Abstract

The purpose of this thesis is to study models of international fisheries management and attempt to analyse under what circumstances there will be conflicts and how can these conflicts be solved. The central model framework that we use is cooperative game theory. We use this framework to study the possibilities, conditions and stability of cooperation in high seas fisheries. The cooperative game theory framework is constructed using the traditional differential games in fisheries economics. This general theoretical framework is then applied to the case of Norwegian spring-spawning herring where we use a discrete time and age-structured population dynamics model as a basis for cooperative game models and risk analysis. We show that external and internal stability of cooperation depends on several factors including technological efficiency and harvesting costs. Furthermore, the problem of uncertainty may be avoided by simple adaptive modifications to the full cooperation strategy. The international management of herring is very important since stock variations and the risk of depletion are relatively high. This is shown in a risk analysis part of the thesis.

Cooperation And Conflicts In High Seas Fisheries

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This dissertation consists of the present summary article and the following papers:

I. T. Bjørndal, V. Kaitala, Marko Lindroos and G. Munro [2000]: "The Management of High Seas Fisheries", forthcoming in *Annals of Operations Research*.

II. S. Touzeau, Marko Lindroos, V. Kaitala and J. Ylikarjula [2000]: "Economic and Biological Risk Analysis of the Norwegian spring-spawning herring Fishery", forthcoming in *Annals of Operations Research*.

III. Marko Lindroos [2000]: "Sharing the Benefits of Cooperation in the Norwegian Spring-Spawning Herring Fishery", manuscript.

IV. Marko Lindroos [2000]: Nash equilibria for a coalitional game of Atlanto-Scandian herring, manuscript.

V. V. Kaitala and Marko Lindroos [2000]: "When to Sign an Environmental Agreement: The Case of High Seas Fisheries", forthcoming in Proceedings of the Conference on the Management of Straddling Fish Stocks and Highly Migratory Fish Stocks, and the U.N. Agreement, Bergen, May 19-21, 1999.

VI. Marko Lindroos [1999]: "Restricted Coalitions in the Management of Regional Fisheries Organisations", manuscript submitted to publication.

VII. V. Kaitala and Marko Lindroos [1998], Sharing the Benefits of Cooperation in High Seas Fisheries: A Characteristic Function Game Approach, *Natural Resource Modeling*, issue 4 - special issue on Environmental Games, volume 11, 275 - 299.

CONTENTS

VII SHARING THE BENEFITS OF COOPERATION IN HIGH SEAS FISHERIES: A CHARACTERISTIC FUNCTION GAME APPROACH

1 INTRODUCTION

The last few decades have seen the collapse of several valuable fish stocks in the high seas. Several species are clearly overexploited and many fisheries suffer from overcapacity. The seas of the world are not an endless source of food and wealth anymore. It was believed until the previous century that there is no limit what the oceans are able to produce. This belief was already expressed in the Freedom of the Seas (Mare Liberum) declaration in the beginning of the 17th century. Technological development of the vessels harvesting marine resources has, however, been rapid during the latter part of the 20th century. Therefore, it is in many cases possible for each fishing nation to deplete a fish stock and thus prevent other nations from future harvesting of the species.

The overuse of the marine resources is the essence of international conflicts in the high seas[1]. In the absence of well-defined property rights, there are often strong incentives to overuse the resource resulting in the depletion of the resources, a phenomenon referred to as the tragedy of the commons[2] (Hardin 1968). It is the task of fisheries economics to seek for solutions to these conflicts. A major challenge, both in theory and in practice, is to find out how to give each country an incentive to manage the fish stocks in a sustainable and optimal way. This thesis explores several models of international fisheries management attempting to study under what circumstances there will be conflicts and how can these conflicts be solved.

1.1 Management regimes in high seas fisheries

The economic importance and the threat of conflicts in the major fisheries of the world have forced the fishing nations to negotiate in the United Nations. The objective has been to find efficient and stable internationally binding agreements on high seas fisheries conservation and management.

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[1] Disputes over management regimes of the ocean are not a very new phenomenon. John Selden presented (Mare Clausum 1635) legal arguments for England's right to sovereignty over the seas between the country and the continent, written in response to Hugo Grotius's Mare Liberum (1609).

The 1982 Law of the Sea Convention defined a new property rights regime[3] for the coastal states of the world. These countries now had sovereign rights to the exploitation of all resources within 200 nautical miles from their coastlines. One could have expected that the change from an open-access fishery to a sole-owner fishery would have erased the whole problem of overfishing, since 90% of the world's ocean harvest of fish are taken within these Exclusive Economic Zones (=EEZ). These are called shared fish stocks in the economic theory of fisheries management. Furthermore, it was generally thought that the fish stocks found adjacent to EEZs in the high seas areas were harvested largely by distant water fishing nations (DWFN) (Kaitala and Munro 1995b).

Overfishing, and conflicts and disputes over marine fish stocks, have continued. One reason is the remaining 10% of the marine fish stocks, namely the straddling and highly migratory stocks[4]. The countries harvesting mostly in the high seas (distant water fishing nations = DWFN) were not fully satisfied with the new regimes of EEZs since they reduced the DWFN possibilities to harvest marine fish stocks - in other words they now had fewer fish to harvest with the same capacity (Colburn 1997). Therefore, it became obvious to the international community that the international law on the use of marine resources, the Law of the Sea (1982), should be renegotiated. The United Nations initiated negotiations to resolve the matter in 1993. After six substantive sessions the U.N. countries were able to complete the Convention on Straddling and Highly Migratory Fish Stocks (1995, hereafter U.N. Agreement or Convention) which is the major international agreement governing these resources. This U.N. Agreement will be in a central place throughout the thesis.

A few important studies have already been published in addition to the U.N. Convention on these stocks. For example, Kaitala and Munro (1993, 1995a, 1995b, 1997) argue that the analysis of straddling and highly migratory stocks differs

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[2] Common property resources should perhaps more accurately be called free access or non-property resources since if the resources are communally owned the bioeconomic implications may be very different (Bromley 1991).
[3] For a review on economic analyses of the management regimes of the ocean see Rettig (1995).
[4] For a review on the straddling and highly migratory fish stocks see Meltzer (1994).

substantially from the well-developed theory of shared fish stocks. The shared fish stocks on the other hand have been analysed by Munro (1979), Clark (1980) and Kaitala & Pohjola (1988).

1.2 Objectives and Methodology

1.2.1 Terminology of high seas fish stocks

Transboundary high seas fishery resources may be classified into four categories (Munro 1999): A) Shared fishery resources that are found within the EEZs of one or more coastal states. B) Anadromous species (for example salmon) which migrate from the EEZ to the high seas and back again. C) Highly migratory stocks (for example tuna species) move to and from the EEZs and the adjacent high seas. D) Straddling stocks (for example Norwegian spring-spawning herring) is a catchall term for all other species that are found both within the EEZs and the adjacent high seas.

The economic analysis for categories C) and D) has been in all applications similar and this approach is also taken in this thesis since the categories are economically and strategically similar. The economic analysis of shared stocks has been widely used as a benchmark or starting point in the analysis of straddling and highly migratory stocks. Therefore, it is also essential to review the main results of the shared stock literature.

1.2.2 Objectives

Research on straddling and highly migratory fish stocks is not by any means comprehensive. Several aspects of the problem are yet unexplored. In this study, we present applications of coalitional bargaining approach or cooperative game theory to this highly complex problem. The main purpose is to gain insights to the multinational bargaining process, which is needed in the analysis of these stocks, since fish are harvested within the jurisdiction of several countries in contrast to the binational harvesting of shared fish stocks. This need for analysis was already indicated in Kaitala and Munro (1993).

It is often claimed that no international institution exists that could enforce cooperative arrangements even if the countries would be able to negotiate such agreements (Jeppesen and Andersen 1998). However, in reality international agreements exist and cooperation has been successful in many instances - see for example Schram Stokke and Hoel (1991) for the case of Barents Sea fisheries where bilateral cooperative arrangements between Norway and Russia are discussed.

Furthermore, during the negotiations for the agreement on Straddling and Highly Migratory Stocks there was true cooperative spirit that is often not seen in similar contexts (Fontaubert 1995). This cooperative spirit is also reflected in the actual Convention text, namely article 8 states that "Coastal States and States fishing on the high seas shall, in accordance with the Convention, pursue cooperation in relation to straddling fish stocks and highly migratory fish stocks either directly or through appropriate subregional or regional fisheries management organisations or arrangements" (United Nations 1995). Thus, a cooperative game-theoretic approach is a natural choice for analysing the problems of high seas fisheries.

1.2.3 Methodology

The central methods used in the current thesis are based on the theory of cooperative games with transferable utility. This theory has long traditions in game theory and has been applied to a variety of fields in economics. Cooperative game theory was already an important part of the work by von Neumann and Morgenstern (1947). For textbooks containing material in cooperative games see Shubik (1984), Friedman (1991), Mesterton-Gibbons (1992), Moulin (1995) and Myerson (1997).

Cooperative game theory allows for any combination of countries to join together, that is, to form coalitions. The characteristic function of the game assigns a real number, a value, to each of these coalitions. Based on these coalitional values solutions can be calculated to the game. These solutions give predictions how the players negotiate and what is the outcome of these negotiations. Note that in the base theory of cooperative games strategies have less direct importance as compared to non-cooperative games.

The cooperative solutions may be sets or single points. An important set of solutions is the core of the game. The core contains all allocations that are individually and coalitionally rational. In other words no country or coalition would be better off by acting on its own inside the core. The solutions producing a single point that are used in the present thesis are Shapley value and nucleolus. Shapley value (1953) calculates the average of the marginal contributions of each country to each coalition when the formation of any coalition is equally likely. Nucleolus (Schmeidler 1969) maximises the satisfaction of the least satisfied coalition. For axioms behind the solutions see essay (VII). For other cooperative value solutions see for example Tijs (1987).

The core conditions are stability conditions for cooperative solutions since if the conditions are not satisfied full cooperation will not be optimal for some of the coalitions[5]. However, it is often necessary to consider stability that arises from the potential free-riders of an agreement. In this thesis the view of Chander and Tulkens (1995) is adopted where the outside players of coalitions play non-cooperatively against the coalition members. In particular, in (IV) and (VI) I study both external and internal stability of the regional fisheries management organisation for Norwegian spring-spawning herring. External stability is essentially the analysis of the new member problem where it may or may not be optimal for the new entrant to join the cooperative management organisation. Internal stability means that no country wishes to leave cooperation. This means that if the benefits of playing non-cooperatively against the rest of the fishing nations are greater than cooperating with those nations then a country wishes to leave the coalition and thus, the coalition is not internally stable.

When we take the view that coalition members play non-cooperatively against outside players we also have to specify what we mean by non-cooperation. In the current thesis non-cooperative behaviour is given by Nash strategies (Nash 1951), that is, equilibrium strategies where unilateral deviations from the equilibrium are not profitable for any coalition. In Costa Duarte et al. (2000) the non-cooperative behaviour of countries and coalitions is given by the traditional open access adaptive strategies where countries increase their fishing effort if profits are positive and vice versa. The methodology used in the essays (III) and (IV) differs from the work by Costa Duarte et al. (2000) with respect to the non-cooperative behaviour of the

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[5] Moulin (1995) sees core stability as self-enforcing but not binding.

outsider countries. For analysis of open access harvesting in the case of Norwegian spring-spawning herring see Bjørndal et al. (2000) and Junttila et al. (1999).

In essays (III) and (IV) the game-theoretic simulation models are quasi-static (see Mesterton-Gibbons 1993) in the sense that the stock of herring evolves dynamically but the players make their decisions at the beginning of the game for the whole duration of the game. However, essay (III) also contains dynamic analysis of the Shapley value.

The essays (V), (VI) and (VII) are models of differential games where the resource dynamics is given by a differential equation that is linear in strategies (controls). Thus, the equilibrium strategies are bang-bang type of discontinuous strategies, that is, harvesting takes place at no effort, maximum effort or steady state effort (see Clark 1980). Essays (VI) and (VII) incorporate the traditional differential game model based on the Clark and Munro optimal control problem (1975) and studied for example by Clark (1980) and Kaitala & Munro (1993) to the theory of cooperative games. Cooperative solutions are also compared to the Nash bargaining solution (1953). In (V), (VI) and (VII) the models are continuous in time and the stock is treated as an aggregated state variable.

The biological modelling of the Norwegian spring-spawning herring case is discrete-time and age-structured[6]. Original biological model is by Patterson (1998) and the simulation model is based on Touzeau et al. (1998). The growth of the stock follows the Ricker function and new recruits to the stock are delivered by the Beverton-Holt function (see Hilborn and Walters 1992). For calibration of the biological model see Junttila et al. (1999). We show there that the model is able to predict the actual development in stock level reasonably well. However, there may be difficulties in long-term forecasting. The economic pert of the model uses cost estimations by Bjørndal and Gordon (1998).

Hilborn and Walters (1992) describe the most common risk indicators as "what percentage of years the stock will be below some specified level". Risk analysis in essay (II) was conducted using this standard idea. However, we also adopted another common risk assessment method described in Francis and Shotton (1997). We performed Monte Carlo simulations to calculate the percentage of risky simulations. A simulation is said to be risky if the critical variable decreases below an associated threshold level at least once. The idea was to assess the economic and biological risks using this twofold measure of risk. For biological risk it is more important to study whether the stock falls below the critical level at least once since then the stock may collapse. However, for the economic risk a more reasonable measure of risk is how long the fishery is making losses. For approaches of risk management and a review of risk analysis literature applied to fisheries see Francis and Shotton (1997). Also see Francis (1991), Ianelli and Heifetz (1995) for similar approaches that have been used in the current thesis.

1.3 Modelling cooperation and conflicts in fisheries

The economic theory of fisheries economics has come a long way from the early work by Gordon (1954)[7]. The developments in dynamic methods and game theory have both benefited the possibilities for detailed analysis. For a recent review on fisheries economics see (Bjørndal and Munro 1998). Markusen (1975) analysed among the first the problems of international common property resources. By comparing the international and national optimums he stressed the importance of transfer payments as a method to sustain cooperation.

The number of applications of economic game theory to problems of international fisheries management has grown rapidly during the 1990's. For reviews see Munro (1990), Mesterton-Gibbons (1993), McKelvey (1997) and Sumaila (1999). Game theory has been seen as a useful tool in analysing cooperative and non-cooperative behaviour of harvesting a common resource. In this thesis, the emphasis is in cooperative game theory. However, all the models contain non-cooperative ingredients as well.

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[6] The simulations in essays (II), (III), (IV) and (V) were all performed using Matlab 5.
[7] In fact the major results of Gordon (1954) of open access equilibrium leading to overexploitation and zero profits were already discovered in 1911 by a Danish economist Jens Warming (Andersen 1983).

The first contributions on economic analysis of the United Nations Convention on Straddling and Highly Migratory Fish Stocks were made by Kaitala and Munro (1993, 1995a and 1995b). They were the first to note the new entrant problem. Article 8 of the U.N. Convention states that any country having real interest in a high seas fishery must be allowed entrance to the existing regional fisheries management organisation. However, if a country refuses to abide by the management regime then membership may be denied. On the other hand, it would be almost impossible to exclude the coastal fishing nations from harvesting within their own Exclusive Economic Zone (EEZ) since the Law of the Sea Convention of 1982 is in force. Kaitala and Munro (1993) predict that the likelihood of achieving stable cooperation will be very low if the new member problem is mishandled. Indeed, also Datta and Mirman (1999) have shown that with an increasing number of countries the inefficiency of the non-cooperative equilibrium generated by the common access feature of high seas dominates and overharvesting increases.

1.3.1 Management of high seas fisheries

Kaitala and Munro (1995a) show that if the new member problem is assumed non-existent then the game characterising the exploitation of high seas fisheries (straddling stocks) will be very similar than in the case of shared stocks. Consequence of non-cooperation will be overexploitation and the need for a cooperative management regime is evident. The optimal cooperative regime will be such that the more efficient (the country with lower unit costs of harvesting) acts as a sole owner in the fishery and compensates the other player through transfer payments. In their model, the excess economic return or cooperative benefits will be divided according to the Nash bargaining solution that gives each player its threat point (non-cooperative) payoff and an equal share of the cooperative benefits.

For the case of new entrants Kaitala and Munro (1995a) consider a three-player game with one coastal and two distant water fishing nations. They show that the consequences of non-cooperation will be almost identical to that of an unregulated open access fishery. For the cooperative case they identify four different cases for study. The cases contain the combinations of whether or not to allow for coalitions and transfer of membership. In this thesis, we shall consider in detail the case where coalitions are allowed. For the case where transferable membership is allowed Kaitala and Munro conclude that it may be possible for some original members to gain from a threat of a possible new entrant. In Kaitala and Munro (1995b) they discuss another solution to the new entrant problem: the waiting period solution where a potential new entrant must go through a waiting period before enjoying benefits from the fishery. Both of these solutions are applied numerically to the management of North Atlantic bluefin tuna by Pintassilgo (2000). He shows that the transferable membership scheme is a better solution in guaranteeing cooperation in the tuna fishery. This view is also taken by Kaitala and Munro (1997).

In their following analysis, Kaitala and Munro (1997) discuss how the price of the membership transfer would be negotiated. Again Pintassilgo (2000) provides with some numerical results in the case of the tuna fishery. The present thesis argues that there may be some hope for solving the new member problem by establishing alternative cooperative solutions (VII). Furthermore, in (IV) I show how technological inefficiency may create incentives for the new members to voluntarily enter an existing regional fisheries management organisation. For a review of the economic issues concerning international fisheries management based on the U.N. Convention see Munro (1999).

Other approaches to the management of high seas fisheries are by Naito & Polasky (1997) and Hannesson (1997). Naito and Polasky show that Exclusive Economic Zones (EEZ) increase total welfare and this increase is higher if the number of harvesting nations increases. Derivation of these results is based on comparing Stackelberg and Nash equilibria for a dynamic game where Stackelberg case refers to the EEZ case and there are two stages in each period. They show further that as the number of distant water fishing nations increases harvests are larger and profits smaller. This is of course nothing more than a supporting result for the new member problem discussed above.

Hannesson (1997) has modelled the problems in high seas fisheries as a supergame, that is, repeated game of an infinite duration. According to the base case he finds that the number of countries in a stable cooperative equilibrium is not very large. This result is similar to the ones obtained in the analysis of global pollution problems (see for example Barrett 1994). The maximum number of participants in a cooperative arrangement is highly sensitive to the discount rate and cost of fishing. As the discount rate gets higher or costs lower the number of countries in a self-enforcing solution is reduced. Furthermore, with cost heterogeneity the number of cooperative countries may be very small. The result concerning the relationship between costs and possibility for cooperation is somewhat comparable and similar to the results obtained in this thesis (IV). In (IV) the inefficient case where cooperation is more likely means also that the costs for the countries are higher since they have to employ more vessels to be able to harvest the same amount of fish.

Hannesson (1997) goes on to investigate the case where some form of simple migration is allowed. He finds that the likelihood of cooperation is increased in the case of migration. Finally, Hannesson studies the case where there is one dominant player in a straddling stock fishery. He shows how even a minor straddling to the high seas may cause substantial losses of efficiency. For earlier version of Hannesson's analysis on likelihood of cooperation see Hannesson (1995a). In this article he stresses that a successful cooperative arrangement should have a limited number of participants. Again, this is the essence of the new member problem.

Another approach to game-theoretic analysis of migratory fish stocks is by Arnason and Magnusson (1999). They show how the migratory behaviour of Atlanto-Scandian herring (or Norwegian spring-spawning herring) affects the non-cooperative and cooperative strategies of the countries. They model the role of distance explicitly in their analysis. Hannesson (1995b) has also studied the effects of migratory patterns in a sequential game framework. He finds that the order in which the countries harvest the stock is crucial. For an overview of various approaches to management of migratory fish stocks see Arnason (1991).

1.3.2 Cooperative game theory in fisheries economics

In fisheries economics an early application of cooperative game theory is by White and Mace (1988). They argue that a fishermen's cooperative would be expected to produce more efficient behaviour than fishermen acting on their own since their harvesting behaviour resembles the sole owner case. They present a static cooperative game model in which prices are constant and costs are divided into fixed and variable costs. The four players include two fishermen and two buyers in the market. Their main result states that the ability to form stable coalitions is affected by changes in price, harvest and regulation. The need for a cooperative approach in fisheries is also studied by Jentoft (1985). The benefits of cooperative organisations are according to him, for example, more equal and fair distribution and better coordination.

The cooperative games that are studied in the current thesis also involve analysis of stability of coalitions. The agreements are said to be stable (and self-enforcing) if the benefits of being a part of the cooperative arrangement are greater than breaking the agreement. In addition, solutions to the games (Shapley value and nucleolus) are calculated which tell us predicted outcomes of the negotiations. In essay (VII) the stability of the grand coalition is guaranteed by the convexity of the game. It follows that the Shapley value always lies in the core. In the analysis of restricted coalitions I show that if the costs of distant water fishing nations are lower than for coastal nations then the restriction is stable, that is, it is optimal for DWFNs to refuse coalition formation with the coastal countries as individual countries. Furthermore, in the cooperative game models of Norwegian spring-spawning herring (IV) it is shown that the stability of coalitions critically depends on the technological efficiency of the fishing fleets. Moreover, in (III) I study the effects of uncertainty and dynamic development of Shapley value to the stability of full cooperation.

Similar studies in fisheries economics have been until the previous years scarce. Applications of cooperative game theory to North Atlantic bluefin tuna modelling (Costa Duarte et al. 2000) have shown similar results to the results in this thesis. In their model the free-rider problem is serious since only partial cooperation is stable. However, transfer payments can be used in some cases to alleviate the problem.

The literature on stable cooperation structures in the field of transboundary and global pollution is fairly large as contrasted with the cooperative fisheries economics literature. Tulkens (1998) and Finus and Rundschagen (1998) give detailed reviews of the main results. The general framework in both fields is fairly similar but there are significant differences since for example the international agreements governing these environmental problems have several points that make the analysis different. On the other hand also the real problems are different historically, geographically and politically. Therefore, it is not within the scope of this thesis to review the results of international pollution problems in detail.

Interesting studies by Jeppesen and Andersen (1998) incorporate commitment and fairness into models on international environmental agreements. In this way they are able to show that the stability of the agreements may be increased. The specific fairness concept is taken from Rabin (1993). Especially, the idea of fairness in the context of international environmental problems resembles remarkably the ideas of Hardin (1968) who talks about the need for higher morality. Cooperative game solutions are also often seen fair since they satisfy some intuitively appealing properties[8]. In dynamic games the effects of commitment periods are studied by Reinganum and Stokey (1985).

1.3.3 Other models of game theory and fisheries economics

Other models of game theory applied into fisheries economics include an early discrete time dynamic game model on fish wars by Levhari and Mirman (1980). They calculate a dynamic Cournot-Nash equilibrium where each participant's reaction depends on the stock of fish and not on previous behaviour. They proceed by starting with the static case and then introduce gradually the n-period horizon to their game. This model is a typical model explaining and illustrating the tragedy of the commons (Hardin 1968) where the non-cooperative steady state stock level is clearly smaller than in the cooperative (duopoly) case where total benefits are maximised. The model by Levhari and Mirman (1980) was later extended to the case of biological externality (Fischer and Mirman 1992) and to a case where both dynamic and biological externalities are present (Fischer and Mirman 1996). For a numerical study confirming the negative bioeconomic effects of a dynamic externality see Sumaila (1995).

[8] Cooperative solutions have been used for a long time. The first applications are found in the Babylonian Talmud (Aumann and Maschler 1985)

Another important early contribution is by Clark (1980). He has shown that the non-cooperative feedback equilibrium is discontinuous in the control variable and only the most efficient country harvests in the equilibrium. These results of Clark (1980) are used in the present thesis (V), (VI) and (VII). Dockner et al. (1989) extend the model by Clark (1980) to the case of duopoly where price depends on the quantity harvested. They show that the player with smaller unit costs is able to choose a higher catch rate. Furthermore, they show that the disadvantage of being a Stackelberg follower can be eliminated by a more efficient technology. Another extension to the Clark (1980) model is by McKelvey (1999) who shows that for closely matched fleets the countries will agree on harvesting policies where the countries may simultaneously harvest the stock and still gain profits.

Munro (1979) considered a two-country game model where the countries negotiate over the weight given to the objectives of the countries. The important assumption there is that the agreement the countries make is binding. Since the countries have different discount rates the countries agree to an optimal compromise stock level that approaches the optimal stock level of the low discount rate country. The case of self-enforcing agreements in the context of the same model class was studied later by Vislie (1987) and Ferrara and Missios (1996). Furthermore, Missios and Plourde (1997) have extended Munro's model into a case where the countries negotiate over the harvest shares. Sumaila (1997a) has confirmed the theoretical results of Munro (1979) in the case of Arcto-Norwegian cod stock.

Kaitala and Pohjola (1988) formulated a differential game model of optimal recovery of a fish stock where the agreement is enforced by trigger strategies. This means that if a country observes deviation from the cooperative agreement by another country it will switch to non-cooperation for the rest of the game. This form of retaliation is shown to sustain cooperation (see also Kaitala 1985).

Kaitala (1993) has applied stochastic games to fisheries management. He shows in a dynamic collusive game framework how cooperative and non-cooperative periods may follow one another and the changes may be frequent. On the other hand the countries may also succeed in cooperation all the time or they may never succeed in the negotiations. In this thesis, we also study a problem where non-cooperation is changed to cooperation at some point in time (V).

Game-theoretic models based on an age structured biological model are studied for example by Sumaila (1997b). He studies the consequences of non-cooperation versus cooperation in the case of two species (cod and capelin) in the Barents sea area. In the current thesis, game models based on an age structured population are found in essays (III) and (IV).

Hämäläinen et al. (1985) have applied the Kalai-Smorodinsky bargaining solution in a differential game framework. Another study that concentrates to analyse different bargaining solutions is by Armstrong (1999). She analyses an existing allocation rule for two vessel groups harvesting in the Norwegian cod fishery.

Fischer (1981) has modelled fishery management as a two-level hierarchical differential game. He shows that using only quota management does not give control over the fishing efforts. Ruseski (1998) studies the problem of excess capacity in the fisheries of the world as a two-stage game between countries where he shows that it may be optimal for the countries to have excess capacity and effort subsidies. In the first stage the countries choose the fleet size or effort subsidy. In the second stage the fleets choose effort to maximise their steady-state rents from the fishery. These results are important since many fisheries suffer from the overcapacity problem.

The non-existence of tragedy of the commons has first been shown in international fisheries context by Chiarella et al. (1984). In addition, they show that there may be multiple equilibria some of which may still result in inefficiency, that is, tragedy of the commons. Dockner and Kaitala (1989) have extended the results of Chiarella et al. (1984) to the case where the countries have zero discount rate. Kaitala (1989) shows in a differential game framework that the Nash non-cooperative feedback solution may be non-unique and for some equilibria when initial stock level is sufficiently large the non-cooperative equilibria result in Pareto-efficient utilisation of the resource. Furthermore, Takayama and Simaan (1984) have shown in a linear-quadratic game that there may be several possible types of strategies in the Nash equilibrium.

The question of whether the non-cooperative games lead to overexploitation, i.e., the tragedy of the commons is studied further by Dutta & Sundaram (1992 and 1993) and Fischer & Mirman (1992). They show that under some special circumstances it is possible that there is no tragedy of the commons, in fact there may be even underexploitation of fish stocks. Dutta and Sundaram (1993) show further that their Markov perfect equilibria are suboptimal in payoff space even if there is underexploitation of resources. However, Fischer and Mirman (1996) study a more complete version of the Fischer and Mirman (1992) model and find that (i) in the case of negative interaction of fish the countries overharvest even more than in Levhari and Mirman (1980), (ii) in the case of symbiotic interaction they overharvest less and (iii) in the case of predator-prey interaction the harvesting of predators is higher than in Fischer and Mirman (1992).

Another paper that studies the existence of the tragedy of the commons is by Datta and Mirman (1999) where they study the countervailing effects of lack of property rights and market power in a dynamic general equilibrium framework. Absence of property rights is known to encourage excessive exploitation of resources whereas market power is known to encourage limited exploitation of resources. Market power gives the ability to affect price and stock level of fish. In addition, in their model there is a biological externality present as in Fischer and Mirman (1992 and 1996). The results in Datta and Mirman (1999) show that there are conditions where the non-cooperative equilibrium is efficient. That is, again under special conditions there is no tragedy of the commons.

Moxnes (1998) conducted an experiment where the subjects were given full property rights but still they were unable to manage the fishery properly. According to his results there may be a further problem in addition to tragedy of the commons: misperception of feedback, that is, the inability to react correctly to dynamic situations. In particular, overinvestments and overutilisation of the fishery were observed.

1.4 Summary of the results

The essays of this thesis study the possibilities, conditions and stability of cooperation. In essay (I) we introduce the economic problems of high seas fisheries. In addition, essay (I) introduces the case study of Norwegian spring-spawning herring that is studied further in essays (II), (III) and (IV) of the thesis. Essay (I) is also a review of the existing literature on management of high seas fisheries.

Essay (II) is an introduction to the base modelling of Norwegian spring-spawning herring. It presents the simulation model that is used and modified in (III) and (IV). Furthermore, it studies the economic and biological risks associated with the harvesting of the herring stock. Such an analysis is very important to keep in mind when analysing the results of the cooperative games since in reality there always exist uncertainties and in the case of herring especially the biological uncertainties have played a crucial role in the past.

The essays (III) and (IV) study three-player cooperative or coalitional games on herring. The purpose is to study the stability of full cooperation and especially in (III) to study the properties of the cooperative solutions in time and under uncertainty. Essay (IV) concentrates to examine the Nash equilibria of the coalitional game. Moreover, in (IV) I study the effects of fleet efficiency to stability of cooperation and the new member problem.

In the fifth essay (V) cooperation arises from a non-cooperative game where the countries decide when they find it optimal to enter cooperation. The last two essays (VI) and (VII) study a theoretical framework that takes into account the formation of coalitions among fishing nations. Here cooperation is assumed in the first place, perhaps it has been formed by a similar process as in (V). However, the countries and coalitions do have non-cooperative options in the game. The characteristic function is calculated by considering these options and solutions are calculated to the cooperative games which give the shares that the countries receive from cooperation. Specifically, in (VI) I apply restricted coalitions to the case of regional fisheries management organisations where distant water fishing nations and coastal states negotiate as groups. The essays (V), (VI) and (VII) form a theoretical framework for the case studies in essays (III) and (IV).

Let us next go through the results of the essays in more detail. At the end of the section I shall briefly discuss some of the shortcomings and needs for future research.

The first essay (I) presents a review of the economic approaches to the management of high seas fisheries. The main conclusions are that the analysis of straddling and highly migratory fish stocks is still at an early stage and the complications as compared to similar modelling are caused mainly by increased number of players and the new member problem. Essay (I) also gives an overview of the United Convention on Straddling and Highly Migratory Fish Stocks (1995) that is important in many of the essays of this thesis. Finally, we introduce the case of Norwegian spring-spawning herring fishery and describe the present status of international management of herring. We explain why it is important to study the cooperative and non-cooperative outcomes in this context. Figure 1 shows the development of spawning stock biomass for the Norwegian spring-spawning herring (see Bjørndal et al. 1998). This is a clear example of a collapse that results if cooperation is not effective. However, the future of the herring fishery looks promising since during the recent years the herring stock has clearly recovered from the collapse.

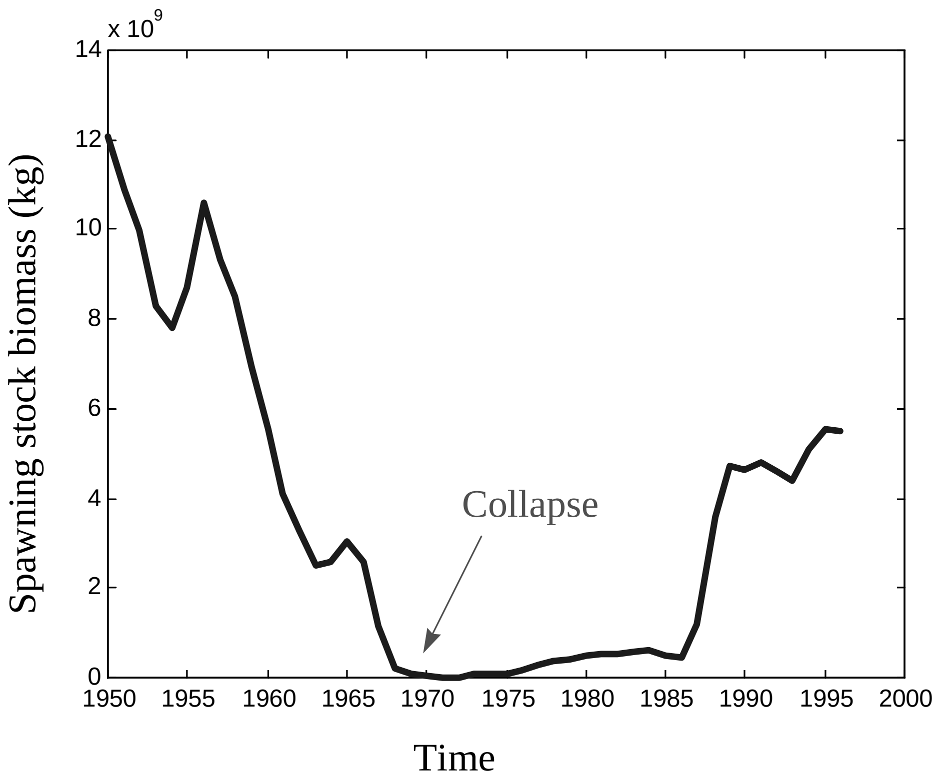

Figure 1: Collapse and recovery of the Norwegian spring-spawning herring stock

The second essay (II) shows that the Norwegian spring-spawning herring fishery is highly vulnerable to small changes in harvesting. These small changes in harvesting policy may result in large increases in biological and economic risks. We also show that if the first harvesting age of herring could be increased then in theory we could have infinite fishing effort and still a large stock level in equilibrium.

Essay (III) introduces a cooperative game model for Norwegian spring-spawning herring fishery. I analyse the shares for each country by calculating Shapley value and studying stability properties of the solution. In (III) Shapley values are also studied in time and it is shown that the grand coalition is stable at each point in time. However, if economic and biological uncertainties are considered then I find that the Shapley value is not in the core in many cases and further, the grand coalition is not stable. I present solutions to avoid the uncertainty problems that are based on simple adaptive modifications to the full cooperation strategy. Note that the optimisation is for constant harvesting policies in essays (III) and (IV). For dynamic optimisation with linear profit function see Kitti et al. (1999).

The solution to the biological uncertainty problem (III) seems to be to have a minimum level under which harvesting will not be allowed. This approach is directly related to the application of the precautionary approach of the U.N. Agreement, article 6. Thus, being cautious tends to increase the stability of cooperative arrangements.

In (IV) the analysis of (III) is extended to include an efficiency parameter. The purpose is to make each unit of fishing mortality costly so that if the countries wish to expand their harvesting they need more fishing vessels. I show that in the efficient case full cooperation is not stable and the potential new entrants do not have an incentive to join the existing regional fisheries management organisation. However, the inefficient case provides with a more optimistic prediction of cooperative behaviour. If the fleets are inefficient then full cooperation is stable and further, the new entrants to the herring fishery do have an incentive to join the cooperative arrangement.

Let us compare our results in (IV) with the results obtained in the literature of global pollution (Barrett 1994) where he founds a paradox that cooperation is possible only if it does not matter, and when it does matter cooperation is not possible. In the efficient case full cooperation is not stable even when switching to partial cooperation is already damaging to the ecosystem since the stock level will be depleted quickly below a minimum safe biological level. Also the economic cooperative benefits in the efficient case are significantly larger than in the inefficient case. However, in the inefficient case cooperation is stable but the countries and the stock would do fairly well even without full cooperation since the stock level is well above the safe level and the economic benefits of coalition (1,2) for example are not very much lower than the value of grand coalition. Thus, the result resembles the Barrett paradox (1994) a great deal.

The result of more stable cooperation structure in the case of inferior technological efficiency is also related to Hardin's tragedy of the commons (1968). He sees freedom of the seas or open access to a resource justifiable only under conditions of low-population density. It is appealing to extend this argument to the case of low technological efficiency. The risk of overexploitation with less efficient fishing fleets is obviously reduced since depletion of the stock with inefficient fishing gear and vessels is not possible. Note that in (IV) the countries could economically drive the herring stock well below the safe biological level if they would find it optimal.

In the fifth essay (V) of the thesis, we study the optimal timing of cooperative fisheries agreement. We show in a two-player game model that there may be cases where one of the countries never wishes to sign the agreement. On the other hand, there are also several cases where both players find it optimal to sign the agreement immediately. Between these extreme cases there are a number of interesting cases where one or both countries wish to wait a few periods before signing the agreement. Note that there is a time lag from the signing of the agreement before the negotiated cooperative phase of the game begins. This feature of the model reflects the actual negotiation process for reaching international environmental agreements.

The main conditions that affect the decisions of the countries are the following. First, if the initial stock level is high enough the most efficient (lowest cost) country will wait one period since in the case of high initial biomass the most efficient country will be able to benefit from an additional period of rapid depletion. Second, in many cases the way the countries share the cooperative benefits may be the key in finding an incentive for both to join cooperation immediately. This is studied using a split parameter that assigns a given percentage of the cooperative benefits to each country. Third, if both countries have a large fishing capacity then each of the countries is a serious threat to one another and consequently, cooperation will begin immediately. Fourth, if the price gets high enough then both countries find it optimal to wait for a few periods. This is due to the possibilities to gain benefits in the non-cooperative phase of the game. Finally, if the discount rate or the economic difference (unit costs of fishing) is large enough then it may be optimal for the most efficient country to never sign the agreement. In the case of high discount rate the countries are simply impatient to wait for benefit streams from the future. However, in the case of large economic difference the most efficient country is able to gain substantial benefits even in the non-cooperative equilibrium and thus, is unwilling to cooperate.

The problem of timing of an environmental agreement studied in essay (V) is one of the important problems in the theory of international environmental agreements. Other two important problems are time inconsistency and interconnectedness of agreements. Time inconsistency means that at some point in time one or several countries may find it optimal to renegotiate the agreement. Time inconsistency in the context of global climate change is studied by for example Kaitala and Pohjola (1995). Interconnectedness means that the environmental negotiations for different problems may affect each other. Furthermore, the countries may be willing to link for example trade negotiations or other political problems to international environmental negotiations. The problems of interconnectedness or issue linkage have been studied for example by Folmer et al. (1993), Folmer and van Mouche (1994), Botteon and Carraro (1998) and Kroll et al. (1998).

Jeppesen and Andersen (1998) analyse the role of commitment in environmental games. However, they do not provide a theory how commitment could form. In (V) we could interpret the willingness to sign the agreement as commitment and we provide with a detailed analysis what factors affect this commitment or moment when the countries find it optimal to sign. Thus, the economic conditions of the countries may be a part of the answer in explaining commitment.

Essay (VI) shows that if the distant water fishing nations (DWFN) have higher unit cost of fishing than the coastal fishing nations then they are better off by refusing to form coalitions individually with the coastal states. Moreover, these restricted coalitions are stable solutions only if the difference between the DWFNs is not very large and if the coastal states are not clearly superior in efficiency (costs). Otherwise, the DWFNs may have incentives to join with the coastal states.

The extension of the cooperative game of (VII) in (VI) to n players shows that there is always a veto coalition that contains the two most efficient countries. The presence of these countries is necessary for a coalition to receive a positive value. Note that the veto coalition can also be called a clan (see Tijs 1990). For the restricted game we showed that the restriction can be understood as one form of link formation. The stability of grand coalition in such cases has been studied for example by Dutta et al. (1998) They show that if link formation is simultaneous with other decisions then in a superadditive game full cooperation is obtained. Thus, there exists support for the stability of the restricted game in (VI).

Finally, in (VII) we show in a dynamic three-player game that only the two most efficient countries can gain surplus benefits of cooperation in addition to the grand coalition. We calculate and compare Shapley value and nucleolus. The results in (VII) are different from previous results obtained by Kaitala and Munro (1993 and 1997) who used Nash bargaining solution since Shapley value and nucleolus may well give a solution that divides the surplus benefits of cooperation unequally. In addition, the results and the game setting is in stark contrast to the model by Li (1998) who does not take into account any dynamic considerations when analysing the cooperative game. Most importantly, Li (1998) does not calculate the important core conditions and thus we can not be sure if individual rationality conditions are satisfied for the countries and coalitions of countries. In our model (VII) we show that the core always exists which is guaranteed by the convexity condition of the game.

Some of the results concerning the Norwegian spring-spawning herring may be seen as case-specific only. However, I have linked the results obtained to earlier research in many instances and shown that they do have similarities in the literature. Therefore, we can be optimistic on how the results could be generalised.

The cooperative game solutions may seem to lack any real application and in international terms it is difficult to be convinced that cooperation could be effectively enforced. However, I have studied the stability issues in (III) and (IV) and the results are consistent with earlier findings. Furthermore, all the cooperative models studied have non-cooperative ingredients as well.

In future research it would be important to study what are the effects of one country or a group of countries deviating from the agreement. The problem of cheating in game theory is well studied in the context of single players. However, it is also necessary to study whether individual or coalitional cheating is a bigger problem.

Another line of research could be what roles do environmental risks and uncertainty play in the decisions of countries and groups of countries. It is often useful to find some limit values and limit probabilities for given ecological indicators. In this way actual decision makers could be provided with relevant information and accurate consequences for given decisions. For game-theoretic analyses taking into account environmental uncertainties would be important since countries may have different attitudes towards environmental risks.

Finally, endogenous coalition formation could be studied in more detail. However, as Dutta et al. (1998) note this is an extremely complicated task. One has to make several simplifying assumptions to keep the model reasonable.

In the current thesis we have studied models of international fisheries management and attempted to analyse under what circumstances there will be conflicts and how can these conflicts be solved. The central model framework that we have used is cooperative game theory. We use this framework to study the possibilities, conditions and stability of cooperation in high seas fisheries. In particular, we apply models of cooperative game theory to the case of Norwegian spring-spawning herring. We show that external and internal stability of cooperation depends on several factors including technological efficiency and harvesting costs. Identifying these factors is crucial for any successful cooperative arrangement that would be negotiated for herring in the future. Furthermore, the problem of uncertainty may be avoided by simple adaptive modifications to the full cooperation strategy. This result is extremely important in the case of herring since natural variations in the stock have been high. Overall, in this thesis I have stressed the importance of sustainable international cooperation of Norwegian spring-spawning herring, and other marine fish stocks.

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