cooperative Game: [Case 2b] The objective function of the cooperative case is:

$$Max\int_0^\infty e^{-\delta t}\left[pAx^bn_1^{1-b}-w_1n_1+pAx^bn_2^{1-b}-w_2n_2\right]dt \quad (3.8)$$

subject to

$$\dot{x}=x(1-x)-Ax^bn_1^{1-b}-Ax^bn_2^{1-b}$$

The current value Hamiltionian is:

$$\tilde{H}=pAx^bn_1^{1-b}-w_1n_1+pAx^bn_2^{1-b}-w_2n_2+\psi\left[x(1-x)-Ax^bn_1^{1-b}-Ax^bn_2^{1-b}\right] \quad (3.9)$$

Cooperation means that marginal costs must be equalized. Here, marginal cost (MC_i) is equal to the marginal product of n_i divided by w_i. The efficiency conditions $MC_1 = MC_2$ are given by:

$$\frac{(1-b)\,x^bn_1^{-b}}{w_1}=\frac{(1-b)\,x^bn_2^{-b}}{w_2}$$

This equation implies that

$$n_2=n_1\left(\frac{w_1}{w_2}\right)^{\frac{1}{b}}$$

The optimal harvest policies should satisfy the following condition:

$$-\frac{w_1 \dot{z}_1}{A(1-b)} = \left[p - \frac{w_1 z_1}{A(1-b)}\right](\delta - 1 + 2x) - \frac{w_1 z_1}{A(1-b)} Abz_1^{\frac{1-b}{b}} \left[1 + \left(\frac{w_1}{w_2}\right)^{\frac{1-b}{b}}\right] \tag{3.10}$$

where

$$z_1 = (n_1/x)^b$$

Note that z_2 is equal to the following:

$$z_2 = z_1 \frac{w_1}{w_2}$$

Comparing the results from cooperation and non-cooperation numerically (see Table 1), the following can be concluded:

(1) Cooperation will make both players better off, and it will lead to a higher stock level, $x_C^* > x_N^*$, and thus higher harvest rates, $h_C^* > h_N^*$, for each player at the steady state.

(2) When the price of landed fish rises, in both the cooperative and non-cooperative cases, each player will be induced to harvest more before the stock reaches its steady state. Therefore, the stock level in steady state, x^*, will fall and the harvest rates in the steady state will decrease as well.

(3) When the social time preference δ increases (indicating an increase in impatience), the harvest policies will change, causing the stock level to decrease. If the rate of time preference is sufficiently high, this would lead to depletion if harvest rate exceeds the natural growth rate of the stock.

Table 1: Two-player non-cooperative and cooperative games

Two-player Game (b=1/2)							
Non-coop	delta	p -price	h -catch	w -cost	z -ratio	x -stock	profit
		$/kg	million tonnes	$/unit effort	effort/tonne	million tonnes	billion $
Player 1	0.05	1	0.1213	1	0.1464	0.4144	0.1124
Player 2		1	0.1213	1	0.1464		0.1124
Player 1	0.05	1	0.1202	1.5	0.1427	0.4211	0.1073
Player 2		1	0.1236	0.5	0.1467		0.1236
Player 1	0.05	1	0.1188	1.9	0.1393	0.4263	0.1031
Player 2		1	0.1258	0.1	0.1475		0.1258
Player 1	0.1	1	0.1186	1	0.1532	0.3873	0.1096
Player 2		1	0.1186	1	0.1532		0.1186
Player 1	0.1	1	0.1176	1.5	0.1491	0.3946	0.1045
Player 2		1	0.1213	0.5	0.1536		0.1213
Player 1	0.1	1	0.1163	1.9	0.1453	0.4004	0.1003
Player 2		1	0.1238	0.1	0.1545		0.1238
Player 1	0.05	2	0.1207	1	0.1483	0.4068	0.2324
Player 2		2	0.1207	1	0.1483		0.2413
Coop	delta	p-price	h-catch	w-cost	z-ratio	x-stock	profit
		$/kg	million tonnes	$/unit effort	effort/tonne	million tonnes	billion $
Player 1	0.05	1	0.1250	1	0.1267	0.4934	0.1171
Player 2		1	0.1250	1			0.1250
Player 1	0.05	1	0.0625	1.5	0.0639	0.4886	0.0595
Player 2		1	0.1874	0.5			0.1874
Player 1	0.05	1	0.0125	1.9	0.0130	0.4783	0.0123
Player 2		1	0.2371	0.1			0.2371
Player 1	0.1	1	0.1246	1	0.1324	0.4702	0.1163
Player 2		1	0.1246	1			0.1246
Player 1	0.1	1	0.0622	1.5	0.0669	0.4649	0.0591
Player 2		1	0.1866	0.5			0.1866
Player 1	0.1	1	0.0124	1.9	0.0137	0.4536	0.0122
Player 2		1	0.2355	0.1			0.2355
Player 1	0.05	2	0.1249	1	0.1290	0.4839	0.2417
Player 2		2	0.1249	1			0.2497

(4) To study the impacts of changes in the cost structures, a comparison was made between the benchmark case, where the two players have the same costs ($w_1 = w_2 = 1$), and other cases, where player 1's cost increases and player 2's cost decreases.

(i) As a result of a change in the cost structure, the stock level increases under non-cooperation (i.e., the fall in h_1 exceeds the rise in h_2), while decreases under cooperation (i.e., the rise in h_2 exceeds the falls in h_1) when compared to the benchmark case. This implies both players would catch more under cooperation before reaching the steady state. Cooperation will make both countries better off because the steady state stock level, $x^*_C > x^*_N$, with cooperation is greater than non-cooperation in all cases.

(ii) The harvest level changes by a greater amount under cooperation than under non-cooperation ($\Delta h^*_C > \Delta h^*_N$). For example, when $w_1 = 1.5, w_2 = 0.5$, under cooperation, the percentage change in h_1 is -49.53% and the percentage change in h_2 is 51.42% ; while under non-cooperation, the corresponding figures are -2.52% and 0.23%. This would indicate that harvest levels are more sensitive to changes in fishing effort cost structure under cooperation than under non-cooperation. This reflects the fact that when side payments are possible, cooperation means that production will become more efficient by equating the marginal costs.

(5) Both under cooperation and under non-cooperation, the steady state stock level is unique and satisfies the saddle point property.

3.3 The Distribution Problem under Cooperation

The next area of interest is the problems associated with the distribution of net profits and surplus from the cooperation between two players. In game theory, "Nash Bargaining Scheme" solutions to determine the outcome are usually used. According to Nash (1951), and subsequent generalizations, the outcome of the bargaining game must maximize the "Generalized Nash Product":

$$\underset{x \geqslant d}{Max} \left(\pi_1 - \pi_1^0\right)^\alpha \left(\pi_2 - \pi_2^0\right)^\beta$$

where (π_1^0, π_2^0) denotes the "threat point" payoffs of player 1 and player 2, and α and β represent their relative bargaining strengths. Using the "Nash Bargaining Scheme", the outcome (π_1^*, π_2^*) is as depicted in Figure 3.3.

The bargaining strengths α and β , are usually interpreted as functions of the degrees of impatience (ρ_1, ρ_2): $\alpha = 1/\rho_1$, $\beta = 1/\rho_2$. Here, ρ_i represents the degree of impatience of player i in the bargaining process, and it might have no direct link with δ which is discount rate used in the objective function. Binmore (1987) stated that the player that is more impatient (i.e., the player with a higher ρ) usually has less bargaining strength in the negotiation. On the other hand, it is also known that the player with a higher δ, in maximizing the present value will have more bargaining advantage because he has a higher "threat point " payoff.

In our model, it was assumed that side payments were permitted. But, in the real world, especially in the salmon fisheries, there are no direct side payments, at least between U.S. and Canada. However, in the absence of direct side pay-

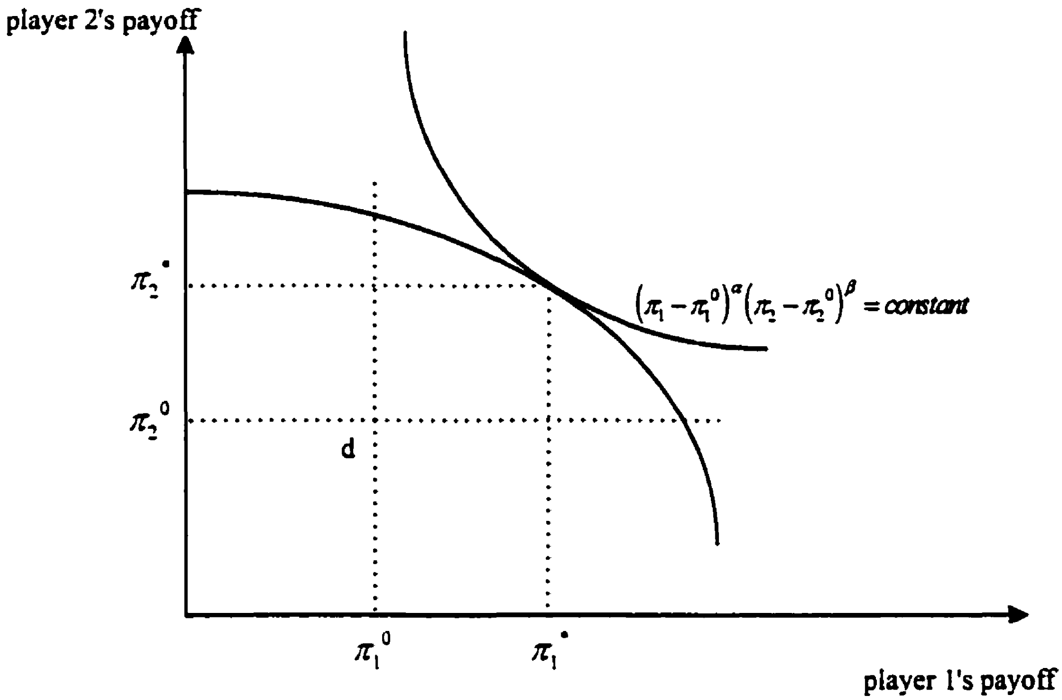

Figure 3.3 Maximizing the Generalized Nash Product

ments in cash, other forms[1] of "surrogate side payments" may exist to ensure the achievement of a cooperative agreement.

3.4 Three-player Game Model

As has been pointed out in chapter 1, the Pacific salmon dispute actually involves more than two players. It is reasonable to suppose that it is a three player game, involving British Columbia, Alaska, and Washington/Oregon. In this subsection, our model is extended to consider a game with three players. The model becomes more complicated and a number of cases have to be considered separately.

When there are three or more players, a non-cooperative game remains relatively straightforward while the cooperative game becomes quite involved because subcoalitions are possible. An interesting question is whether there is some form of subcoalition cooperation that yield higher payoffs for every member of the subcoalition.

3.4.1. Full Non-cooperation, no Subcoalition: [Case 4a] If the three players do not cooperate with each other, then each of them maximizes their own objective, while taking into account the other two players' strategies.

The current value Hamiltonian for player i is:

$$\tilde{H}_i = (pAx^b n_i^{1-b} - w_i n_i) + \psi_i \left[x(1-x) - \sum_{i=1}^{3} Ax^b n_i^{1-b} \right] \tag{3.11}$$

[1] For example, in the "Economist" January 31st, 1998, British Columbia threat to cancel its lease of a torpedo-testing range used by the American navy to put pressure on the negotiations.

The optimal harvest policies must satisfy the following condition:

$$\left(-\frac{\dot{n}_i}{n_i}+\frac{\dot{x}}{x}\right)\left[\frac{w_i b}{A(1-b)}\left(\frac{n_i}{x}\right)^b\right]=P\left[\delta-1+2x+Ab\sum_{j\neq i}^{3}\left(\frac{n_j}{x}\right)^{1-b}\right] \tag{3.12}$$

where

$$P=p-\frac{w_i b}{A(1-b)}\left(\frac{n_i}{x}\right)^b$$

These optimal harvest activities will bring the stock to a steady state which satisfies:

$$\left[p-\frac{w_i b}{A(1-b)}\left(\frac{n_i}{x}\right)^b\right]\Delta-\frac{w_i b}{1-b}\left(\frac{n_i}{x}\right)=0 \quad (i=1,2,3) \tag{3.13}$$

where

$$\Delta=\left[\delta+1-2A\left(\frac{n_1}{x}\right)^{1-b}-A(2-b)\left(\frac{n_2}{x}\right)^{1-b}-A(2-b)\left(\frac{n_3}{x}\right)^{1-b}\right]$$

and

$$\left[x(1-x)-\sum_{i=1}^{3}\left(\frac{n_i}{x}\right)^b\right]=0$$

<u>3.4.2. Full Cooperation: [Case 4b]</u> If the three players decide to cooperate with each other, then their objective becomes one of maximizing the sum of the current value of net profits from fishing with the same "shadow price" ψ. This is the same optimization problem as that of a sole owner, because side payments are permitted.

$$\underset{n_i}{Max}\int_0^{\infty}e^{-\delta t}\left(\sum_{i=1}^{3}pAx^b n_i^{1-b}-w_i n_i\right)dt \tag{3.14}$$

subject to

$$\dot{x}(t)=x(1-x)-\sum_{i=1}^{3}Ax^b n_i^{1-b}$$

The current value Hamiltonian is:

$$\tilde{H} = (p - \psi)\left(\sum_{i=1}^{3} Ax^b n_i^{1-b}\right) - \sum_{i=1}^{3} w_i n_i + \psi\left[x\left(1-x\right)\right] \qquad (3.15)$$

According to the maximum principle, then:

$$\frac{w_1 \dot{z}_1}{A(1-b)} = -\left[p - \frac{w_1 z_1}{A(1-b)}\right]\left\{(\delta - 1 + 2x) + \frac{w_1 b z_1^{\frac{1}{b}}}{1-b}\left[1 + \left(\frac{w_1}{w_2}\right)^{\frac{1-b}{b}} + \left(\frac{w_1}{w_3}\right)^{\frac{1-b}{b}}\right]\right\} \qquad (3.16)$$

where

$$z_i = \left(\frac{n_i}{x}\right)^b$$

and

$$\dot{x} = x\left[(1-x) - 2z_1^{\frac{1-b}{b}}\left(1 + \frac{w_1}{w_2} + \frac{w_1}{w_3}\right)\right] \qquad (3.17)$$

For simplicity, assume that $b = 1/2$, $A = 2$, then in a steady state, setting $\dot{x} = 0$:

$$x = 1 - 2\left(1 + \frac{w_1}{w_2} + \frac{w_1}{w_3}\right) z_1 \qquad (3.18)$$

And for $\dot{z}_1 = 0$, it must satisfy:

$$-(p - w_1 z_1)\left[\delta + 1 - 4\left(1 + \frac{w_1}{w_2} + \frac{w_1}{w_3}\right) z_1\right] + w_1 z_1^2 \left(1 + \frac{w_1}{w_2} + \frac{w_1}{w_3}\right) = 0 \quad (3.19)$$

From (3.18) and (3.19), the steady state values of stock and harvest rates can be computed.

<u>3.4.3. Subcoalition between two players</u> The game becomes more complicated when it is possible for two players to form a coalition against the third. In this case, the Nash Bargaining Scheme does not apply. Referring to the Pacific salmon fishery case, one can reasonably contemplate the following possible subcoalitions:

Subcoalition 1. Subcoalition between British Columbia and Washington/Oregon

It is possible that British Columbia and Washington/Oregon may have an incentive to form a subcoalition if Alaska refuses to obey an agreement. For example, under the Pacific Salmon Treaty, Alaska has to reduce its interception or transfer part of its profits to the other two players. The subcoalition could be formed because Washington/Oregon and British Columbia may claim their ownership of the salmon species which originated in their areas. They could establish a common property rights regime under which the two members are equal in the use rights of the stock while non-members are excluded. If Alaska keeps on intercepting, then it could be taken to court. This is a quite explicit property rights case. However, national political considerations make it unlikely that such a subcoalition will be formed.

Subcoalition 2. Subcoalition between Alaska and Washington/Oregon. This is the most probable case because according to the present "rules of the game", before an agreement between U.S and Canada is reached, there must be a consensus between Washington/Oregon and Alaska. The following cost structure was assumed: $w_1 < w_2 < w_3$ (where $1, 2, 3$ denote Alaska, British Columbia and Washington/Oregon respectivelly). A subcoalition between Alaska and Washington/Oregon is a coalition between the lowest and highest cost producers in order to maximize their discounted present value of net profits. This subcoalition will then decide to cooperate or not with British Columbia (Canada).

In what follows, the proceeding model is extended to allow for a subcoalition between two players. The outcomes from this three player cooperative game with a subcoalition are quite different from the outcomes of the full cooperative and full non-cooperative games. Only the case of a subcoalition between Alaska and Washington/Oregon will be considered below, because it is a politically more likely scenario. However, it should be clear that the same method of analysis applies to other forms of subcoalitions.

Subcoalition between Alaska (player 1) and Washington/Oregon (player 3) versus British Columbia (player 2): [Case 4c] The optimization problem of the subcoalition is to jointly decide on the time paths of effort levels $n_1(t)$ and $n_3(t)$ so as to maximize the discounted flow of the sum of net profits of the two subcoalition members. The subcoalition takes as given the time path of effort level $n_2(t)$ of the non-member (British Columbia).

$$\underset{n_1, n_3}{Max} \int_0^{\infty} e^{-\delta t} \left[\left(pAx^b n_1^{1-b} - w_1 n_1 \right) + \left(pAx^b n_3^{1-b} - w_3 n_3 \right) \right] dt \tag{3.20}$$

such that

$$\dot{x}(t) = x(1-x) - \sum_{i=1}^{3} Ax^b n_i^{1-b}$$

The current value Hamiltonian is:

$$\tilde{H} = (p-\psi)\left(Ax^b n_1^{1-b} + pAx^{\frac{1}{2}} n_3^{\frac{1}{2}} \right) - w_1 n_1 - w_3 n_3 + \psi \left[x(1-x) - Ax^b n_2^{1-b} \right] \tag{3.21}$$

For British Columbia (player 2), the optimization problem is to choose $n_2(t)$ to maximize its discounted flow of net profits. It takes the time paths $n_1(t)$ and

$n_3(t)$ as given.

$$Max \int_0^\infty e^{-\delta t}\left(pAx^b n_2^{1-b} - w_2 n_2\right) dt$$

such that

$$\dot{x}(t) = x(1-x) - \sum_{i=1}^{3} Ax^b n_i^{1-b}$$

The current value Hamiltonian is:

$$\bar{H} = (p - \psi_2)\left(Ax^b n_2^{1-b} - w_2 n_2 + pAx^b n_3^{1-b}\right) + \psi_2\left[x(1-x) - Ax^b n_1^{1-b} - Ax^b n_3^{1-b}\right] \tag{3.22}$$

Again, let $z_i = n_i/x$. Since the subcoalition equates their marginal costs, then:

$$z_3 = z_1 \frac{w_1}{w_3}$$

Therefore, an independent differential equation for z_3 is not needed. The game between the subcoalition and player 2 (non-member) results in the following differential equations:

$$\dot{z}_1 = -\left(\frac{p}{w_1} - z_1\right)(\delta - 1 + 2x + z_2) + \left(1 + \frac{w_1}{w_3}\right) z_1^2 \tag{3.23}$$

$$\dot{z}_2 = -\left(\frac{p}{w_2} - z_2\right)\left[\delta - 1 + 2x + z_1\left(1 + \frac{w_1}{w_3}\right)\right] + z_2^2 \tag{3.24}$$

$$\dot{x} = x\left[(1-x) - 2z_1 - 2z_2 - 2z_1\left(\frac{w_1}{w_3}\right)\right] \tag{3.25}$$

There exists a unique pair of time paths (z_1, z_2) of harvest activities which satisfy (3.23), (3.24) and (3.25) which leads the stock to a steady state x_S^*. This steady state has the usual saddle point property. Technically, this means that the above system of three differential equations (3.23), (3.24) and (3.25) has a negative eiganvalue, so that starting from any $x(0)$, a unique pair $(z_1(0), z_2(0))$ can be found, which takes the system to the steady state.

The systems of equations are non-linear and rather complicated, and therefore it was decided to use numerical calculations in order to compare the outcomes of the various cases. In order to make these comparisons, b and A were set, $b = 1/2, A = 2$, and various values were used for the discount rate δ, the price p, and the effort costs w_1, w_2, and w_3. The detailed findings are reported in Table 2, 3 and 4. Some important findings are highlighted below:

(1) Full Non-cooperation. Compared with the two-player non-cooperative game, it was found that:

(i) The steady state level of stock is lower because there are more players in the industry.

(ii) The changes in cost structure cause the stock level to decrease under both cooperative and non-cooperative games (the decrease in h_1 is smaller than the increase in h_3, when player 2's effort cost was held constant).

(2) Full Cooperation. Compared with non-cooperation, it is found that:

(i) The steady state level of stock under cooperation is greater than that under non-cooperation, $x_C^* > x_N^*$. The reason for this is the same as in the two-player game.

(ii) In the benchmark case, the following cost structure was assumed: $w_1 = w_2 = w_3 = 1$. Keeping w_2 constant, w_1 was allowed to rise and w_2 to fall. It was found that the stock levels changed by a greater amount with cooperation than that under non-cooperation. For example, with $\delta = 0.05$ and $p = 1$, when $w_1 = 1.5, w_2 = 0.5$, under cooperation the percentage fall in the steady state stock level is -0.46% , compared with -0.04% under non-cooperation. This may be explained as follows: under cooperation, the fall in w_3 by 50% actually more than compensates for the rise in w_1 by 50% because the cost functions are concave in factor prices. Therefore, the harvest increases and the stock level falls.

Compared with the two-player game, changes in price and cost structure cause the stock level to change in the same direction.

(3) Subcoalition. Compared with full cooperation, it is found that:

(i) The stock level in the steady state under subcoalition x_S^* is smaller than that under full cooperation . This implies that the non-member will catch more than under full cooperation before the stock reaches its steady state. This can be explained by the rivalry between the subcoalition and the non-member leads to insufficient conservation of the stock.

(ii) Changes in cost structure were compared with the benchmark case where $w_1 = w_2 = w_3 = 1$. Cost structure was changed to reflect the following: $w_1 = 1.5, w_3 = 0.5$, while w_2 remains at 1. The following observations were made: Under full cooperation, the percentage change in h_1 was -45.47%, in h_2 was -18.2%, in h_3 was 63.6%. Under the sub-coalition, the corresponding changes were -49.59%, 83.88%, 51.22% and the sum of h_1 and h_3 increased by 0.82%.

(iii) British Columbia, as a non-subcoalition member, was better off in this game.

Table 2: Three-player non-cooperative game

Three-player Non-cooperative Game (b=1/2)							
Non-coop	delta	p-price	h-catch	w-cost	z-ratio	x-stock	profit
		$/kg	million tonnes	$/unit effort	effort/tonne	million tonnes	billion $
Player 1	0.05	1	0.0783	1	0.1038	0.3772	0.0742
Player 2	0.05	1	0.0783	1	0.1038		0.0742
Player 3	0.05	1	0.0783	1	0.1038		0.0742
Player 1	0.05	1	0.0743	1.5	0.0985	0.3771	0.0688
Player 2	0.05	1	0.0782	1	0.1036		0.0741
Player 3	0.05	1	0.0824	0.5	0.1093		0.0802
Player 1	0.05	1	0.0712	1.9	0.0945	0.3768	0.0648
Player 2	0.05	1	0.0778	1	0.1033		0.0738
Player 3	0.05	1	0.0858	0.1	0.1139		0.0853
Player 1	0.05	1	0.0711	1.9	0.0943	0.3766	0.0647
Player 2	0.05	1	0.0776	1	0.1031		0.0736
Player 3	0.05	1	0.0861	0.05	0.1143		0.0858
Player 1	0.05	1	0.0728	1.5	0.0970	0.3756	0.0675
Player 2	0.05	1	0.0766	1	0.1019		0.0727
Player 3	0.05	1	0.0851	0.01	0.1133		0.0851
Player 1	0.1	1	0.0756	1	0.1087	0.3480	0.0715
Player 2	0.1	1	0.0756	1	0.1087		0.0715
Player 3	0.1	1	0.0756	1	0.1087		0.0715
Player 1	0.1	1	0.0716	1.5	0.1029	0.3478	0.0661
Player 2	0.1	1	0.0755	1	0.1085		0.0714
Player 3	0.1	1	0.0798	0.5	0.1147		0.0775
Player 1	0.1	1	0.0684	1.9	0.0985	0.3474	0.0620
Player 2	0.1	1	0.0751	1	0.1081		0.0710
Player 3	0.1	1	0.0832	0.1	0.1197		0.0827
Player 1	0.05	2	0.0780	1	0.1044	0.3735	0.1519
Player 2	0.05	2	0.0780	1	0.1044		0.1519
Player 3	0.05	2	0.0780	1	0.1044		0.1519

Table 3: Three-player cooperative game

Three-player Cooperative Game (b=1/2)							
Cooperation	delta	p-price	h-catch	w-cost	z-ratio	x-stock	profit
		$/kg	million tonnes	$/unit effort	effort/tonne	million tonnes	billion $
Player 1	0.05	1	0.0833	1	0.0855	0.4870	0.0797
Player 2	0.05	1	0.0833	1			0.0797
Player 3	0.05	1	0.0833	1			0.0797
Player 1	0.05	1	0.0454	1.5	0.0468	0.4847	0.0438
Player 2	0.05	1	0.0681	1			0.0671
Player 3	0.05	1	0.1362	0.5			0.1357
Player 1	0.05	1	0.0114	1.9	0.0119	0.4780	0.0113
Player 2	0.05	1	0.0316	1			0.0316
Player 3	0.05	1	0.2165	0.1			0.2165
Player 1	0.1	1	0.0829	1	0.0895	0.4632	0.0792
Player 2	0.1	1	0.0829	1			0.0792
Player 3	0.1	1	0.0829	1			0.0792
Player 1	0.1	1	0.0452	1.5	0.0490	0.4607	0.0435
Player 2	0.1	1	0.0678	1			0.0667
Player 3	0.1	1	0.1355	0.5			0.1350
Player 1	0.1	1	0.0113	1.9	0.0125	0.4533	0.0112
Player 2	0.1	1	0.0215	1			0.0214
Player 3	0.1	1	0.2150	0.1			0.2150
Player 1	0.05	2	0.0832	1	0.0865	0.4809	0.1628
Player 2	0.05	2	0.0832	1			0.1628
Player 3	0.05	2	0.0832	1			0.1628

Table 4: Three-player sub-coalition game (1)

Three-player Subcoalition : Player 1,3 Vs. Player 2 (b=1/2)							
	delta	p-price	h-catch	w-cost	z-ratio	x-stock	profit
		$/kg	million tonnes	$/unit effort	effort/tonne	million tonnes	billion $
Player 1	0.05	1	0.0627	1	0.0764	0.4103	0.0603
Player 2	0.05	1	0.1165	1	0.1420		0.1083
Player 3	0.05	1	0.0627	1	0.0764		0.0603
Player 13	0.05	1	0.1254	1			
Player 1	0.05	1	0.0316	1.5	0.0386	0.4093	0.0307
Player 2	0.05	1	0.1153	1	0.1409		0.1072
Player 3	0.05	1	0.0948	0.5	0.1159		0.0921
Player 13	0.05	1	0.1265				
Player 1	0.05	1	0.0064	1.9	0.0079	0.4070	0.0064
Player 2	0.05	1	0.1126	1	0.1383		0.1048
Player 3	0.05	1	0.1223	0.1	0.1502		0.1214
Player 13	0.05	1	0.1287				
Player 1	0.05	1	0.0033	1.9	0.0041	0.4067	0.0033
Player 2	0.05	1	0.1122	1	0.1379		0.1044
Player 3	0.05	1	0.1258	0.05	0.1547		0.1253
Player 13	0.05	1	0.1291				
Player 1	0.05	1	0.0006	1.99	0.0008	0.4063	0.0006
Player 2	0.05	1	0.1118	1	0.1376		0.1041
Player 3	0.05	1	0.1288	0.01	0.1585		0.1287
Player 13	0.05	1	0.1294				
Player 1	0.05	1	0.0013	1	0.0016	0.4063	0.0013
Player 2	0.05	1	0.1118	1	0.1376		0.1041
Player 3	0.05	1	0.1281	0.01	0.1577		0.1280
Player 13	0.05	1					
Player 1	0.05	2	0.0614	1	0.0758	0.4050	0.1204
Player 2	0.05	2	0.1182	1	0.1460		0.2279
Player 3	0.05	2	0.0614	1	0.0758		0.1204
Player 13	0.05	2	0.1227	1			

Table 4: Three-player sub-coalition game (2)

	delta	p-price	h-catch	w-cost	z-ratio	x-stock	profit
		$/kg	million tonnes	$/unit effort	effort/tonne	million tonnes	billion $
Player 1	0.1	1	0.0613	1	0.0801	0.3828	0.0589
Player 2	0.1	1	0.1136	1	0.1484		0.1052
Player 3	0.1	1	0.0613	1	0.0801		0.0589
Player 13	0.1	1	0.1227	1			
Player 1	0.1	1	0.0309	1.5	0.0405	0.3817	0.0300
Player 2	0.1	1	0.1123	1	0.1471		0.1041
Player 3	0.1	1	0.0928	0.5	0.1215		0.0899
Player 13	0.1	1	0.1237				
Player 1	0.1	1	0.0063	1.9	0.0083	0.3791	0.0062
Player 2	0.1	1	0.1095	1	0.1444		0.1016
Player 3	0.1	1	0.1196	0.1	0.1578		0.1187
Player 13	0.1	1	0.1259				
Player 1	0.1	1	0.0032	1.9	0.0043	0.3787	0.0032
Player 2	0.1	1	0.1090	1	0.1439		0.1012
Player 3	0.1	1	0.1231	0.05	0.1625		0.1226
Player 13	0.1	1	0.1263				
Player 1	0.1	1	0.0006	1.99	0.0008	0.3784	0.0006
Player 2	0.1	1	0.1086	1	0.1435		0.1008
Player 3	0.1	1	0.1260	0.01	0.1665		0.1259
Player 13	0.1	1	0.1266				

From the above numerical simulation, player 2, British Columbia, as a non-coalition player was found to be made better off. The explaination of this result is as follows. When British Columbia knows that the other two players, Washington/Oregon and Alaska, have formed a subcoalition which is aimed at conserving the stock by sub-cooperation, then it will change its harvest strategy by catching more to maximize its own profit. In other words, British Columbia will benefit from the American subcoalition. This is another instance of the free rider problem. So, the only way to conserve the stock, in this three player model, is to achieve full cooperation by all players.

Subcoalition 3. Subcoalition between British Columbia and Alaska. This subcoalition is unlikely, because if Alaska refuses to cooperate, then British Columbia can punish them only by hurting Washington/Oregon while having no effect on Alaska's fishery production. The more probable subcoalitions are either between Washington/Oregon and Alaska (subcoalition 2) or British Columbia and Washington/Oregon (subcoalition 1).

One of the most striking results of the model is that while it is always beneficial to form a coalition involving all players, it is not the case that two players can gain by forming a subcoalition. This result may sound counter-intuitive at first, because one would have thought that given player 2's harvest plan, player 1 and 3, by forming a subcoalition, cannot be worse off, as they could always do what they did before. However, upon reflection, this argument is flawed: when the subcoalition is formed, player 2 (the non-member) will not leave his harvest plan unchanged.

Rather he would take advantage of the subcoalition's conservationist interest. This kind of result has its parallel in the theory of mergers. Salant et.al. (1983) have shown that in an oligopoly with identical firms, any merger that consists of less than 80% of the firms in the oligopoly will be non-profitable, because the remaining firms will free ride on the merger's attempt to reduce industry output. Mergers will be profitable only if the merger firm can achieve economies of scale. This is not the case in Salant's model, nor is it the case in the fishery under consideration.

CHAPTER 4

CONCLUSIONS

The purpose of this thesis is to provide a theoretical framework for analyzing the problems of conflicts and cooperation in the exploitation of a transboundary fish stock. A theoretical model was developed to capture the essential features of strategic interactions in a dynamic context. It is hoped that the model sheds light on the conflict concerning the Pacific salmon disputes between U.S. and Canada. Unlike other renewable natural resources, fish are mobile. Some species, like the Pacific salmon, exhibit a regular migratory pattern. This migratory behavior implies that certain fish stocks are a transboundary resource and are therefore subject to two or more countries' jurisdiction and management places. These countries are typically in a "Prisoner's Dilemma" situation if they can not make a binding agreement to jointly manage the resource. However, the simple "Prisoner's Dilemma" model is insufficient to capture complicated interactions in a dynamic framework. Static game theory is a useful apparatus to analyse the behavior of interactive decision makers, however, to fully understand the conflicts involving the fishery, it is essential to incorporate dynamic elements into the model. In this thesis, the techniques of optimal control theory and differential games were used.

Most fishery models share a common characteristic: a specific linear production function with respect to effort level. Because of this feature, the optimal harvest policies are characterized by the so called "bang-bang" policy, i.e., the optimal harvest rate is either zero or equal to the maximum possible harvest rate. However, in the real world, harvest rates usually take some intermediate value between zero and the maximum possible rate. The main reason why the existing literature relies heavily on the linear specification is theoretical tractability.

In this thesis, a non-linear production function is adopted to describe the harvest behavior. The optimal harvest policy depends on optimal stock level and also optimal fishing effort. The added realism obtained from introducing non-linearity makes the model more suitable for analysing strategic behavior in the "fish war", and sheds light on the real world conflict.

Cooperative and non-cooperative games were analysed in this thesis involving three players. Because of this added complexity, the model does not yield a convenient closed form solution. The analysis was therefore carried out numerically.

The model is easily understood in its simplest form, where there are only two players. In this case, comparing the results from the cooperation and the non-cooperation scenarios, it was found that cooperation will make both countries better off. There will be a higher stock level in the steady state, and thus higher steady state harvest rates for both countries. In formulating the cooperative game, it was assumed that side payments were permitted. In the Pacific salmon dispute the main issue of contention is what are acceptable harvest shares, since direct side payments do not seem to be feasible or acceptable to the parties involved. However, there are real world situations where side payments are possible and have actually been used. An example is the fur seal fishery in the Pacific Northeast.

Four countries, Russia, Canada, United states and Japan, share the same resource. Realizing that protection is needed in order to avoid the collapse of the resource, the four countries transformed their competitive harvesting behavior into a cooperative one in 1911, in which Canada and Japan, with higher harvest costs, reduced their harvests to zero while Russia and U.S. agreed to pay Canada and Japan a certain amount of annual output (direct side payments). This case of side payments has proven to be profitable for all four players and also proved to be effective as a means of conserving the resource. Thirty years after the cooperative agreement, the stock level had increased eighteen times its size[1]. This case shows that it is not totally unrealistic to consider some form of side payments as a possible means to achieve cooperation in the Pacific salmon dispute.

With the use of numerical simulation, it was found that when the price of landed fish rises, each player will be induced to harvest more before the stock reaches its steady state. Therefore, the stock level in steady state will fall and the harvest rates in the steady state will decrease as well. This result suggests that if the price increases, there will be a possibility of a worsening of the conflict.

Another result which seems intuitively plausible is that when the rate of social time preference increases, indicating an increased impatience, the steady state stock level will decrease. This can result in a possible depletion if the non-cooperative harvest rate exceeds the natural growth rate of the stock.

The impacts of changes in cost structure are more complicated. When com-

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[1] FAO, 1992.

paring the outcomes with the benchmark situation where all players have identical cost, the following results are worth reporting:

(1) The stock level will increase under non-cooperation when the magnitude of the decrease in the harvest of the player who experiences an increase in costs is greater than the increase in the harvest of the player who experiences a decrease in cost. Under cooperation, however, the same change in the cost structure leads to a lower steady state stock level. This is because cooperation implies equalization of marginal cost, and this rule means that the player with lower effort cost should harvest much more, which implies that aggregate catch increased under cooperation. Therefore, cooperation will make both countries better off.

(2) Under coperation, production becomes more sensitive to cost changes. This is because of the productive efficiency under cooperation.

A major contribution of this thesis is the analysis of the three-player case. The numerical simulations indicate the following tendencies:

When all three players are non-cooperaitve, it was found that, compared with the two-player non-cooperative game, the steady state stock level will decrease. This is because there are more players competing for the same fishery resource. It was also found that changes in the cost structure will lead the stock level to decrease in both the cooperative and the non-cooperative games. The empirical results show that the magnitute of increase in the harvest rate of the player who experience a decrease in cost is greater than the decrease in the harvest rate of the player who suffers an increase in cost.

In the three-player game, a comparison of the three-player non-cooperative scenario with the three-player cooperative scenario showed that the stock level in the steady state will increase under cooperation. This is qualitatively the same as in the corresponding two-player games. The impacts of changes in price and in cost structure on stock level in the three-player cooperative game are similar (in direction, though not in magnitude) to the impacts in the case of a two-player cooperative game.

The possibility of subcoalition enriches the results of the analysis. For concreteness, the case of a subcoalition between Alaska and Washington/Oregon was analysed. This subcoalition seems to be the most plausible one because of political considerations. The non-coalition member is British Columbia. A subcoalition between two players result in a lower steady state stock level than that obtained under full cooperation. The harvest rates of the coalition and the non-member are both higher than under full cooperation before the stock reaches its steady state.

It was also found that the non-subcoalition member, British Columbia, will be better off in this game. This occurs because, knowing that the other two players, Washington/Oregon and Alaska, form a subcoalition which is aimed at conserving the stock, British Columbia will free ride on the subcoalition's restraints, and change its harvest strategy by catching more to increase its own profit. This implies that the benefit from stock conservation by a U.S. subcoalition would go partly to the Canadian fishers. The subcoalition's profit will fall. This result may seem at first surprising, but actually it is accordance with the static theory of mergers.

The main conclusion of this theory (see Salant et. al. (1983)) is that mergers may not be profitable unless the cost of the merged firm becomes substancially lower. This is because other firms will free ride on the merger's output restriction. The model developed in this thesis suggests that the only way to conserve the stock, when more than two players are involved, is to try to achieve full cooperation. This result may help to explain, at least partly, the reason why the American side has not achieved a subcoalition agreement. It may also explain why the Canadian side tries to bargain with the U.S. at the national level rather than seperately with Alaska or Washington/Oregon.

The game-theoretic approach was adopted in this thesis because its basic assumptions of rationality and strategic behavior seem to fit a variety of real world situations, and in particular the Pacific salmon fish war. The reader is cautioned that the model has not been empirically estimated. However, one should expect that the policy conclusions derived from an empirically estimated model to be similar to the ones identified in this thesis.

Further research involving empirical analysis is needed. For such empirical research, it is essential to estimate the natural growth function of the various salmon species, as well as the harvesting production functions. Data on natural growth functions and on stocks are unfortunately very inadquate. This is partly because the reproduction rates of salmon are very difficult to estimate, compared with other fish species.

Appendix 1

[Case 1a]: Two-player Game Under Non-cooperation

The current value Hamiltonian is:

$$\tilde{H} = 2x^{\frac{1}{2}}n_1^{\frac{1}{2}} - n_1 + \psi_1 \left[x(1-x) - 2x^{\frac{1}{2}}n_1^{\frac{1}{2}} - 2x^{\frac{1}{2}}n_2^{\frac{1}{2}} \right]$$

According to maximum principle, the necessary conditions are:

$$\frac{\partial \tilde{H}}{\partial n_1} = 0, (1-\psi_1)\, x^{\frac{1}{2}}n_1^{-\frac{1}{2}} - 1 \leqslant 0, (=0, \quad \text{if} \quad n_1^* > 0) \tag{4.1}$$

$$\dot{\psi}_1 = \delta\psi_1 - \frac{\partial \tilde{H}}{\partial x} = \left(\delta - 1 + 2x + x^{-\frac{1}{2}}n_2^{\frac{1}{2}}\right)\psi_1 - x^{\frac{1}{2}}n_1^{-\frac{1}{2}}(1-\psi_1) \tag{4.2}$$

$$\dot{x}(t) = \frac{\partial \tilde{H}}{\partial \psi_1} = x(1-x) - 2x^{\frac{1}{2}}n_1^{\frac{1}{2}} - 2x^{\frac{1}{2}}n_2^{\frac{1}{2}} \tag{4.3}$$

From (4.1), if $n_1^* > 0$, then:

$$1 - \psi_1 = x^{-\frac{1}{2}}n_1^{\frac{1}{2}} \tag{4.4}$$

Differentiate (4.4) with respect to time, it can be obtained:

$$-\dot{\psi}_1 = \frac{1}{2}x^{-\frac{1}{2}}n_1^{-\frac{1}{2}}\dot{n}_1 - \frac{1}{2}x^{-\frac{3}{2}}n_1^{\frac{1}{2}}\dot{x} \tag{4.5}$$

Adding (4.2) , (4.5), and using (4.4), we can get the following equation:

$$-\frac{1}{2}x^{-\frac{1}{2}}n_1^{-\frac{1}{2}}\dot{n}_1 = \left[1 - \left(\frac{n_1}{x}\right)^{1/2}\right]\left[\delta - 1 + 2x + \left(\frac{n_2}{x}\right)^{1/2}\right] - \frac{n_1}{x} - \frac{1}{2}x^{-\frac{3}{2}}n_1^{\frac{1}{2}}\dot{x} \tag{4.6}$$

where

$$\frac{1}{2}x^{-\frac{3}{2}}n_1^{\frac{1}{2}}\dot{x} = \frac{1}{2}\left(\frac{n_1}{x}\right)^{1/2}\left[(1-x) - 2\left(\frac{n_1}{x}\right)^{1/2} - 2\left(\frac{n_2}{x}\right)^{1/2}\right]$$

Similarly, for player 2:

$$-\frac{1}{2}x^{-\frac{1}{2}}n_2^{-\frac{1}{2}}\dot{n}_2 = \left[1 - \left(\frac{n_2}{x}\right)^{1/2}\right]\left[\delta - 1 + 2x + \left(\frac{n_1}{x}\right)^{1/2}\right] - \frac{n_2}{x} - \frac{1}{2}x^{-\frac{3}{2}}n_2^{\frac{1}{2}}\dot{x} \tag{4.7}$$

where

$$\frac{1}{2}x^{-\frac{3}{2}}n_2^{\frac{1}{2}}\dot{x} = \frac{1}{2}\left(\frac{n_2}{x}\right)^{1/2}\left[(1-x) - 2\left(\frac{n_2}{x}\right)^{1/2} - 2\left(\frac{n_1}{x}\right)^{1/2}\right]$$

Using symmetry, $n_1 = n_2 = n$, and solving equations (4.3), (4.6) and (4.7) at the steady state, $\dot{x} = 0$, it is obtained:

$$\left(\frac{n}{x}\right)^{1/2} = (1-x)/4 \tag{4.8}$$

and $\dot{n} = 0$, it can be obtained:

$$\frac{1}{2}\left(\frac{n}{x}\right)^{1/2}\left[\delta - 1 + 2x + 2\left(\frac{n}{x}\right)^{1/2}\right] - \frac{n}{x} = 0 \tag{4.9}$$

By solving (4.8) and (4.9), the steady state stock level under non-cooperation is determined by:

$$x_\infty^N = \left[-(5+\delta) + \sqrt{(5+r)^2 + 6(2.5 - 3\delta)}\right]/3 \tag{4.10}$$

for (4.10)$\geqslant 0$, if $2.5 - 3\delta \geqslant 0$. In the steady state, the optimal catch rate is given as:

$$h_\infty^N = 1/2x_\infty^N\left(1 - x_\infty^N\right) \tag{4.11}$$

Appendix 2

[case 1b]: Two-player Game Under Cooperation

The current value Hamiltonian is:

$$\tilde{H} = \left[2x^{\frac{1}{2}}n_1^{\frac{1}{2}} - n_1 + 2x^{\frac{1}{2}}n_2^{\frac{1}{2}} - n_2\right] + \psi\left[x(1-x) - 2x^{\frac{1}{2}}n_1^{\frac{1}{2}} - 2x^{\frac{1}{2}}n_2^{\frac{1}{2}}\right] \quad (4.12)$$

According to maximum principle, to maximize $\tilde{H}$ by choosing n_1, n_2, that is:

$$\frac{\partial \tilde{H}}{\partial n_1} = 0, \qquad \frac{\partial \tilde{H}}{\partial n_2} = 0$$

which generate the following two equations:

$$x^{\frac{1}{2}}n_1^{-\frac{1}{2}}(1-\psi) - 1 \leqslant 0, \ (=0, \quad \text{if } n_1^* > 0)$$

$$x^{\frac{1}{2}}n_2^{-\frac{1}{2}}(1-\psi) - 1 \leqslant 0, \ (=0, \quad \text{if } n_2^* > 0) \quad (4.13)$$

Using symmetry to assume that $n_1 = n_2 = n$, and from the optimality necessary conditions, it can be obtained:

$$\dot{\psi} = \delta\psi - \frac{\partial \tilde{H}}{\partial x} = (\delta - 1 + 2x)\psi - \left(x^{-\frac{1}{2}}n_1^{\frac{1}{2}} + x^{-\frac{1}{2}}n_2^{\frac{1}{2}}\right)(1-\psi_1) \quad (4.14)$$

Solving (4.13) and (4.14):

$$-\frac{1}{2}x^{-\frac{1}{2}}n^{-\frac{1}{2}}\dot{n} = \left[1 - \left(\frac{n}{x}\right)^{1/2}\right][\delta - 1 + 2x] - 2\frac{n}{x} - \frac{1}{2}x^{-\frac{3}{2}}n^{\frac{1}{2}}\dot{x} \quad (4.15)$$

The transition equation is:

$$\dot{x}(t) = \frac{\partial \tilde{H}}{\partial \psi} = x(1-x) - 2x^{\frac{1}{2}}n_1^{\frac{1}{2}} - 2x^{\frac{1}{2}}n_2^{\frac{1}{2}} = x(1-x) - 4x^{\frac{1}{2}}n^{\frac{1}{2}} \quad (4.16)$$

In a steady state, $\dot{x} = 0 = \dot{n}$, from (4.15) and (4.16), it can be obtained:

$$-\left[1 - \left(\frac{n}{x}\right)^{1/2}\right](\delta - 1 + 2x) + 2\frac{x}{n} = 0 \quad (4.17)$$

and

$$\left(\frac{n}{x}\right)^{1/2} = (1 - x)/4 \tag{4.18}$$

solving (4.17), (4.18), the steady state level of stock under cooperation is determined by:

$$x_{\infty}^{Coop} = \left[-(6+\delta) + \sqrt{(6+\delta)^2 + 6(3.5 - 3\delta)}\right]/3 \tag{4.19}$$

and the steady state catch rate is given by:

$$h_{\infty}^{Coop} = 1/2x_{\infty}(1 - x_{\infty}) \tag{4.20}$$

Appendix 3

[Case 2a]: Two-player Game Under Non-cooperation

The current value Hamiltonian is:

$$\tilde{H} = \left(pAx^b n_1^{1-b} - w_1 n_1\right) + \psi_1 \left[x(1-x) - Ax^b n_1^{1-b} - Ax^b n_2^{1-b}\right]$$

$$\frac{\partial \tilde{H}}{\partial n_1} = A(1-b)(p-\psi_1)\left(\frac{n_1}{x}\right)^b - w_1 = 0 \tag{4.21}$$

$$\dot{\psi}_1 = \delta\psi_1 - \frac{\partial \tilde{H}}{\partial x} = \psi_1\left[\delta - 1 + 2x + Ab\left(\frac{n_2}{x}\right)^{1-b}\right] - Ab(p-\psi_1)\left(\frac{n_1}{x}\right)^{1-b} \tag{4.22}$$

From (4.21):

$$(p-\psi_1) = \frac{w_1}{A(1-b)}\left(\frac{n_1}{x}\right)^b \tag{4.23}$$

Differentiate (4.23), it can be obtained:

$$-\dot{\psi}_1 = \frac{bw_1}{A(1-b)}\left(\frac{n_1}{x}\right)^b\left[\frac{\dot{n}_1}{n_1} - \frac{\dot{x}}{x}\right] \tag{4.24}$$

Adding (4.22), (4.24), we can get:

$$-\frac{bw_1}{A(1-b)}\left(\frac{n_1}{x}\right)^b\left[\frac{\dot{n}_1}{n_1} - \frac{\dot{x}}{x}\right] = \left[p - \frac{w_1}{A(1-b)}\left(\frac{n_1}{x}\right)^b\right]\Theta_2 - \frac{bw_1}{(1-b)}\left(\frac{n_1}{x}\right) \tag{4.25}$$

where

$$\Theta_2 = \left[\delta - 1 + 2x + Ab\left(\frac{n_2}{x}\right)^{1-b}\right]$$

Similarlly, we can get player $2's$ equation:

$$-\frac{bw_2}{A(1-b)}\left(\frac{n_2}{x}\right)^b\left[\frac{\dot{n}_2}{n_2} - \frac{\dot{x}}{x}\right] = \left[p - \frac{w_2}{A(1-b)}\left(\frac{n_2}{x}\right)^b\right]\Theta_1 - \frac{bw_2}{(1-b)}\left(\frac{n_2}{x}\right) \tag{4.26}$$

where

$$\Theta_1 = \left[\delta - 1 + 2x + Ab\left(\frac{n_1}{x}\right)^{1-b}\right]$$

$$\dot{x} = x(1-x) - Ax\left(\frac{n_1}{x}\right)^{1-b} - Ax\left(\frac{n_2}{x}\right)^{1-b} \tag{4.27}$$

In a Steady State: $\dot{x} = \dot{n}_1 = \dot{n}_2 = 0$, from (4.27), (4.25) and (4.26), the following three equations are obtained:

$$(1-x) - A\left(\frac{n_1}{x}\right)^{1-b} - A\left(\frac{n_2}{x}\right)^{1-b} = 0 \tag{4.28}$$

$$\left[p - \frac{w_1}{A(1-b)}\left(\frac{n_1}{x}\right)^b\right]\left[\delta - 1 + 2x + Ab\left(\frac{n_2}{x}\right)^{1-b}\right] - \frac{bw_1}{(1-b)}\left(\frac{n_1}{x}\right) = 0 \tag{4.29}$$

$$\left[p - \frac{w_2}{A(1-b)}\left(\frac{n_2}{x}\right)^b\right]\left[\delta - 1 + 2x + Ab\left(\frac{n_1}{x}\right)^{1-b}\right] - \frac{bw_2}{(1-b)}\left(\frac{n_2}{x}\right) \tag{4.30}$$

Let's define: $y_1 = n_1/x$, $y_2 = n_2/x$, then the above three equations become as follows:

$$x = 1 - Ay_1^{1-b} - Ay_2^{1-b} \tag{4.31}$$

$$\left[p - \frac{w_1}{A(1-b)}y_1^b\right]\left[\delta - 1 + 2x + Aby_1^{1-b}\right] - \frac{bw_1}{(1-b)}y_1 = 0 \tag{4.32}$$

$$\left[p - \frac{w_2}{A(1-b)}y_2^b\right]\left[\delta - 1 + 2x + Aby_2^{1-b}\right] - \frac{bw_2}{(1-b)}y_2 = 0 \tag{4.33}$$

Substitute (4.31) into (4.32), (4.33), we can get the following two equations, from which the optimal problem can be solved:

$$\left[p - \frac{w_1}{A(1-b)}y_1^b\right]\left[\delta + 1 - 2Ay_1^{1-b} - (2-b)Ay_2^{1-b}\right] - \frac{bw_1}{(1-b)}y_1 = 0 \tag{4.34}$$

$$\left[p - \frac{w_2}{A(1-b)}y_2^b\right]\left[\delta + 1 - 2Ay_2^{1-b} - (2-b)Ay_1^{1-b}\right] - \frac{bw_2}{(1-b)}y_2 = 0 \tag{4.35}$$

For example, let: $b = 1/2$, $A = 2$, and $z_1 = y_1^{1/2}$, $z_2 = y_2^{1/2}$, then (4.34) gives the following equation:

$$[p - w_1 z_1]\,[(\delta + 1) - 4z_1 - 3z_2] = w_1 z_1^2 \tag{4.36}$$

Solving for z_2 in terms of z_1:

$$3z_2 = (\delta + 1) - 4z_1 - \frac{w_1 z_1^2}{p - w_1 z_1} \tag{4.37}$$

Similarly

$$3z_1 = (\delta + 1) - 4z_2 - \frac{w_2 z_2^2}{p - w_2 z_2} \tag{4.38}$$

Appendix 4:

[Case 2b]: Two-player Game Under Cooperation

The objective function is:

$$Max \int_0^{\infty} e^{-\delta t} \left[pAx^b n_1^{1-b} - w_1 n_1 + pAx^b n_2^{1-b} - w_2 n_2\right] dt \tag{4.39}$$

subject to

$$\dot{x} = x(1-x) - Ax^b n_1^{1-b} - Ax^b n_2^{1-b}$$

The current value Hamiltonian is: $\tilde{H} = pAx^b n_1^{1-b} - w_1 n_1 + pAx^b n_2^{1-b} - w_2 n_2 + \psi\left[x(1-x) - Ax^b n_1^{1-b} - Ax^b n_2^{1-b}\right]$

$$\frac{\partial \tilde{H}}{\partial n_1} = A(p-\psi)(1-b)\left(\frac{n_1}{x}\right)^{-b} - w_1 = 0 \tag{4.40}$$

$$\frac{\partial \tilde{H}}{\partial n_2} = A(p-\psi)(1-b)\left(\frac{n_2}{x}\right)^{-b} - w_2 = 0 \tag{4.41}$$

$$\dot{\psi} = \delta\psi - \frac{\partial \tilde{H}}{\partial x} = \psi(\delta - 1 + 2x) - (p-\psi)Ab\left(\frac{n_1}{x}\right)^{1-b} - (p-\psi)Ab\left(\frac{n_2}{x}\right)^{1-b} \tag{4.42}$$

From (4.40), (4.41), it can be obtained:

$$\left(\frac{n_2}{n_1}\right)^b = \left(\frac{w_1}{w_2}\right) \tag{4.43}$$

Substituting, it can be obtained:

$$-\frac{w_1 \dot{z}_1}{A(1-b)} = \left[p - \frac{w_1 z_1}{A(1-b)}\right](\delta - 1 + 2x) - \frac{w_1 z_1}{A(1-b)} Abz_1^{\frac{1-b}{b}}\left[1 + \left(\frac{w_1}{w_2}\right)^{\frac{1-b}{b}}\right] \tag{4.44}$$

where $z_i = (n_1/x)^b$

Appendix 5

[Case 4a]: Three-player Game Under Full Non-cooperation

For player i, his optimization problem is:

$$\underset{n_i}{Max} \int_0^{\infty} e^{-\delta t} \left[A x^b n_i^{1-b} - w_i n_i \right] dt$$

such that

$$\dot{x}(t) = x(1-x) - \sum_{i=1}^{3} A x^{\frac{1}{2}} n_i^{\frac{1}{2}}$$

The current value Hamiltonian is:

$$\tilde{H}_i = A x^b n_i^{1-b} - w_i n_i + \psi_i \left[x(1-x) - \sum_{i=1}^{3} A x^{\frac{1}{2}} n_i^{\frac{1}{2}} \right] \tag{4.45}$$

Solve player i's optimization problem, the following conditions are obtained :

$$\left(-\frac{\dot{n}_i}{n_i} + \frac{\dot{x}}{x} \right) \left[\frac{w_i b}{A(1-b)} \left(\frac{n_i}{x} \right)^b \right] = \left[p - \frac{w_i b}{A(1-b)} \left(\frac{n_i}{x} \right)^b \right] \left[\delta - 1 + 2x + Ab \sum_{j \neq i}^{3} \left(\frac{n_j}{x} \right)^{1-b} \right] \tag{4.46}$$

In the steady state, the following equations can be obtained:

$$\left[p - \frac{w_1 b}{A(1-b)} \left(\frac{n_1}{x} \right)^b \right] \Delta - \frac{w_1 b}{1-b} \left(\frac{n_1}{x} \right) = 0$$

$$\left[p - \frac{w_2 b}{A(1-b)} \left(\frac{n_2}{x} \right)^b \right] \Delta - \frac{w_2 b}{1-b} \left(\frac{n_2}{x} \right) = 0$$

$$\left[p - \frac{w_3 b}{A(1-b)} \left(\frac{n_3}{x} \right)^b \right] \Delta - \frac{w_3 b}{1-b} \left(\frac{n_3}{x} \right) = 0$$

where

$$\Delta = \left[\delta + 1 - 2A \left(\frac{n_1}{x} \right)^{1-b} - A(2-b) \left(\frac{n_2}{x} \right)^{1-b} - A(2-b) \left(\frac{n_3}{x} \right)^{1-b} \right]$$

Appendix 6

[Case 4b]: Three-player Game Under Full Cooperation

The objective function is:

$$\underset{n_1,n_2,n_3}{Max} \int_0^{\infty} e^{-\delta t} \sum_{i=1}^{3} \left(pAx^b n_i^{1-b} - w_i n_i\right) dt$$

such that:

$$\dot{x}(t) = x(1-x) - \sum_{i=1}^{3} Ax^b n_i^{1-b} \tag{4.47}$$

The current value Hamiltonian is:

$$\tilde{H} = (p-\psi)\left(\sum_{i=1}^{3} Ax^{\frac{1}{2}} n_i^{\frac{1}{2}}\right) - \sum_{i=1}^{3} w_i n_i + \psi\left[x(1-x)\right] \tag{4.48}$$

According to the Maximum principle, it can be obtained:

$$\frac{w_1 \dot{z}_1}{A(1-b)} = -P\left\{(\delta - 1 + 2x) + \frac{w_1 b z_1^{\frac{1}{b}}}{1-b}\left[1 + \left(\frac{w_1}{w_2}\right)^{\frac{1-b}{b}} + \left(\frac{w_1}{w_3}\right)^{\frac{1-b}{b}}\right]\right\} \tag{4.49}$$

where

$$P = p - \frac{w_1 z_1}{A(1-b)}$$

and

$$\dot{x} = x\left[(1-x) - 2z_1^{\frac{1-b}{b}}\left(1 + \frac{w_1}{w_2} + \frac{w_1}{w_3}\right)\right] \tag{4.50}$$

In a steady state, with $b = 1/2$, $A = 2$, for $\dot{x} = 0$, it must satisfy:

$$x = 1 - 2\left(1 + \frac{w_1}{w_2} + \frac{w_1}{w_3}\right) z_1 \tag{4.51}$$

for $\dot{z}_1 = 0$, it must satisfy:

$$-(p - w_1 z_1)\left[\delta + 1 - 4\left(1 + \frac{w_1}{w_2} + \frac{w_1}{w_3}\right) z_1\right] + w_1 z_1^2 \left(1 + \frac{w_1}{w_2} + \frac{w_1}{w_3}\right) = 0 \tag{4.52}$$

from (4.51) and (4.52), the steady state conditions can be obtained.

Appendix 7

[Case 4c]: Subcoalition

(1). Coalition optimization problem is:

$$\underset{n_1,n_3}{Max} \int_0^{\infty} e^{-\delta t} \left[\left(pAx^b n_1^{1-b} - w_1 n_1 \right) + \left(pAx^b n_3^{1-b} - w_3 n_3 \right) \right] dt$$

such that

$$\dot{x}(t) = x(1-x) - Ax^b n_1^{1-b} - Ax^b n_2^{1-b} - Ax^b n_3^{1-b}$$

For simplicity, assume that $b = 1/2$

$$\tilde{H} = (p-\psi)\left(Ax^{\frac{1}{2}} n_1^{\frac{1}{2}} + pAx^{\frac{1}{2}} n_3^{\frac{1}{2}} \right) - w_1 n_1 - w_3 n_3 + \psi \left[x(1-x) - Ax^{\frac{1}{2}} n_2^{\frac{1}{2}} \right] \quad (4.53)$$

$$\frac{\partial \tilde{H}}{\partial n_1} = (p-\psi)\left(\frac{n_1}{x}\right)^{-\frac{1}{2}} - w_1 = 0 \quad (4.54)$$

$$\frac{\partial \tilde{H}}{\partial n_3} = (p-\psi)\left(\frac{n_3}{x}\right)^{-\frac{1}{2}} - w_3 = 0 \quad (4.55)$$

$$\dot{\psi} = \delta\psi - \frac{\partial \tilde{H}}{\partial x} = \psi\left[\delta - 1 + 2x + \left(\frac{n_2}{x}\right)^{\frac{1}{2}}\right] - (p-\psi)\left[\left(\frac{n_1}{x}\right)^{\frac{1}{2}} + \left(\frac{n_3}{x}\right)^{\frac{1}{2}}\right] \quad (4.56)$$

From (4.54) and (4.55), it can be obtained:

$$\left(\frac{n_3}{n_1}\right)^{\frac{1}{2}} = \left(\frac{w_1}{w_3}\right) \quad (4.57)$$

Substitute (4.57) into (4.56):

$$\dot{\psi} = \psi\left[\delta - 1 + 2x + \left(\frac{n_2}{x}\right)^{\frac{1}{2}}\right] - (p-\psi)\left[\left(\frac{n_1}{x}\right)^{\frac{1}{2}} + \left(\frac{n_1}{x}\right)^{\frac{1}{2}}\left(\frac{w_1}{w_3}\right)\right] \quad (4.58)$$

From (4.54), it can be obtained:

$$\left(\frac{n_1}{x}\right)^{\frac{1}{2}} = \frac{p-\psi}{w_1}\ ,\ (p-\psi) = w_1\left(\frac{n_1}{x}\right)^{\frac{1}{2}} \tag{4.59}$$

Differentiate (4.59) with respect to time:

$$-\dot{\psi} = \frac{1}{2}w_1\left(\frac{n_1}{x}\right)^{\frac{1}{2}}\left[\frac{\dot{n}_1}{n_1} - \frac{\dot{x}}{x}\right] \tag{4.60}$$

From (4.58) and (4.60):

$$\frac{1}{2}w_1\left(\frac{n_1}{x}\right)^{\frac{1}{2}}\left[\frac{\dot{x}}{x} - \frac{\dot{n}_1}{n_1}\right] = \left[p - w_1\left(\frac{n_1}{x}\right)^{\frac{1}{2}}\right]\tilde{D} - w_1\left(\frac{n_1}{x}\right)^{\frac{1}{2}}\left[\left(\frac{n_1}{x}\right)^{\frac{1}{2}}\right]\left(1+\frac{w_1}{w_3}\right) \tag{4.61}$$

where

$$\tilde{D} = \left[\delta - 1 + 2x + \left(\frac{n_2}{x}\right)^{\frac{1}{2}}\right]$$

Let

$$z_i \equiv \left(\frac{n_i}{x}\right)^{\frac{1}{2}}$$

then

$$\frac{\dot{z}_1}{z_1} = \frac{1}{2}\left[\frac{\dot{n}_1}{n_1} - \frac{\dot{x}}{x}\right]$$

and from (4.57):

$$z_3 = z_1\left(1+\frac{w_1}{w_3}\right) \tag{4.62}$$

so (4.61) becomes:

$$\dot{z}_1 = -\left(\frac{p}{w_1} - z_1\right)(\delta - 1 + 2x + z_2) + \left(1+\frac{w_1}{w_3}\right)z_1^2 \tag{4.63}$$

And from (4.54), it can be obtained :

$$\dot{x} = x\left[(1-x) - 2z_1 - 2z_2 - 2z_1\left(\frac{w_1}{w_3}\right)\right] \tag{4.64}$$

(2). For British Columbia, its optimization problem is:

$$Max \int_0^\infty e^{-\delta t}\left(pAx^b n_2^{1-b} - w_2 n_2\right) dt$$

such that

$$\dot{x}(t) = x(1-x) - Ax^b n_1^{1-b} - Ax^b n_2^{1-b} - Ax^b n_3^{1-b}$$

The current value Hamiltonian is:

$$\tilde{H} = (p-\psi_2)\left(Ax^{\frac{1}{2}}n_2^{\frac{1}{2}} - w_2 n_2 + pAx^{\frac{1}{2}}n_3^{\frac{1}{2}}\right) + \psi_2\left[x(1-x) - Ax^{\frac{1}{2}}n_1^{\frac{1}{2}} - Ax^{\frac{1}{2}}n_3^{\frac{1}{2}}\right]$$

Similarly, it can be obtained:

$$\dot{z}_2 = -\left(\frac{p}{w_2} - z_2\right)\left[\delta - 1 + 2x + z_1\left(1+\frac{w_1}{w_3}\right)\right] + z_2^2 \tag{4.65}$$

The steady state of the game between U.S (with subcoalition between Washington/Oregon and Alaska) and Canada (British Columbia) can be obtained from (4.63), (4.64) and (4.65) by setting $\dot{z}_1 = \dot{z}_2 = \dot{x} = 0$

$$z_1^2\left(1+\frac{w_1}{w_3}\right) - \left(\frac{p}{w_1} - z_1\right)\left[\delta + 1 - 3z_2 - 4z_1\left(1+\frac{w_1}{w_3}\right)\right] = 0 \tag{4.66}$$

$$z_2^2 - \left(\frac{p}{w_2} - z_2\right)\left[\delta + 1 - 4z_2 - 3z_1\left(1+\frac{w_1}{w_3}\right)\right] = 0 \tag{4.67}$$

Solving (4.66) and 4.67) numerically, (z_1^*, z_2^*, z_3^*) in a steady state can be calculated. Then, we can compute the steady state level of stock, which is given by:

$$x^* = 1 - 2z_1^*\left(1+\frac{w_1}{w_3}\right) - 2z_2^*$$

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