# Fishery Economics and Game Theory

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# Abstract

Game theory is an analytical tool for modeling strategic interaction between agents. Strategic interaction in fishery is interpreted as the harvest by one agent highly affects other agents' decision. This paper is a commented literature study on the fishery economics and game theory. It tends to describe how fishery models using game theory are build up. These models consist of an underlying biological models and the game-theoretical computational concepts. The paper then describes different types of fishery and how these types are related to game theory. Special features as externalities and irreversible capital are discussed. The paper then presents two classic models of fishery economics using game theory. Two newer papers using game theory are discussed. Finally, the paper concludes with ideas for further research.

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# 1. Introduction

This paper is a survey of the game-theoretic literature with fishery economics as topic and aims at describing the different concepts in the game-theoretic fisheries models focusing on challenges still remaining for further research.

Game-theoretic fisheries models combine an underlying biological model of fisheries and game-theoretic solution concepts.

Originally from two 'benchmark'-articles by Nash (1951), (1953) game theory has evolved into a powerful analytical tool for analyzing strategic interaction. The early papers of Nash discuss the effects of having two agents interacting in a non-cooperative case and in a non-cooperative case.[1] The theories, though, have been surprisingly little applied in the area of renewable resources. In renewable resources the strategic interaction between agents is of highly relevance, since renewable resources generally are exploited by several agents and one agent actions affect other agents actions.

One of the earliest applications of game theory is in political science, where Sharpley and Shubik (1954) used a solution mechanism defined by axioms, called the Shapley value, to determine the power of members of the UN Security Council. Other early applications of game theory are in philosophy, see Braithwaite (1955), in economics, see Shubik (1962) and in insurance, see Borch (1962). The application of game theory to fishery economics is relatively new; see Munro (1979) or Levhari and Mirman (1980). Munro (1979) investigates the question of optimal management of a renewable resource jointly owned by two agents. Munro combines a dynamic model of fisheries with the theory of two-person cooperative games by Nash (1953). Levhari and Mirman (1980) investigate a resource jointly owned by two agents in discrete time settings. Levhari and Mirman study the catch in a non-cooperative case relative to the catch when threat-strategies are applied and relative to catch when agents combine their resource and maximize a convex combination of discounted utilities. The application of game theory in models of fisheries has steadily increased into a general tool when discussing renewable resources. Arnason (1990) applies game theory when investigating differences between a

1 Neumann & Morgenstern (1944) are also often referred to as the introduction to the modern game theory.

sole owner-ship and a jointly owned renewable resource and further when discussing different management tools. Kaitala and Pohjola (1988) apply negotiations and threat-strategies when investigating the optimal management of a shared renewable resource. Ruseski (1998) applies the game theoretic tools when discussing motives behind subsidized fleets. A promising area for further research are, though, models of fisheries with several but a limited number of agents exploiting the renewable resource. Further, the dynamic aspect in game theoretic fisheries models has often been a discrete analog to the differential continuous time settings. Hannesson (1997) considers a model in a discrete setting when investigating the number of agents compatible with a cooperative, self-enforcing equilibrium.

The underlying biological models are introduced in section 2. Section 3 describes game-theoretical computational methods for solving problems. The following sections combine game theory and models of fisheries. Firstly, section 4 discusses different ways of having access to a fishery resource; secondly section 5 and 6 mention special features of fishery model. Thirdly, section 7 presents two of the very basic fishery economic models using the oligopoly game-theoretic concepts. Fourthly, section 8 discusses how to manage a fishery. Section 9 discusses the effect of cooperation versus non-cooperation, and how many agent are consistent with a cooperative solution. Section 10 discusses the motives behind a subsidized fleet, though the fishery suffers from overcapacity. Section 11 concludes and discusses perspectives for further research.

## 2. Underlying Biological Models

Knowledge about the ecosystem is needed in order to build up resource models. In fishery economics, to illustrate real world settings, knowledge about the resource stock and its development is required. Therefore, a biological model underlies the game-theoretic model. The biological model underlying game-theoretic fishery models can be classified into two categories; the models of the lumped parameter type and the cohort models. This section describes these two categories. The models of the lumped parameter type are the underlying biological model-type for the game-theoretic models in this paper. The cohort models are in contrast only briefly described to illustrate the differences in the biological models.

## *2.1 Model of the Lumped Parameter Type*

The model of the lumped parameter dates back to Ricker (1954) and Schaefer (1954). Ricker developed models in discrete time while Schaefer extended the model to consider continuous time. As mostly game-theoretic models are described in continuous time Schaefer's model is the most widely used. Schaefer describes the classic yield-curve relating the effort employed in the resource to the biomass level. The models of the lumped parameter type are a modest interpretation of the real world setting as the parameters describing the resource (mortality, the relationship between parent stock, explicit growth etc.) are reduced to a two parameter-model. The model of lumped parameter types is often used because of the simple structure. The following section describes the classic Schaefer-model in continuous time.

### 2.1.1 The Sustainable Yield

The Schaefer-model as described in Clark (1980) sets out the biological and production related characteristics of the fishery.

It is assumed throughout that the fish stock is a common property of the two countries. *Common property* is defined as several entities having property rights of the resource.

The model assumes a single fish stock, x, exploited by two countries, i=1,2.[2] The dynamic equation, that describes the change in the fish stock over continuous time, t, is defined as the natural growth rate, G, minus the sum of harvest rates, H.

$$\frac{dx}{dt} = G(x) - \sum_{i=1}^{2} H_i \tag{2.1}$$

The natural growth of the fish stock can be described two parameters both related to the renewable resource stock. The constant, r, is called the *intrinsic growth rate* since the proportional growth rate for small fish stocks, x,

2 The number of exploiters of the resource can easily be enlarged.

approximately equals r. The intrinsic growth rate is assumed to be positive. The constant, K, describes the *carrying capacity*, which is the capacity corresponding to an unexploited resource. The carrying capacity is also referred to the saturation level. Both the intrinsic growth rate and the carrying capacity are assumed to be constant throughout and are determined by the ecosystem. The natural growth of the fish stock is capacity times the stock yet dependent on the stock size relatively to the carrying capacity.

$$G(x) = rx\left(1 - \frac{x}{K}\right) \tag{2.2}$$

The harvest function for the fleet in a country is assumed linear for both countries. Harvest is determined by the catchability coefficient and the effort employed. The measurement for the effort employed are for instance total number of vessel-days per unit time or the number of nets, lines or traps hauled per unit of time. Employed effort is the choice variable for agents exploiting the resource. The catchability coefficient is a technological coefficient describing the ratio of catch per unit of effort of effort employed. In this case, the catchability coefficient is assumed identical for agents. Differences in the catchability coefficient can be interpreted as technological advantage.

$$H_i = qE_i x \tag{2.3}$$

The catchability coefficient is assumed equal for the two countries, which amount to assume that neither of the countries has a technological advantage over the other. Technological innovations are not considered. Further, it is assumed that there is a zero rate of discounts in both countries. The steady state is evaluated by assuming harvest equals natural growth, the change in the resource stock over time equals zero. A unique steady-state equilibrium over resource stock is derived.

$$x = \frac{K}{r}\left(r - q\sum_{i=1}^{2} E_i\right) \tag{2.4}$$

The *sustainable yield*, Y, (where yield equals harvest) is determined from (2.3) and (2.4), at the harvest level corresponding to the steady state stock level.

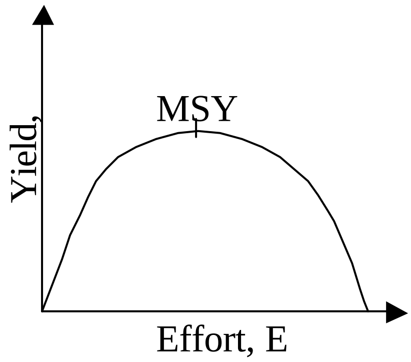


***Figure 2.1. Yield-effort curve for the Schaefer model.***

The sustainable *yield-effort curve* illustrated in figure 2.1 describes the annual catch to be sustained over a long run if a fixed level of effort is maintained. The maximal reachable yield corresponds to the maximum of the curve called the *maximum sustainable yield* (MSY). At a sufficiently high level of effort the yield falls to zero. *Biological overfishing* occurs if an effort level higher then the effort level corresponding to the MSY is employed.

### 2.1.2 Discussion on the Schaefer-model

The model assumes identical discount rates equal to zero. This assumption implies that agents are willing to make an arbitrarily large sacrifice in the current period for an arbitrarily small current sacrifice but permanent gain in the future. A positive discount rate is applied in newer models of fisheries; see for example Arnason (1990) and Hannesson (1997) showing that the discount rate is of high relevance for the harvest level. Further, the real rate of interest (equal 1 plus discount factor) is fixed but in newer literature is used in discussing returns on renewable resources; see for instance Clark (1980). The model does not operate with potential entrants e.g. new agents entering the fishery and harvesting the resource.

## *2.2 Cohort Model*

Cohort models, in contrast to the models of lumped parameter type, explicitly recognize that fish grow over time and suffer natural mortality. Beverton and Holt (1957) described the most commonly used model of this type.

This type of models argue that both the age at which fish are captured, the relationship between parent stock, average weight, number of fish in the biomass and recruitment play an important role in determining yields, see Andersen (1979). The cohort model has an important weighing between two opposite effects for a single year of recruitment; the number of fish in the biomass decreases over time as fish suffers a natural mortality but in contrast the average weight of the year increases. Therefore, it would seem realistic to consider optimal harvest using a model, which incorporates dependency of recruitment upon parent stock. The main critique on the cohort models is the assumption that recruitment is independent of the size of the stock. The rather limited application of cohort model is due to the large information requirement on the parameters describing the resource stock.

# 3. Game Theoretic Computational Methods for Solving Fishery Models

In order to define and solve game theoretic fishery models some game-theoretic concepts and computational techniques are needed. This section describes and defines some general game-theoretic concepts and computational techniques for identifying the equilibrium solutions.

## *3.1 The Non-Cooperative Strategy*

The non-cooperative simultaneous-move equilibrium is also called a Nash-equilibrium after Nash (1951). The Nash equilibrium is; A pair of strategies satisfying that each player's strategy is a best response to the other's equilibrium strategies.

A *prisoner's dilemma*-situation emerges when for every player the strategies leading to inefficient outcomes are dominant strategies. In such a situation the rents from the game are incomplete dissipated.

## *3.2 The Cooperative Strategy*

Agents playing a cooperative strategy act jointly as a single harvester maximizing aggregated profit. The cooperative solution is often called the *good-neighbors* or *social optimal* solution and is used for welfare comparisons.

Often when considering a cooperative solution, the division of the net return is not considered.

The main difference between cooperative and non-cooperative game theory is the ability to have binding agreements in the cooperative case.

Different scenarios can occur when discussing a cooperative equilibrium; Munro (1990) discusses the scenario where two agents share a resource that migrates between zones.[3] If countries have identical views to management goals, the optimization problem is straightforward; that is choosing the strategy as a sole-owner, and bargaining then takes place over the division of the net economic returns. On the contrary, the case becomes more complicated when the management goals are not uniform. The first question then is whether side payments are allowed or not. With side payments the system is the most flexible and generates the most satisfactory result, see Munro (1979). Side payments are often used in modeling fishery models, see for instance Hannesson (1997), but in practice side payments are seldom used. An example is the Arcto-Norwegian cod stock. This stock is jointly managed between Norway and Russia. Norway and Russian have different social rates of discount and different harvesting cost which leads to different management goals. A sensible economic policy for the Norwegians would appear to be renting out their fishery rights to the resource entirely to Russia which equals receiving a side payment, but Norway refuse to contemplate such a policy, see Armstrong and Flaaten (1989). Without side payments the optimization becomes a two stage bargaining process in which an agreement is first reached on harvest shares and in which attention is then turned to the question of optimal management strategy. Munro (1990) refers to this as *constrained cooperative management case*. Among bargaining approaches are to be mentioned; the Nash Axiomatic Bargaining, the Rubinstein sequential bargaining or the Kalai-Smordinsky solution, see Osborne & Rubinstein (1994).

Kaitala and Pohjola (1988) mention this limitation in the Nash Axiomatic bargaining approach as the outcome of the negotiation is assumed to be binding, which prevents the countries from deciding their strategies dynamically.

3 Called a transboundary resource, please see section 4.4 for definition.

A sustainable agreement is, according to Kaitala (1985), an agreement in which neither player has an incentive to deviate from the agreement over time e.g. there is no free riding. Therefore, Kaitala (1985) suggests that each player establishes a credible system of threats to make an agreement achievable. That is; the agents cooperating can have an incentive to deviate from cooperative strategy if a higher payoff is reachable, therefore, each party should adopt a monitoring and harvest decision strategy that would bring instant punishment to the deviator from a cooperative strategy. Kaitala and Pohjola (1988) refer this as *threat-strategies* or *Trigger-strategies* because deviation triggers a switch to play another predefined strategy. The non-cooperative strategy is often referred to as threat strategy. A *Memory-strategy* is a version of the Trigger-strategy where the agents memorize the evolution of the agreement and memorize deviations from the agreement, and thereby can decide whether to continue cooperation or not, the longer memorizing period, the stronger bargaining power.

Kaitala and Pohjola (1988) raise a second problem then cheating. That is, the problem arising from the fact, that once the cooperative management program commences, the bargaining strength of the joint owners may change as strategies are played.

The '*Tragedy of the Commons*' emerges when the common resource is over-utilized because each harvester only considers own incentives, not the effect of own actions on other harvester(s), see Hardin (1968). The 'Tragedy of the Commons' is characterized by a too high harvest level compared to the social optimum.

## *3.3 Stackelberg Equilibrium and Backwards Induction Mechanism*

A Stackelberg game is a sequential-move game, where an agent, the Stackelberg-leader, takes into account its ability to manipulate other agent's decision; the Stackelberg-follower follows the Nash non-cooperative strategy.[4] The Stackelberg game is in particular applied in models of fisheries in two scenarios; Firstly, when one country has a relative large fishing industry and therefore has the power to act as a leader. Secondly, the Stackelberg model is

4 The leader is often called, the rational or sophisticated player, while the follower is often called naïve.

applied in the discussion of stocks that migrate for instance between an Exclusive Economic Zone and the adjacent high sea, see Naito & Polasky (1997).

The Stackelberg game is usually solved using *backwards induction* if agents have complete and perfect information.[5] Complete and perfect information account for that at each level of the game each player knows the history of the game and the players' payoffs from each feasible combination of moves is common knowledge.

### *3.4 Information System in Game Theory*

Different categories of information sets are briefly described in this section. Having *open loop* information in dynamic games indicates that the players cannot observe the state of the system after time the beginning of the game and will therefore stick to the initial strategies throughout the game. A slightly modified version of the open loop solution allows players to observe the state of the system after time equals to zero but the players are not able to change strategies. The main point of the open loop solution system is the commitment to a strategy *only* in the start of the game or a pre-commitment to a sequence of actions through time only depending on the initial stock size.

In *closed loop* dynamic games players have full information on the development of the game (or the evolving of the stock) so far and are able to change strategies during the game. The actions change as a function of the state stock. The strategies depend on the current resource stock, which involves a strategic aspect. With closed loop information there is no commitment.

The *feedback* structure allows actions to be a function of the state stock. Agents have only information on the current stage not on the evolving so far. The feedback and the closed loop are often treated as one type of information set.[6]

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5 Backwards induction is also called Bellman's principle.

6 The feedback solution gives subgame-perfect equilibrium. A Nash equilibrium is *subgame-perfect* if the players' strategies constitute a Nash Equilibrium in every subgame, see Gibbons (1992). A *subgame* is a 'piece' of game that remains to be played beginning at any point at which the complete history of the game evolving thus far is common knowledge among players.

The feedback and the closed loop controls allow the players more rationality and flexibility but due to the difficulty of computing these solutions, according to Sumaila (1999), there has been a tendency in the literature to resort to the use of open loop solution concepts.

A *Supergame* has standard information and is repeated an infinite number of times. The information set is a closed loop as each agent knows all of other's agents past moves. A Supergame therefore represents a situation in which a group of agents face exactly the same situation infinitely often and always have complete information about each other's past behavior.

# 4. Types of Fishery

Different types of fishery stocks when modeling fishery economics are outlined in a game-theoretical perspective.

## *4.1 A Shared Stock*

The most common used model of fishery is a duopolistic model, consisting of two countries sharing a resource. This model is usually determining the level of the resource stock in a social optimal solution then compared to the non-cooperative and the Stackelberg equilibrium; see Levhari & Mirman (1980). This type of model, however, fails to take account of potential entrants. The information system is usually the closed loop, where agents have information about the evolving so far and have the opportunity to change strategy in each period. An enlargement of the duopolistic model to take N agents into account does not make any remarkably changes in the relative size of the resource stock level but affects the sustainability of a cooperative solution (Hannesson (1998)).[7] Throughout this paper these models are referred to as classic fishery models, there are further discussed in section 6.

## *4.2 Open Access*

An *open access fishery* is a fishery in which exploitation is completely uncontrolled. Agents can either modify effort level or there is free entry-exit

7 Section 9 gives a further discussion on the number of agents exploiting a jointly owned resource.

e.g. the number of harvesters adjusts. The Gordon-model (Gordon (1954)) as described in Clark (1990) is among the first models of fishery economics illustrating how an unregulated or open access fishery is expected to lead to economic inefficiency also called economic overfishing, while biological overfishing is expected to occur whenever price/cost ratios are sufficiently high.

The cost is evaluated as an opportunity cost and is assumed to be proportional to the effort level. The revenue is described as the yield times the price, the price is assumed constant and exogenous given, why the revenue curve has the same shape as the sustainable yield curve originally derived by Schaefer (1954). The *bionomic equilibrium* is determined where cost is equal to revenue. [8] In the bionomic equilibrium the economy is in equilibrium (profit equals zero) and the biology is in equilibrium as the change in the resource stock over time equals zero, e.g. the resource stock is able the regenerate itself at the given yield/effort level.

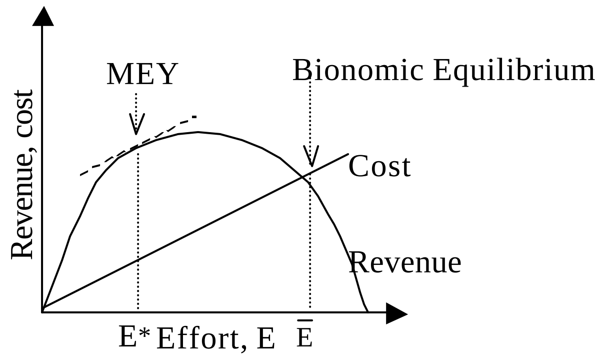


***Figure 4.1 Gordon's model of open access fishery.***

In bionomic equilibrium, where profit equals zero, each agent is acting only considering individual incentives leading to a non-cooperative equilibrium. *Biological overfishing* is defined where the effort-level employed in the resource exceeds the effort-level from which the maximum sustainable yield (MSY) can be extracted. The scenario illustrated in figure 4.1 suffers from biological overfishing as the equilibrium point falls below the MSY, popularly it is said the resource stock suffers from an overexploitation. This occurs where the costs of fishing are relative low, and thereby the price-cost ratio is relative high. The resource also suffers from *economic overfishing* as a higher economic return can be gained by reducing effort level, given the price-cost ratio. Reducing the effort level significantly (slope on the cost curve is unchanged) reaches the social optimum point E* where profit is maximized. The social optimal point is referred to as the *Maximum Economic Yield* (MEY). If the equilibrium falls below the MEY the fishery is said to suffer from economic overfishing. MEY can be difficult attain from other points on the yield curve. If the equilibrium coincides with the bionomic equilibrium it takes time to regenerate the resource stock to reach the MEY, and during the first periods returns might be small. Further, having a MEY-equilibrium is not sustainable without entry deterrence because potential entrants are attracted by the positive profit. The following section investigates the effects of a regulated open access and a limited access.

### *4.3 Regulated Open Access versus Limited Access*

In fishery models of *limited access* the number of fishing units or fishing power is controlled, this is not the case in *regulated open access*, see Anderson (1995).[9] The restricted open access is characterized by controlling only activities not fishing power or units.[10] The main instruments in a regulated open access are area and seasonal closure, limitations in fishing gear and a total allowable catch (TAC). The limited access is either direct (number of boats, traps, horse power or gross tonnage) or indirect (Individual Transferable Quota system, ITQ) control. Clark (1980) evolves a limited access case with N-exploiters with different efficiency level, the result is that inefficient producers will be eliminated but the fishery will still suffer from overfishing unless capacity happens to be small or a cooperative solution is sustainable.

The regulated open access has a limited effect on the overfishing problem in the long run as the fishermen have the opportunity to adjust their effort to the regulation, thereby are costs increased compared to the unregulated case and the economic gains are zero. This is illustrated in the following example.

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8 Bionomic is an abbreviation of biologic and economic equilibrium (bioeconomic).

9 A regulated open access is also called a restricted open access. A limited access is also called a controlled access.

10 A controlled access may also control the activities of the participants in the fishery, but the crucial point is that the number of participants is restricted.

Consider the Gordon-model (1954) is subject to a regulated open access as a seasonal closure aiming at reducing the effort level to the effort level corresponding to the MEY. The short run effect is MEY is attained if stock is assumed to regenerate immediately (!), but in the long run fishermen will adjust to the regulation. Potential entrants will enter the market or active fishermen will increase their effort by investments, to gain from the positive profit. This will increase the overall effort level, but also increase the costs. In order to maintain the yield at the desired level the season closure is increased further. This continues until agents of effort are no longer attracted to the fishery. In equilibrium the situation with overfishing is replaced by overcapacity and a highly reduced season length.[11] See figure 4.2. Though the same effort as in the original MEY is employed, it is no longer a social optimum as the costs have increased and profit is reduced to zero.

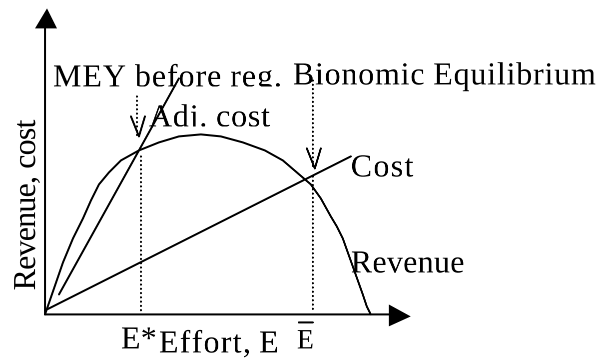


***Figure 4.2. Gordon's model with a regulated open access fishery and thereby adjustments in the cost curve.***

Another type of regulated open access is described in Homans and Wilen (1997). The industry is assumed to commit capacity each season until rents are dissipated. Regulators are assumed to set a desired harvest quota each season and then choose a season length, which ensures that the quota is achieved. The TAC is thereby obtained indirectly by setting the season length. Regulated open access equilibrium is achieved by the interaction of the industry and regulators each season. Biomass evolves between seasons according to whether the corresponding harvest is greater than equal to or less than biological growth. A long run steady state is achieved when the biomass is in equilibrium and when

11 The new equilibrium also suffers from economic overfishing as the increase in the cost function makes the MEY move to the left.

industry and regulatory behaviour are constant. Some of the properties of the regulated open access model are different from those predicted by the pure open access model. In Gordon's model rents generate excess capacity, which in turn results in excessive harvest levels. These harvest levels, coupled with biological dynamics, determine an approach to a bionomic equilibrium. In the regulated open access the existence of the regulatory structure decouples the effects of economic parameters from impacts on the biomass.

In the long run, higher biomass levels and generally even higher levels of inefficient input use, than the Gordon-model (1954) of open access would predict, characterize the regulated open access fishery.

### *4.4 Transboundary Resources*

A transboundary resource is a resource that moves, migrates or straddles across boundaries. The transboundary fishery resource models therefore also include migratory and straddling stocks models. Transboundary resource stocks can be interpreted as stocks that come and go with seasons or as stocks that covers several areas/boundaries often referred to an Exclusive Economic Zone (EEZ), see Naito & Polasky (1997). An EEZ is the zone where a coastal country has an exclusively right to fishing. The EEZ is generally defined as 200 nautical miles, where it exists.

The fisheries in the Mediterranean is subject to Highly Migratory Fishery Stocks which has the special feature that it moves from exclusive economic zones to the adjacent high seas. Tuna is an example of such a resource.

Transboundary resources may suffer from overfishing because one country does not take into account the negative effect its harvest has on other fishing countries, see Naito & Polasky (1997). Transboundary resources may result from introducing a management like EEZ. Transboundary resources are usually modeled as Stackelberg games because of the sequential move structure.

# 5. Externalities

Externalities in fishery economics can generally by defined as an exogenous effect on someone's harvest. The exogenous effect can be causes by other harvesters, the market or multispecies. The first part of this section gives a more formal definition of externalities while the second part discusses externalities in models of fisheries.

## *5.1 Defining Externalities*

Following two conditions are generally used for defining externalities.

> *'An externality is present whenever some individual's (say A's) utility or production relationships includes real (that is, nonmonetary) variables, whose values are chosen by others (persons, corporations, governments) without particular attention to the effects on A's welfare.' (Source: Baumol & Oates (1994) p. 17)*

> *'The decision maker, whose activity affects others' utility levels or enters their production functions, does no receive (or pay) in compensation for this activity an amount equal in value to the resulting benefits (or costs) to others.' (Source: Baumol & Oates (1994) p. 17)*

The first condition outline the consensus of an externality, while the second condition is required if the externality is to have all of the unpleasant consequences, including inefficiencies and resource misallocation.

Proper pricing or tax-subsidy arrangements can eliminate the misallocations. One may define an externality whenever first condition holds whether or not payments occur. Even if an efficient tax is levied harvest from a resource will no doubt be reduced but it will not be reduced to zero e.g. the externality will still occur. In such a case it seems more natural to say the externality has been reduced to an appropriate level rather then claiming the externality has been eliminated.

## *5.2 Externalities in Models of Fisheries*

In models of fisheries externalities are defined depending on who are inducing the externality. The externality induced by other harvesters on a resource stock is defined as a *dynamic externality* or *stock externality*. One harvest affects the total stock size and thereby affects other harvesters cost negatively as the resource stock is reduced. Generally, the dynamic externality is the bionomic loss, which arises when a single dynamic population is exploited by a finite number of fishers. No matter the details of the models developed, the negative bionomic effects of dynamic externality are quite significant.

The externality induced by the market is called a *market externality* and is of particular interest in duopolistic models; see Sumaila (1999) and Levhari and Mirman (1980). In these models the price of landed fish is not constant but depends on the quantity harvested by the producers. The welfare functions are therefore often measured in utility-level and not in profit functions. Profits would complicate the case as a second externality, the market externality, is introduced. That is, the countries will have to take the affect on prices into account. Further, the utility measure also takes the consumers surplus into account when discussing a country's welfare.

Multispecies interaction can also induce an externality called either *multispecies interaction externality* or *biological externality*. The externality is caused by interdependency of species in the resource stock. The species do for some reason interact and this interaction affects agents' welfare when harvesting the stock. The species can interact in three different ways; Firstly, species can interact corresponding to a symbiotic relation, where the number of one species improve the living circumstances for the other species and vice versa. Secondly, species can compete for a resource or be mutual predators a higher stock of one species decrease the number of the other species and vice versa. Thirdly, the interaction between species can correspond to a predator-prey interaction, a higher stock size of one species, say A, decrease the stock size of the other species, say B, but a higher stock size of species B increases the number of the stock size A. Traditionally, the multispecies externality has been regulated by either managing the total industry catch or aggregated industry output or ad hoc regulations of individual species not taking the multispecies interaction into account. Fischer & Mirman (1996) discuss the traditional way of regulating multispecies; Individual species harvested in separate production processes with no technological and cost interrelationships. Squires (1987) suggest that an understanding of multiproduct production at the level of the firm and limited empirical information on the firm's transformation and substitution possibilities can increase the benefits of multispecies regulation. Squires (1987) therefore suggest that, management of multispecies should be approached by regulating the production of individual multiproduct firms, this will directly regulate more than one input.

The *crowding externality* or the congestion externality is induced when an area is being such an attractive area that vessels congestion occur and therefore induces additional harvest cost on each other, see Smith (1969).[12]

## *5.3 A Pigouvian Tax*

The introduction of an appropriate tax can reduce the social damage caused by an externality. A Pigouvian tax (or effluent fee) equal to the marginal social damage levied on the generator of the externality is a policy setting that can ensure the Pareto-efficient solution. The Pigouvian tax serves to internalize the external costs that the externality-generating agent imposes on others. The externality-imposing agent faces a wrong price for his action and a corrective tax can be imposed that will lead to efficient resource allocation. The corrective tax is defined equal to the marginal 'damage' imposed by the externality. This provides an incentive for externality-imposing agent to limit the externality.

In fishery economics, as earlier mentioned, the most crucial externality is the dynamic externality. If the Pigouvian tax is used to reduce the dynamic externality the harvesters will all face a tax on harvest (e.g. landings or effort levels). The Pigouvian tax is in contrast only indirect applicable on the biological externalities; if the interaction between species is know, then a carnivorous species can be subsidized in order to reduce the stock of this species and thereby increasing the stock of the prey.

12 Smith (1969) further defines the mesh externality as the externality occurring if the mesh size (or other kind of gear restrictions) affects not only private costs and revenues of the fishermen but also the growth behavior of the fish population. Other externalities may be defined.

### 5.4 *Externalities and Property Rights*

The source of an externality is typically to be found in the absence of fully defined property rights. The following example illustrates the distortions resulting from an externality. The example also discusses the elimination of such distortion simply by an appropriate redefinition of rights.

Consider a lake to which all fishermen have free access, see Hardin (1968). One fisherman's harvest imposes a negative externality on the others as this harvest reduces the expected catch of other fishermen e.g. there is a dynamic externality. The fishermen maximize welfare individually.

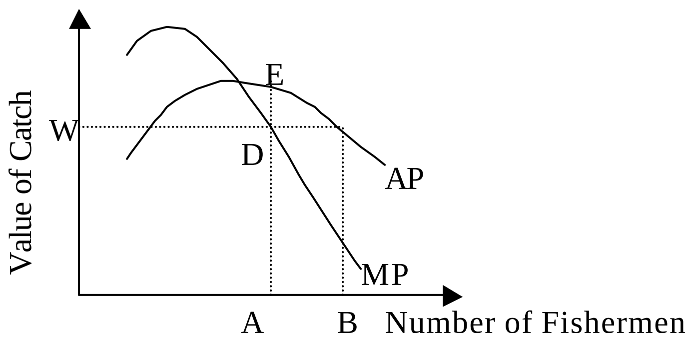


***Figure 5.1. Employment in a free access fishery.***

Assume W represents the wage (and marginal product) of alternative employments. The fishermen will then fish until their average product, AP, in money terms from fishery equals the wage they can obtain elsewhere, that is if average product from fishery employment is higher then wage from alternative employment, individuals from alternative employment will switch to fishery and the average product will decrease and vice versa. See figure 5.1. This results in B fishermen, which is obviously a too large number of fishermen compared to the social optimum because individual's fishing activity imposes costs on others because of the dynamic externality. The social optimal number of fishermen, A, is reached where the wage from alternative employment equals the marginal product, MP because the cost on an additional unit of employment (the wage) equals the gains from an additional unit of employment (the marginal product). The efficient solution can be reached by imposing a tax for admission to the lake. The Pigouvian tax equals the difference between the average product and the marginal product to the optimal number of fishermen employed, that is the difference between D and E in figure 5.1. This tax effectively internalizes the external costs a fisherman imposes on others and makes the solution efficient, but still there is no gain to the fishery unless the tax is distributed among harvesters.

Another approach to the correction of the distortion from the externality is to turn the public owned lake into a private owned lake, where one agent hires fishermen at a wage W and gets the catch in return. This will result in the owner of the lake hiring no more then A fishermen to maximize the value of the catch. The private owner or sole-owner solution is efficient.

# 6. Other special Features in Fishery Economics

## *6.1 Malleable and Non-Malleable Capital in Fishery*

Capital invested in fishing vessels is often for simplicity assumed completely reversible or completely malleable. Clark (1985) shows, that for a sole-owner the completely reversibility of capital turns cost of capital into a variable cost. Considering the capital completely malleable simplifies the cost function.

The completely irreversible capital or non-malleable capital has no resale market whatsoever for excess capacity.[13] Clark (1985) investigates the irreversibility of capital in the light of a sole-owner ship solution. The solution is divided into whether the owner has excess capacity or not at each point of time. With exceed capacity the capital level exceeds the desired capital level considering variable costs. Fixed costs therefore become irrelevant to the owner's future policy. Therefore, an optimal biomass level will correspond to the optimal biomass level chosen, when only variable costs are considered. However, if the initial capital level depreciates then at some point of time sustainable yield only considering variable costs is no longer attainable unless new vessels are brought in; fixed costs are relevant. The irreversible capital seems to give two optimal equilibrium situations in the sole-owner ship case, according to Clark (1985). One of the optimal solutions is a line of solutions,

13 In this context irreversible capital is called non-malleable though it has a depreciation rate, some would call this quasi-malleable capital.

only considering variable costs, but caused by depreciation of capital, this solution is only temporary. The unique long-run equilibrium is the same equilibrium as obtained in the case with completely reversible capital because in the very long run capital must be reversible if it is assumed to depreciate away. Clark (1985) finally mentions the case where capital has an alternative use, but is sold at a reduced price. This case evolves to the same unique long-run equilibrium.

The conclusion is, in the sole-owner solution, the irreversibility of capital does not affect the long-run solution, while short-run solution depends highly on, whether capital is irreversible or not and the initial level of capital, this is also pointed out by Clark, Clarke & Munro (1979).

Capital invested in fishing vessels and gear should be considered as something in-between malleable and non-malleable capital to be as close as possible to real world settings. The capital has more alternative use then for instance capital invested in railroads but contrary in common property fisheries excess capacity is often considered a serious problem. The depreciation factor should also be considered as, for instance, vessels and gear get lost at sea.

The irreversibility of capital makes it difficult for investors in fishery to switch to other sectors, as new capital is required. The irreversibility can make it hard to attract new investors in the industry. In real word settings especially the missing new capital in the fishery sector is a problem, for instance in the Harbor of Esbjerg, Denmark, the newest vessel in the fleet is 3 years old and the second newest vessel in the harbor is build in 1988, see Fishery Yearbook (2000).

## *6.2 Uncertainty and Fishery Economics*

Uncertainty arises as a consequence of a decision not being a single sure outcome but rather a number of possible outcomes.

Three kinds of variables play a role in a fishery economic system. Firstly, the choice variable for the decision maker plays a part in fishery economic models. The decision variable usually corresponds to the harvest level (indirect) for the fleet or the effort level (direct) employed by the fleet. The decision variable is endogenously derived in the model. Secondly, the determined variables play a role in the fishery economic system. These variables are determined by operation of the economic system, like prices in a competitive market. They are determined endogenously in the model, but are exogenously[14] to the decision maker in the model or individual agent. Finally, the environmental variables play a role. These variables are determined by some mechanism outside the economic system. They influence the outcome of the system, but the system cannot influence the variable. An obvious example of an environmental variable is the weather or the state of the nature.

Only the environmental variables are subject to direct uncertainty. Uncertainty can also arise from incomplete information. The regulator can, because of asymmetric information, have uncertainty about agents harvest functions in terms of uncertainty about the agent's cost from harvesting.

The main sources of uncertainty for sustainable fisheries management includes; the dynamic nature of the fish populations and the variability and complexity of the ecosystems of which they are a part. Further, the impact of fishing activity upon the resources, and the fact that perfect monitoring and control of harvesting in fisheries will always be problematic. Therefore, uncertainty can simply arise connected to the dynamic externality. Harvesters are without any knowledge of the level of another's harvest, which affects the size of resource stock and thereby increase cost per harvest.

# 7. Classic Examples of Fishery Model

Some classic game theoretic fishery models are presented in this section. Initially the classic results of the duopolistic fishery model are introduced comparing the social optimal solution with the non-cooperative and Stackelberg equilibria. The section continues with an oligopolistic fishery model comparing the social optimal solution to a non-cooperative equilibrium.

14 The determined variables, like prices, are, though exogenously determined to the decision maker, not necessarily fixed.

## *7.1 A Duopolistic Fishery Model*

Among the first incorporating both dynamic and strategic aspects in models of fisheries are Lehvari & Mirman (1980). The dynamic aspect enters in the biologic growth function for the fish population and the strategic aspect enters in the competition for fish between the duopolists. Three classic game-theoretic solutions are analyzed. The solutions derived in Levhari & Mirman (1980) are; the cooperative case, the Nash equilibrium and the Stackelberg case. The model is set up as an infinite repeated game in discrete time with evaluation of agents utility in each period, implying a closed loop trajectory. The essence of the problem is the dynamic externality caused by agents taking account on others strategy and that the resource stock is changing implying that actions by both agents affect future size or rate of growth.

Levhari and Mirman (1980) shows the today well-known result, that the cooperative case unambiguously results in the highest steady state stock level and the highest total welfare. The welfare is measured in utility terms to avoid the price externality on the market side. That the cooperative solution gives the highest welfare is not surprising as this is the mean of finding the cooperative solution. To compare the different solutions it must be assumed that the countries have identical discount factors. The Nash solution has a higher steady state stock quantity level then the Stackelberg case, which is caused by the Stackelberg ‘leader’ enjoying the short run catch. These results coincide with the general duopolistic theory, as the model is a traditional duopolistic model repeated to infinity and a dynamic aspect caused by the resource stock population.

### 7.1.1 Conclusion on the Duopolistic Model

The paper by Levhari and Mirman (1980) is a benchmark-article in the area applying the game-theoretical tool in models of fisheries, though a lot of critique can be given to the model. The model is a quite simple duopolistic model not yet ready for discussing topics as multispecies, market externalities etc. The critique on this model is only restricted to few comments, as development in the area has gone far beyond since; To be mentioned is the discrete time setting, it is widely agreed that the continuous time settings are closer to real world settings. Also, the assumption on identical agents, hereunder time preferences and harvesting cost has a large effect on the degree of conservatism of the fish stock. Clark (1980) shows that, if two identical agents, except from one agent being more efficient from the other, exploit a resource, then by reducing the resource stock to an appropriate level the efficient agent can eliminate its competitor. Munro (1979) shows, that a difference in social rate of discount makes the low-discount-rate country the conservationist of the two countries. If harvesting costs are unequal, the high-cost country will be the conservationist. A cooperative solution can, therefore, be difficult if side payments are not allowed. Armstrong & Flaaten (1989) investigates an empirical example of a constrained cooperative management, the case of Arcto-Norwegian cod, where side payments not are an option because of politic decisions. The consequences of non-cooperation are estimated as severe for both Norway and the former Soviet, who are the joined owners of the resource. Munro (1990) shows that the country with the lower discount rate is more patient then the other. The outcome in a linear model, where countries have different discount factors, the weight in the near future will be high for the country with the high discount factor while high value is given to the patient country in the distant future. Over time, the share will asymptotically approach the preferences of the patient country. Kaitala & Pohjola (1988) investigate the optimal recovery of a shared resource stock and conclude that the optimal recovery of the resource is not possible when no-memory feedback strategies are applied.

## *7.2 An Oligopolistic Fishery Model*

This section investigates a fishery model with several agents exploiting a single resource stock. The model is an 'enlargement' of the duopolistic model taking a fixed number of potential exploiters of the resource into account. The model compares the non-cooperative Nash equilibrium with the social optimum. The investigated model is originally discussed in Arnason (1990). The model discusses the differences in shadow price on biomass for society and a single firm. It is build up as the duopolistic model with each firm maximizing profit in each period leading to a closed loop trajectory. The model is handled in continuous time. The solution is characterized by higher social welfare in the cooperative case compared to the non-cooperative case.

### 7.2.1 The Model with N Agents

This section describes the mathematical settings of an oligopolistic model of fishery. Assume a fixed number, N, of potential agents exploit a single resource stock. At a given point of time some of the firms may not be operating in the industry.

The harvesting functions, H(·), for all potential fishing firms is determined by the effort employed in the resource and the size of the resource stock at a given time. The harvesting function is not necessary linear.

$$H_i(E_i(t), x(t)) \qquad i = 1,2,\ldots,N \tag{7.1}$$

$$E_i(t), x(t) \geq 0, \quad H(E,0) = H(0,x) = 0, \quad H_E'(E,0) = H_x'(0,x) = 0$$
$$H_E', H_x' \geq 0, \; H_E'', H_x'' \leq 0$$

Assumptions related to real world settings are made; It is assumed that the effort level, $E_i(\cdot)$ and the biomass of the fish stock x(t) are greater then or equal to zero and it is assumed that there is no harvest if there is no effort and there is no harvest if the stock is empty (the biomass of the stock is equal to zero). The marginal harvest level equals zero if the stock is empty and the change in harvest when the size of the biomass changes is equal to zero if no effort is employed.

The cost function for a single firm is determined by the effort level employed by this firm. By assumption, there are no costs for an inoperative firm and operative fishing firms experience costs even if they do not exert any fishing effort. This can be explained in real world settings, as an active firm has to pay fees for a mooring space or pay installments on the capital. The assumption on no costs for an inoperative firm is discussed in the conclusion.

$$C_i(E_i) \qquad \begin{array}{l} C(0) > 0 \text{ operative firms} \\ C(0) = 0 \text{ inoperative firms} \end{array} \tag{7.2}$$

$$C_E'(E_i) \geq 0, C_E'' \geq 0$$

The growth of the fish stock is defined by a differential equation as in the standard Schaefer model (1954) (see section 2). The change in the fish stock over time is described by the natural growth in the fish stock minus the total harvest from the fishing industry.

Market prices are exogenous given as a market price of catch, p, and a discount rate, ä, p is assumed finite and p, ä > 0. The social shadow price on biomass is defined as the value the society ascribes to an additional unit of biomass. The social shadow price on harvest equals the value the society ascribe to an additional unit of harvest. The social shadow price on the time-value of money is the value the society ascribes to an additional current unit of return relative to future return. Both price on catch and discount rate coincide with the social shadow prices why the present value of the fishing firms profits over time can be taken as a measure of social benefits.[15] Instantaneous profit function for a representative fishing firm is defined as revenue minus cost.

$$\pi_i(E_i, x, p) = p \cdot H_i(E, x) - C_i(E_i) \tag{7.3}$$

The profit function is twice differentiable and concave in the effort level and the fish stock, this is to ensure a maximum point when optimizing. The present value of a firm's future profit is defined as the discounted profit function.

$$PV_i(E_i, \{x\}, p, \delta) = \int_0^\infty \pi_i(E_i, x, p) \cdot e^{-\delta t} dt \tag{7.4}$$

The shadow price ascribed to the biomass is different depending on the single firm's view and the society's view. The central question to be examined further is the difference between the shadow prices allocated to an additional resource unit. It is obvious that the two cases are identical if there is only one firm in the industry. The social problem is determined in section 7.2.2, the single firm's problem is examined in section 7.2.3. Section 7.2.4 compares the two situations.

### 7.2.2 The Society

The social solution is defined as a sole-owner solution maximizing total welfare. To find maximum welfare an optimal time path of the fishing effort for

15 As prices coincide with social shadow prices the aggregated return from the industry equals society's welfare. If the prices did not coincide with social shadow prices consumers' should have been taking into account when deriving society's welfare.

the fishing firms is derived. The optimal path must maximize the present value of industry profits subject to the biological and the technical constraints. The mathematical problem is as follows.

$$\underset{\text{all}\{E_i\}}{\text{Max}} \sum_i PV_i(\{E_i\},\{x\},p,\delta) = \underset{\text{all}\{E_i\}}{\text{Max}} \sum_i \int_0^\infty \pi_i(E_i,x,p)\cdot e^{-\delta t}dt \qquad (7.5)$$

$$\text{s.t.} \qquad x_t' = G(x) - \sum_i H_i(E_i,x)$$

$$x, E_i \geq 0 \ \forall i$$

Where G(x) is the natural growth rate of the fish stock.

To solve the problem the Hamiltonian function is determined and the necessary conditions are then derived. The Hamiltonian is a modern control theory concept; a technique to solve dynamic optimization problems, see Conrad and Clark (1987). The Hamiltonian is determined as the objective function (here aggregated present values of firms' profit) plus the shadow value corresponding to the biological constraint times the biological constraint at steady state (here biological growth minus aggregated harvest). The first-order conditions from the Lagrangian can be written from the Hamiltonian function. A *Modified Golden Rule* for renewable resources emerges from this solution technique, giving a capital theoretic interpretation on the solution to the optimal control problem, initially introduced by Clark and Munro (1975). The golden rule originates from the Neoclassic Economic as the marginal product of capital equating the natural growth rate in the population. The modified golden rule in addition includes the discount rate, stating change in growth plus marginal stock effect equals the discount rate. The solutions technique states that two necessary conditions are meet in optimum.

The first of the necessary conditions states that the optimal harvest maximizes the Hamiltonian. In this specified case each firm's marginal benefits of effort evaluated at market prices less the shadow value of the biomass should equal its marginal costs of effort. ì describe the social shadow value of the biomass.

$$(p-\mu)H_{E_i} - C_{E_i} = 0 \ \forall i \qquad (7.6)$$

The second of the necessary conditions describes the movement of the shadow value on biomass. The movement of the shadow value is defined as the discounted social shadow value less the first order derivative of the Hamiltonian with respect to the biomass level.

$$\mu' = \mu\left(\sum H_x + \delta - G_x\right) - p\sum H_x \tag{7.7}$$

Where ì describes the current shadow price of an additional unit of the biomass along the optimal path and ì' describes the optimal time path for the social shadow price.

The bionomic equilibrium consists of equilibria in both the biological system and the economic system. In a bionomic equilibrium the changes in the resource stock must equal zero, the biological equilibrium, and the changes in the effort level must equal to zero, the economic equilibrium; $x'(t) = E_i'(t) = 0$. This corresponds to a steady-state equilibrium.

The social optimal shadow price of an additional unit of biomass as a function of the optimal level of effort E* is then as follows.

$$\mu = \frac{p \cdot \sum H_x(E^*, x)}{\sum H_x(E^*, x) + \delta - G_x(x)} \tag{7.8}$$

The shadow value of the biomass, ì, in the social optimal steady-state equilibrium depends directly on several things; First, the harvesting function of all active firms, second, the biomass natural growth function affects the social shadow value positively. Third, the economic prices, p, ä; the price on harvest affects shadow value positively, while the discount rate has the opposite effect. Finally, the cost function as each firm's optimal effort depends on the cost function.[16]

### 7.2.3 The Single Agent

Each firm aims at maximizing individual profits subject to technical and biomass constraints. It is assumed the firms are rational; the firms take

16 The modified golden rule is not determined in this case as the question in this section is to compare the differences in the shadow values for society and single firm.

appropriate notice of all variables and relationships affecting their profit functions. This includes the resource growth constraint and each other's fishing effort. Each firm cannot in advance observe the move of other firms. If the firms correctly predict each other's fishing effort the game will end up in Nash equilibrium. Outside the bionomic equilibrium the Nash equilibrium is only momentary since changes in biomass require adjustment in the individual fishing effort-level, only in the bionomic equilibrium is the biomass level constant (as x'(t)=0). The mathematical problem for a single firm is defined as follows.

$$\underset{\{E_i\}}{\mathrm{Max}}\, PV_i(\{E_i\},\{x\},p,\delta) = \underset{\{E_i\}}{\mathrm{Max}} \int_0^{\infty} \pi_i(E_i, x, p)\cdot e^{-\delta t}dt \tag{7.9}$$

s.t. $\quad x'(t) = G(x) - \sum_i H_i(E_i, x)$

$x, E_i \geq 0 \ \forall i$

$E_j$ is given for $i \neq j$

The modern control solution technique is applied for solving the dynamic optimization problem. As before, the Hamiltonian is determined and the necessary conditions for optimum are derived. ó$_i$ describes the single firm's evaluation of the current shadow price of an additional unit of the biomass. The difference from the social optimal conditions is that the firms modify the market catch price by ó$_i$ instead of social price value, ì.

$$(p-\sigma_i)H_{E_i} - C_{E_i} = 0 \ \forall t, i \text{ for which } E_i>0 \tag{7.10}$$

The second necessary condition describes the movement of the shadow value for biomass.

$$\sigma_i' = \sigma_i\left(\sum H_x + r - G_x\right) - pH_x \ \forall i \tag{7.11}$$

The bionomic equilibrium is derived for the non-cooperative firms. In order to be in the bionomic equilibrium the firm's expectations of each other must be correct. Therefore being in a bionomic equilibrium is also being in Nash equilibrium.

The single firm's private optimal shadow price of an additional unit of the biomass as a function of own level of effort is defined in the following formula.

$$\sigma_i = \frac{p \cdot H_i{}'_x(E_i, x)}{\sum_i H_i{}'_x(E_i, x) + \delta - G'_x(x)} \forall i \tag{7.12}$$

The shadow value depends, as before, on harvest, prices, cost and growth functions.

The following section compares the shadow values when firms are cooperating versus not cooperating.

### 7.2.4 Comparing Social and Single Firm's Optima

This section compares the social and single firm's optimal shadow values on biomass. The social optimum is characterized by a cooperative solution while the single firm's optima are characterized by non-cooperation. The shadow values on biomass for same level of biomass and for same value of individual effort levels are compared [compare (7.8) and (7.12)].

$$\mu = \frac{p \cdot \sum H_x(E^*, x)}{\sum H_x(E^*, x) + \delta - G_x(x)} \geq \frac{p \cdot H_i{}'_x(E_i, x)}{\sum_i H_i{}'_x(E_i, x) + \delta - G'_x(x)} = \sigma_i \tag{7.13}$$

It is seen that the social shadow value is larger than the individual firms shadow value if there is more then one active firm. If there is exactly one active firm operating in the industry, the firm acts as a sole owner and there is no difference in the shadow values. The economic interpretation of this result is, that a marginal increase in the biomass stock has a higher value to the society as whole then to a single firm. This appears because; a single firm shares among several firms the gain from an increase in the resource stock why the shadow value for each firm is less then for the society as a whole.

If there is more than one active firm the competitive fishing effort, $E_i$, will exceed the optimal fishing effort, E*, and the steady-state stock level will therefore be highest in the cooperative solution. This conclusion shows the known result that the competitive utilization of a common fish stock generally yields sub-optimal economic results, the '*Tragedy of the Commons*'.

So far, there have been no assumptions on whether the firms are identical or not. Consider the special case with identical firms. When firms in the fishing industry are identical the individual evaluation of the shadow value of biomass decreases monotonously with the number of active firms in the industry. The more active firms in the fishing industry the less is the individual shadow value of an additional unit of biomass. An additional unit has to be shared among a higher amount of active firms. As the number of fishing firms exploiting a common fishing resource increases the non-cooperative solution becomes more inefficient compared to the social optimal solution. The inefficient solution is due to external diseconomies in production. The study has gone some way towards explaining why a device to a regulatory regime, which is capable of realizing as much of the economic benefits as possible, is desirable. The following section introduces some of the fisheries management systems as tax or subsidy on catch and individual transferable quota system.

## *7.3 Conclusion on the Oligopolistic Model*

Arnason (1990) assumes that potential but inoperative exploiters have no cost. This seems like a stringent assumption compared to real world settings. The fishing fleet has a special feature on capital. The capital employed in the resource is partly irreversible, making it quite difficult to have potential agents with no cost.

Further, the model only takes the dynamic externality into account. As discussed in section 5 other types of externalities exist, such as market externalities and multispecies externalities.

Finally, the model assumes identical discount rates for the firms employed in the industry, though different discount rates complicates the equilibrium as one might want to conserve a higher stock level then other agents, this is a more likely setting in real world.

# 8. Fishery Management

Fundamental externality of a common-property resource appears from the resource base itself. The resource stock is a factor affecting welfare in each of the harvesting firms or vessels. By harvesting activity the firms imposes a production diseconomy on each other, a dynamic externality, this leads without regulation to an excessive fishing effort and overexploitation of the resource.

To handle the fundamental externality of a common-property resource various methods of regulation of a common property fishery are suggested. Among these are; vessel licenses, taxes or subsidies on production, royalties and physical controls such as: gear restrictions, seasonal closures, entry limitations, effort restrictions, escapement regulation and area closures and different quota systems. Some methods of fishery management have concerned primarily on the protection of the resource stock not considering the economic diseconomies imposed, such as seasonal or area closure, total catch quotas or restrictions on vessels or gear characteristic.[17]

The difficulty of inducing a management regime in fisheries is that it must satisfy a number of social and economic requirements. It must be cost effective and that the data requirements of the management system are manageable; the ability of the resource manager to obtain necessary information to determine the optimal management. This section does far from give a complete discussion on management problems; this is an immense area. The section introduces some different management schemes and discusses the information needed for the management schemes. Different categories of management regimes are mentioned in section 4.3; the regulated open access and the limited access categories were investigated.

The aim of the following sections is partly to discuss different management schemes and partly to discuss the information requirement for different management schemes. Arnason (1990) proceeds to show the existence, under fairly unrestrictive conditions, of a market-based manage systems that require minimal information for the operation and still lead to efficiency in the

17 This is shown in section 4.3, where a regulatory regime 'seasonal closure' is introduced. The Gordon (1954) model predicts a higher biomass stock level and higher level of inefficient input use compared to the unregulated regime.

common-property fisheries. One such system is the Individual Transferable Share Quotas (ITSQ).

Section 8.1 discusses tax on catch, section 8.2 discusses Individual Transferable Quota system called ITQ system. The Individual Transferable Share Quotas, ITSQ, are discussed in section 8.3. Finally, section 8.4 defines the Minimum Information Management Scheme, MIMS.

## *8.1 Tax on Catch*

This section describes how the misallocations induced by the dynamic externality are reduced by introducing a tax on catch. The effects of a tax on catch and the information requirement for the regulator in order to use the tax on catch for regulation are discussed. A Pigouvian tax on catch can according to the discussion of externalities (section 5) reduce the externality induced by the firm's harvesting activity.

To find the appropriate tax on catch the optimal profit maximizing conditions for the social and individual firms are compared. Derived from the oligopolistic model in section 7.2 the appropriate tax equals the differences in shadow prices. The net output price for a firm is ($p-\sigma_i$) and the appropriate social optimal net output price is (p-ì), the difference in the two net output prices determines the corrective output tax for this firm.

$$\tau = \mu - \sigma_i \tag{8.1}$$

The optimal tax is determined as the damage induced by a single firms unit-harvest on the society. By reducing the biomass with a single unit the society have a loss equal to the social shadow value but the harvesting firm had a gain from the unit-harvest, which gains society as a whole.

The movement or development of the tax for a firm is determined by the difference in the movement in the shadow value of the resource stock for society and the movement in the firm's shadow value of the resource stock. Two things are worth noticing about the optimal tax on catch. First, the optimal tax is in general not uniform over firms unless firms are identical. Rational firms have different evaluations of the shadow price and of biomass, which is reflected in the individual corrective tax. Second, informational requirements for determining the optimal tax are immense. The requirements are to solve the dynamic maximization problem for each individual firm and the society. Tax authorities need all relevant data to the fishing firms, full knowledge of the resource growth function, the harvesting and cost functions of all firms at all points of time. The authorities will have to monitor the state of the stock and the movement of the price. This result assumes the model operates under full information. According to Jensen & Vestergaard (2000) a closer real world setting is when agents have private information on their cost function; the model is developed with asymmetric information. The tax-regime is then shown to correct part of the market failure associated with fishery and to secure correct revelation of agent's type of cost. Using these settings, the information requirements are reduced compared to the full information case.

## *8.2 Individual Transferable Quota System*

Individual Transferable Quotas, ITQ's, corresponds to fisheries regulated by means of individual catch quotas. Catch quotas stipulates the maximum rate of catch permitted to each fishing firm at a point of time. The quota authority issues the catch quota continuously at each point of time. The sum of catch quotas constitutes the total quota. The catch quotas are transferable without any constraints and they are perfectly divisible. The quotas thus constitute a homogeneous transferable commodity. By assumption, there exist a market for the quotas and the market is open to everyone. The ITQ's are an output restriction in the limited access. The ITQ's only place an implicit restriction on the number of participants, but the regime is nevertheless characterized as limited access as agents cannot legally operate without an ITQ.

Trading of ITQ's takes place at an equilibrium price, s. The authority may allocate quotas to firms free of charge or through the quota market. Let $q_0(i,t)$ denote the free allocation of quota from authority to firm i at time t and let z(i,t) denote firm i's instantaneous quota purchase at time t. Then the total quota constraint is the sum of the quotas free of charge and the quota purchase for each firm.

$$Q(t) = \sum_i \left(q_0(i,t) + z(i,t)\right) \quad \forall t \tag{8.2}$$

The individual quota constraint states that the sum of the free allocated catch quotas and purchased catch quotas exceed or equal harvested quantity; thereby it is assumed no one is holding unused catch quotas. The model operates in continuous time settings. The problem is mathematically illustrated as follows.

$$\underset{\{E\}\{z\}}{\text{Max}} \int_0^\infty \left(pH_i(E,x) - C(E) - s \cdot z\right)e^{-\delta t}dt \tag{8.3}$$

$$\begin{aligned} \text{s.t.} \quad & q_0 + z \geq H_i(E,x) \\ & x' = G(x) - \sum_i H_i(E,x) \\ & E \geq 0 \end{aligned}$$

The optimal solution is determined by the Hamiltonian function and the necessary conditions. The solution includes that if the price of the quota, s, is positive, then the firms will not leave any quotas unused. Total catch will therefore equal total quotas. Second necessary condition states that the marginal benefit from an extra unit of effort when quotas have to be bought at market price must equal the marginal cost of employing an additional unit of effort.

$$(p-s)H_{E_i} - C_{E_i} = 0 \quad \forall i \text{ for which } E_i > 0 \tag{8.4}$$

If this necessary condition is compared to the social optimal condition derived in the oligopolistic model [compare (8.4) with (6.6)], it is seen that private harvesting will be optimal if the social shadow value on biomass equals the market price on the quota. [ì=s]

The price of the quota depends, among other things, on the total supply of quotas. Equilibrium is found where the sum of harvest is equal to total quotas.

$$Q = \sum_i H_i(E,x) \tag{8.5}$$

The quota price then yields a function dependent on price on harvest and harvested quantity, $s = s(p,Q)$. By supplying the appropriate quota the authority can control the quota price and ensure optimal utilization of the fish resource.

This type of management is relatively elegant and uncomplicated to solve analytically, but the volume of information needed is, as in the tax-management, immense. As in the tax-management the profit-maximizing problem for each individual firm must be solved when the firms are not identical. Still, the catch quota compared to the output tax has one slight advantage. It does not require the calculation of individual firms shadow value of the biomass, ó$_{i}$. This is caused by the quota system eliminating the dynamic externality; therefore the individual shadow value does not influence the behavior of the fishing firms.

### *8.3 An Individual Transferable Share Quota*

This section investigates the question whether there exist a way for the quota authority to use the market information in order to determine the optimal quota; the Individual Transferable Share Quota (ITSQ) is introduced.
Consider a continuous quota system, where quotas are permanent shares of the total allowable rate of catch. The essentials of the quota system are defined by the following assumptions; The individual catch quotas are *shares* of the total allowable catch and the share quotas impose an upper limit on the firm's permitted catch. The share quotas are permanent in the sense that the share in the total quota is never-ending. The share quotas are transferable and perfectly divisible and there exist a market for share quotas. The quota authority issues the initial shares and subsequently decides on the total quota at each point of time.

A quota system satisfying these properties is called an ITSQ. The difference between ITQ's and ITSQ's is that share quotas are permanent shares in the total allowable catch rate. The main significance is that under the share quota system a change in the Total Allowable Catch (TAC) is reflected by uncompensated increase or decrease for the individual firms, while under an ordinary quota system the TAC adjustments may be affected by trades in the quota markets.

Let á describe a single firms share of the TAC, the share multiplied with the TAC then describes the individual quota holding at a given time.

$$q(i,t) = \alpha(i,t)Q(t) \quad \forall i,t, \quad 1 \geq \alpha(i,t) \geq 0 \tag{8.6}$$

The share held by a firm is divided into the initial share plus the purchase or sale of shares over time.

$$\alpha(i,t) = \alpha(i,0) + \int_0^t z(i,\tau)d\tau \tag{8.7}$$

The instantaneous profit for a firm at time t can be determined and is equivalent to the profit derived in the unmanaged system [for this result see (6.3)] except from the cost of purchasing share quotas.[18] For simplicity it is assumed that firms are not holding unused quotas. Therefore, the quota holding equals the harvest and determines the total effort.

The social optimality problem is to maximize economic benefits from the fishery. The problem is solved determining the Hamiltonian and the necessary conditions. The solution to the problem satisfies the following necessary conditions.

$$\left(p - C_E E_{q(i)}\right) = \mu \text{, for all active firms} \tag{8.8}$$

$$\left(p - C_E E_{q(i)}(0,x)\right) < \mu \Rightarrow \alpha(i) = q(i) = 0 \text{, for all inactive firms}$$

$$\mu' - \delta \cdot \mu = \sum_i C_E \cdot E_x - \mu \cdot G_x \tag{8.9}$$

Where ì is the current shadow value of the resource along the optimal path. Equation (8.8) is divided into two conditions; one for active firms and one for inactive firms. The condition for active firms measures the maximal level of the objective function to the marginal contribution of additional biomass. Second condition states that inactive firms will not hold share quotas.

Equation (8.9) states that firm i should acquire additional share quotas when the marginal profits created by the share quotas exceed the shadow value of the corresponding resource units and vice versa.

Maximizing individual profits solves the individual firm's problem of profit maximization under the ITSQ. Again from the Hamiltonian, the problem must satisfy the following necessary conditions.

$$s = \sigma \text{, for all active firms} \tag{8.10}$$

18 Negative cost of purchasing quotas is interpreted as sale of share quotas.

$s \geq \sigma$, for inactive firms

$$\sigma' - \delta \cdot \sigma = -\left(p - C_E E_q\right) \cdot Q \tag{8.11}$$

Firms should purchase additional units of share quotas in the market as long as their shadow values exceed their market price and vice versa.

Combining the two necessary conditions for the individual profit maximization [combining (8.2) and (8.11)] yields the following time path of the quota prices.

$$\delta \cdot s - s' = \left(p - C_E E_q\right) \cdot Q \tag{8.12}$$

The time path states that firms should sell or buy share quotas until the total costs of holding a unit of share quota is equal to the marginal profits of holding a unit of share quotas. According to a rewritten version of Hotelling's lemma[19] the rate of asset price increase must equal the marginal profits of quota holdings. Let á*(i,t) denote the share quota holdings by a firm at time t that solves the private profit maximization problem, and let á**(i,t) denote the share quota holding by some firm at time t that solves the social problem. Then following conclusion can be shown (for proof see Arnason (1990) p. 643).

For a given initial biomass and a time path of quotas the optimal quota holding for a firm at a given time is identical no matter if the private profit maximization or the social benefit problem are solved. The total quota will always be caught in the most efficient manner. The quota authority can ensure optimal utilization of the fish stock by selecting the appropriate time path of total quotas.

If the optimal share quotas are written as follows $\alpha^*(i) = \alpha^{**}(i) = \Gamma(x(0), \{Q\}, i)$ the formal problem of the quota authority can be written as a function of prices, p, ä, optimal share quotas, Ã, total quota quantity, Q. The ITSQ-solution requires fewer control variables then other regimes, though the quota authority still needs to have knowledge about each firms harvesting and cost functions in detail to be able to solve the maximization problem. The procedure, however,

19 Hotelling's lemma is also called 'the derivative property'.

requires much less information compared to the two management schemes discussed above; tax on catch and individual transferable quota system.

## *8.4 Minimum Information Management Scheme*

Arnason (1990) has been pointed out that the quota authority requires immense amounts of information to set the optimal level of quotas or the appropriate Pigouvian tax. An alternative process is proposed, where the only needs of the quota authority is to monitor the quota market price to get knowledge to the same information.

The fundamental idea is that within the framework of the ITSQ the prevailing quota market price reflects all relevant information about the current and future conditions in the fishery available to the fishing firms or participants in the quota market.

Two assumptions are made; first, the expectations of the fishermen (who are assumed to be rational) are the best available predictor of the future conditions in the fishery. Second, the resource rents and profits are equivalent.

The Minimum Information Management Scheme (MIMS) can be defined; Given the individual transferable share quota system (ITSQ), and given the two assumptions made above, adjusting current total quotas to maximize the market value of total outstanding quotas at each point of time is equivalent to the maximization of profits attainable from the resource. Mathematically this can be expressed as follows.

$$\underset{\{Q\}}{\mathrm{Max}}\, s(0) \Leftrightarrow \underset{\{Q\}}{\mathrm{Max}} \sum_{i} \int_{0}^{\infty} \left(p \cdot q * - C\left(E\left(q^*, x\right)\right) e^{-\delta\tau}\right) d\tau \tag{8.13}$$

Not all quota systems have the convenient management properties of the share quota system described above. Quota permanence seems to be a prerequisite for minimum information management schemes. Also, it appears that a system of quantity quotas, even if permanent, requires more information for optimal management than the share quota system.

### *8.5 Conclusion*

Some of the traditional management systems as tax on catch and individual catch quotas are discussed. It is shown that the optimal management solutions require a huge amount of information for the manager, why these systems are of very little practical use. The Individual Transferable Share Quota (ITSQ) system is introduced. This management schemes requires under certain conditions a minimal collection of information. The management scheme is referred to as the minimum information management. As mentioned earlier, these settings are derived under the assumption of full information about fishermen's harvest function. If the fishermen prevails some private information for instance on their cost function a tax on catch might be a realistic setting, not requiring too much information.

Regulation aims at reducing the diseconomy imposed in an unregulated fishery. Regulation can be introduced with two goals partly to increase the social welfare by aiming at a cooperative solution and partly to conserve the fish stock as many resource stocks are overexploited. This section only introduced some of the concepts of fishery economics regulation as subsidy on effort, tax on catch, ITQ's and ITSQ's. Which type of regulation that is preferred is only based on their required information level, already is criticized because of the assumption on full information in the model. Asymmetric information may lead to other results. Another discussion concerning regulation is the compliance with a set of regulations.

# 9. Sustainable Cooperative Solution

This section questions the number of agents consistent with a cooperative strategy. Most important issue when discussing whether a cooperative strategy is sustainable or not is whether the time horizon is infinite or finite, and if the period is finite is the time of finish certain or uncertain. Investigating a renewable resource, the number of exploiters also affects the sustainability of a cooperative strategy because; if number of exploiters is to high the threat by punishment is weakened.

Hannesson (1997) considers the importance of the number of agents sharing a fish stock for obtaining a cooperative solution. The problem is formulated as a Supergame in discrete time settings.

## *9.1 The Model*

Hannesson (1997) develops a model to discuss the consistency of a cooperative equilibrium. Consider N identical agents exploiting a shared renewable resource stock. Suppose the agents plan to harvest their stock for an infinite (or at least indefinite) horizon. The growth of the stock is describing how much of the stock is left behind after harvesting, e.g. the stock at the beginning of a period is a function of the left behind in the previous period. [20] The natural mortality of the stock is ignored while it is being fished. The model ignores the individual agent level and only specifies the total rents from the resource. The strategic interaction between agents usually considered in these types of model is therefore not discussed.

The stock, $x_t$, in the beginning of the period t is described by the discrete variant of the logistic growth function. $G(x_{t-1})$ describes the stock size in the beginning of period t, while $x_t$ describes the stock size at the end of period t.

$$G(x_{t-1}) = x_{t-1}\left[1 + r\left(1 - x_{t-1}/K\right)\right] \tag{9.1}$$

Where r is the intrinsic growth rate of the fish stock and K is the carrying capacity of the fish stock. The marginal growth is dependent on the intrinsic growth, the current stock size and the carrying capacity.

$$G'(x_t) = 1 + r\left(1 - 2x_t/K\right) \tag{9.2}$$

The harvest, h, is determined in each period t as $h=G(x_{t-1})-x_t$. The price on catch is exogenously given, p and is not affected by the quantities caught. The revenue, R, in period t is price times quantity caught, $R_t = p\left[G(x_{t-1}) - x_t\right]$. The marginal cost of catch is inversely proportional to the size of the stock at any point and the cost per unit of effort is assumed to be constant. This describes the

20 The size of the stock left behind is often referred to as the abandonment level.

special case, where the stock is evenly distributed over a given area, though simple, it is not a too unreasonable cost function.

$$C_t = \int_{x_t}^{G(x_{t-1})} \frac{c}{s} ds = c[\ln G(x_{t-1}) - \ln x_t] \qquad (9.3)$$

$C_t$ describes the total cost a single agent is defrayed in the period t. c is a cost parameter and s is the size of the fish stock which is caught in period t. The cost function and the marginal cost of catch are increasing in the quantity caught.

The present value, PV, of fishing rents for an infinite time horizon is described in discrete time, which is the discounted sum of profit over the period. The present value describes the present value for the industry as a whole; each agent will receive 1/Nth of the total profit.

$$PV = \sum_{t=0}^{\infty} \delta^t \{p[G(x_{t-1}) - x_t] - c[\ln G(x_{t-1}) - \ln x_t]\} \qquad (9.4)$$

Where ä=1/(1+a) describes the discount factor and a the discount rate. If the discount rate is low, the discount factor is close to 1, then future return is discounted with a high factor, meaning present value has a relative small weight compared to future return.

## *9.2 Cooperative and Non-cooperative Solution*

The cooperative solution is determined when agents act as a single agent. The non-cooperative solution is considered when further depletion is unprofitable, where marginal cost equals price.

### 9.2.1 The Cooperative Case

The cooperative solution is determined as a single agent exploits the resource. The cooperative solution is derived where the present value of the return is maximized, without considering the strategic interaction among agents. To find the maximizing present value from equation (9.4), the first order condition with respect to stock at time t is derived.

$$-(p - c/x_t^0) + \delta[p - c/G(x_t^0)]G'(x_t^0) = 0 \qquad (9.1)$$

G' describes the first derivative of the growth function G, $x^0$ is the optimum value of the stock. The growth function and the derivative of the growth function from (9.1) and (9.2) are inserted in the first order condition from (9.5). This derives the optimal stock size in a cooperative equilibrium.

$$x^0 = \frac{(K + rK)(\delta p - p) + cr}{r(\delta p - p)} \tag{9.2}$$

The size of the optimal biomass level is determined by the carrying capacity, the intrinsic growth rate, the discount factor, the cost parameter and the exogenously given price. The size of the biomass is seen relative to the size of biomass reached in a non-cooperative solution.

The present value of the rent generate from fishing the resource is then for a single agent defined as follows one Nth of the present value for the industry.

$$PV^0 = \frac{\pi^0}{N}\frac{1}{1-\delta} \tag{9.7}$$

Where $\pi^0 = p\left(G\left(x^0\right) - x^0\right) - c\left(\ln G\left(x^0\right) - \ln x^0\right)$ describes the profit in a single period.

### 9.2.2 The Non-Cooperative Case

The non-cooperative solution is defined where the resource stock is fished down until further depletion becomes unprofitable. That is, each agent is fishing down the stock in each period until marginal cost of catch equals price; further depletion becomes unprofitable. An abandonment stock level is determined when the stock is fished down. From differentiating the cost function in equation (9.3) then equaling price stock in the non-cooperative case is derived to equal cost relative to price.

$$x^* = c/p \tag{9.8}$$

By some simple calculus, and remembering 0<ä<1 it can be shown that the biomass stock level in the cooperative case is higher than the biomass stock level in the non-cooperative case, $x^0 > x^*$.

The profit for the industry in the non-cooperative case is $\pi^* = p(G(x^*) - x^*) - c(\ln G(x^*) - \ln x^*)$, which is by smaller than the profit in the cooperative case. The present value for a single firm is the discounted value of one Nth of the profit.

$$PV^* = \frac{\pi^*}{N}\frac{1}{1-\delta} \tag{9.9}$$

### 9.2.3 The Case where an Agent Deviate

The discussion so far have not questioned whether the cooperative solution is possible or not, and what is happening if an agent deviate from this solution. To ensure the stability of the cooperative solution the benefits from deviating must be offset by a loss, when the deviation is recognized, done by a Trigger strategy, where agents are memorizing the history of the game. The agents have full information on the development of the game so far, but cannot observe other agents action before they choose own action in the following period, there is closed loop information structure in the game. If an agent deviates from the cooperative solution it triggers a switch to a non-cooperative solution forever after. The non-cooperative solution is the best response to an agent deviating. The time before a deviator is detected is one period but may be set arbitrarily. The deviator will in the period of deviation receive partly one Nth of the profit from cooperation and partly the whole profit from the deviation. The deviator will employ additional effort and fish down the stock until the non-cooperative abandonment is reach. The deviator alone will receive this profit gain. The present value of the profit for the single agent that deviates in the current period is described as follows.

$$PV^d = \frac{\pi^0}{N} + \pi^d + \frac{\pi^*}{N}\frac{\delta}{1-\delta} \tag{9.10}$$

Where $\pi^d = p(x^0 - x^*) - c(\ln x^0 - \ln x^*)$ describes additional profit received from deviating.

## *9.3 A Sustainable Cooperative Strategy*

The present value of return from the cooperative strategy must exceed the present value from deviation to ensure the cooperative strategy to be sustainable. The sustainability depends, ceteris paribus, on the number of agents sharing the resource stock. Comparing the present values on return from cooperation with the present value from deviation derives the constraint on the number of agents in order to secure the cooperative equilibrium. From (9.7) and (9.10) the following constraint can be derived.

$$N < \frac{\delta}{1-\delta}\frac{\pi^0 - \pi^*}{\pi^d} \tag{9.11}$$

To refresh; ð$^0$ describes the profit for the industry when agents are cooperating, ð* describes the profit for the industry in the non-cooperative equilibrium and ð$^d$ describes the one-shot profit to the deviating firm in the period the firm is deviating and is not detected. The equation depends on the number of agents because profits are derived for the industry as a whole and then shared by the number of agents in the industry. Equation (9.11) determines on the right hand side the discounted value of the relative profit gain. The profits ð$^0$, ð* and ð$^d$ are constant, when the number of agents is changing. An increase in the number of agents results, therefore, in a relative higher gain from deviating compared to cooperating because the cooperative profit for a single firm is decreasing when number of agents is increased. The incentives to deviate therefore increase with the number of agents exploiting the resource.

When present profit has same value as future profit that is the discount factor goes towards one then the right hand side of equation (9.11) goes towards infinity and deviation will never be profitable compared to the cooperative equilibrium. For a positive discount rate (ä<1) the temporary gains of defecting may outweigh the long-term loss of playing non-cooperatively rather then cooperatively, depending on the number of firms.

Hannesson (1997) concludes that a higher discount rate (lower discount factor) makes cooperative solution less likely and an increase in agents harvesting the resource makes the cooperative solution The temptation of defecting becomes greater the more participants there are, this is simply because the probability of the constraint to being met declines as N increases.

### *9.4 Conclusion*

The conclusion of the model is that as the number of firms exploiting a renewable resource increases the likelihood of a sustainable cooperative strategy decreases. This conclusion holds under certain assumptions. For instance it is assumed that a deviation is detected in the following period, there is only one period of gain when deviating. A longer detection period would make the cooperative equilibrium even more unlikely. Also, it is assumed, that as defection is noted all agents switch to a Trigger strategy forever after, the period with non-cooperative equilibrium could be shortened, but this only strengthen the probabilities for deviation as the punishment declines.

A lower discount factor makes the cooperative solution less likely. Future return is weighted relatively less then present return, therefore the rents from deviation has a relatively higher value than the lower rent caused by non-cooperation in the following periods.

The model is using discrete time settings. The game is repeated, but each period consists of separate games only strategic connected by harvest affecting stock level. This is reflected by the maximization problem described in formula (9.3), each period is maximized individually as the aggregation over time is determined by the discrete time settings.

# 10. Motives behind Subsidized Fleets

This study is going some way towards understanding to the question why a fleet is subsidized when the resource suffers from over-utilization; see Brander and Spencer (1985) for the benchmark-article in the area of subsidies and market share rivalry.

Two examples state that fleets in real world settings have tendency to have overcapacity and still are being subsidized; firstly, according to FAO Fisheries Technical Paper 1999 70 % of the world's marine capture fisheries are overexploited, fully exploited or recovering and still government are supporting fisheries by subsidizing. Secondly, when visiting the European Commission's fisheries site on the web it flashes under *Hot Topics* "Fishing effort still too high" and still the European Union (EU) subsidizes its fleets.[21] Subsidizing a fleet is interpreted in different ways in EU-framework. Directly as subsidies for construction of new fishing vessels and modernization of existing vessels, as well as subsidies to encourage the retirement of vessels from national fleets. Indirectly as paying compensation for landings of fish which fail to find a market at specified minimum prices.

This section aims to provide an explanation for the persistence of subsidized national fleets that exploit depleted fish stocks.

### *10.1 The Effort Subsidy Model*

The model discussed in this section provides an explanation for subsidizing the fleets even though the fleets exploit depleted resource stocks. This model only focuses on subsidies directly evaluated on the effort level employed in the fishery. Effort can be defined as in EU-framework as capacity[22], in tonnage or engine power multiplied by activity expressed in days spent at sea.

The model is a two period static game where each period is modeled in two stages,[23] as is solved by backwards induction. Brander & Spencer (1985) originally developed this type of model; Ruseski (1998) developed the model to the area of fishery economics. The game consists of two countries, each having a fleet with a number of firms. The size of the fleet in each country is assumed to be fixed, but not necessarily equal in the countries. The firms in the fleets individually decide their effort level, which is equal for all firms in one fleet as the firms are identical. The countries individually decide the effort subsidy level for own fleet. Both firms and countries have full knowledge about other players the pay-off functions.

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21 The European Commission's fisheries website can be found at www.europa.eu.int/comm/fisheries/policy_en.htm Web last visited September 25th, 2000. For the European Unions Common Fisheries Policy please refer to the web.

22 Currently, there is a discussion in fishery economics on how to measure capacity in fishery. Typically, capacity is, as in this section, defined by input-factors, but newer research, as a result of FAO-meeting in 1999 in Mexico, is measuring capacity in terms of output, using Data Envelopment Analysis (DEA).

23 The static game abstracts from the important strategic effects, as the effects of a change in fleet size. (Quinn & Ruseski (2000)).

In each period the countries in the first stage unilaterally chooses the level of effort subsidy in its fleet taken into account the full knowledge of how effort subsidies influences the second stage equilibrium and taking the domestic and foreign fleet size and foreign effort subsidy level as given. In the second stage, firms choose the effort that maximizes the individual steady-state rents. The individual firm takes the effort level by domestic and rival firms and the domestic level of effort subsidy as given.

Each country plays a Stackelberg game in the effort level against the other fleet as the country safeguard own industry's interests and know both how own and foreign fleet will react on their policy. A country therefore maximizes own welfare when choosing policy, knowing that foreign fleet will act as a follower in the second period. Each country plays in addition a Nash game in effort subsidy policies against the foreign country, because countries are making their decisions simultaneously. Each firm is playing Nash game towards competitors in domestic and foreign fleets. A closed loop trajectory is found.

The effort subsidy has two effects; firstly, to reduce the domestic inefficiency, which is arising from competition between firms in the domestic fleet. With no strategic interaction between domestic and foreign fleets the strategic domestic objective would involve at negative effort subsidy or an effort tax. Secondly, the effort subsidy influences the strategic interaction between the domestic and foreign fleets. With no domestic externality, which can be achieved by having a single firm in the domestic fleet, the strategic objective would involve a positive effort subsidy.

The game is dynamic with complete and perfect information, therefore the backwards induction-mechanism is used for solved the game. The model is based on the classic Schaefer model, introduced in section 2.1.

### 10.1.1 The Backwards Induction Solution

The backwards induction solution is derived; In the second stage each firm in every country maximizes its individual steady-state rent, which corresponds to maximize the profit described by revenue minus costs of harvesting, using the effort level for a representative firm, $e_{iv}$, as the decision variable. The firms are all assumed identical in each country.

$$\max_{e_{iv}} \pi_{iv} = \max_{e_{iv}} \left(pqe_{iv}x - (c - s_i)e_{iv}\right) \tag{10.1}$$

Where the variables are defined as; p is the price the firm receives pr unit of harvest from the stock, q is the catchability coefficient, $e_{iv}$ is the effort level of firm v in the fleet in country i, x is the steady-state level of the resource, derived using Schaefer's model, c is the unit price of effort, $s_i$ is the unit size of the effort subsidy employed by the fleet in the $i^{th}$ country.

By assuming that firms are symmetric in a fleet, each firm in this country will employ the same amount of effort ($e_{iv} = e_i$ for all $v \in n_i$). Solving for the equal effort level for each firm in the fleet in one country, $e_i$, and then multiplying with the number of firms in the country, $n_i$, the reaction curve of the $i^{th}$ fleet to the effort level chosen by the $j^{th}$ fleet can be derived.

$$E_i(E_j, d_i) = \begin{cases} \frac{1}{q}\left(\frac{n_i}{1+n_i}\right)\left[r(1-b+d_i) - qE_j\right] & \text{if } r(1-b+d_i) > qE_j \\ 0 & \text{Otherwise} \end{cases} \tag{10.2}$$

Where $d_i = \frac{s_i}{pqK}$ is the direct effort subsidy parameter, and E is the effort level employed in the fleet and K refers to the carrying capacity defined in the Schaefer model.

An increase in the subsidy-level results in an increase in the subsidy parameter, which again results in a higher effort level employed by the domestic fleet. The effort subsidy parameter is a ratio of the effort subsidy relative to the price multiplied with the catchability coefficient and the carrying capacity of the fish ground. The sign of the effort subsidy parameter depends on the sign of the subsidy; a negative effort subsidy parameter indicates an effort tax in the country.

The reaction curve describes the optimal effort level a fleet can choose given the size of the direct effort subsidy parameter in the country to different levels of effort chosen by the other fleet.

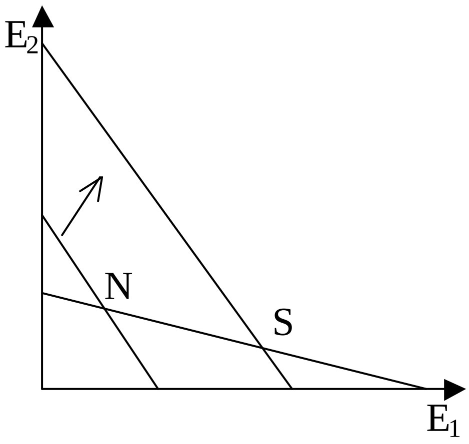


***Figure 10.1. The effect of an increase in effort subsidy in country one.***

The reaction curves have a negative slope and the slope of the reaction curve for country 2 is flatter then the slope on the reaction curve for country 1, there is a unique stable equilibrium in the second stage effort level, which is derived as the intersection between the two reaction curves, shown as equilibrium N in figure 10.1.

If the effort subsidy parameter is increased, say in country 1, the reaction curve for country 1 makes a parallel shift outwards. This can be seen from formula (10.2), that an increase in d does not affect the slope on the reaction curve, but only the intersection. The effort subsidy parameter does not affect the slope on the reaction curve only the intersections with the axis. This leads to an increase in the effort level for the domestic fleet and a decrease in the effort level for the foreign fleet, as moving from equilibrium point N to S. The same conclusion is made if there initially is no effort subsidy increasing to a positive effort subsidy level.

The equilibrium point is described mathematically as

$$E_i(d_i, d_j) = \frac{r}{q}\left(\frac{n_i}{1+n_i+n_j}\right)\left[1-b+(1+n_j)d_i - n_j d_j\right] \qquad (10.3))$$

An increase in the subsidy of effort has thereby two effects, a direct and a strategic effect. A direct effect as the effort in the home country increases. A strategic effect as the effort level in the foreign country decreases. As the effort level for the two countries moves in opposite directions it is difficult to say whether total effort level moves one way or the other, and thereby to say what happens to the steady-state level. Therefore, the steady-state level is evaluated in the effort subsidy parameter. Inserting the equilibrium values for the effort level in the steady-state stock-level describes the steady-state stock level as a function of the effort subsidy parameter for both countries.

$$x(d_i, d_j) = \left[\frac{1 + (n_i + n_j)b - n_i d_i - n_j d_j}{1 + n_i + n_j}\right] K \tag{10.4}$$

The change in the steady-state stock level if the effort subsidy in country i increases ceteris paribus is evaluated. It is seen that the steady-state level will decrease, as the first derivative of (.4) with respect to the direct effort subsidy parameter, $d_i$, is negative. This means that the direct effect of an effort subsidy is stronger then the strategic effect of the effort subsidy and an increase in subsidies in one country ceteris paribus, decreases the steady-state stock level.

By taking the first derivative of the profit functions with respect to the effort subsidy parameter in the country it can be seen that the equilibrium rent in the second stage increases for the fleet who receives the subsidy while it decreases for the other.

In the following the results are summarized;

Given the size of two fleets, $i^{th}$ and $j^{th}$, fleet and the effort subsidy in country j, a small increase in the effort subsidy in country i

1. lowers the equilibrium size of the fish stock.
2. lowers the equilibrium rent accruing to the $j^{th}$ fleet.
3. raises the equilibrium rent accruing to the $i^{th}$ fleet.

This indicates that by giving or increasing the effort subsidy in the fleet in one country ceteris paribus, there is an unambiguously shift in the equilibrium rent from the non-subsidized fleet to the subsidized fleet.
The information derived by solving the second stage of the game is known in the first stage of the game, as there is complete and perfect information. The effort subsidy is derived from maximizing the incremental welfare arising from the fishery, which is assumed to be the rent accruing to fleet i in the second

stage minus the costs of the effort subsidy minus the fleet cost management, which is assumed linear to the number of agents in the fleet.

$$\max_{d_i} W_i(d_i, d_j) = \max_{d_i}(\pi_i(d_i, d_j) - pqKd_i E(d_i, d_j) - n_i F) \tag{10.5}$$

The fleet size is fixed, and the management cost is a constant marginal cost pr. firm, the fleet management cost is then also fixed. The size of the effort subsidy is determined by the equilibrium effort level depending on the effort subsidy parameter chosen by the firms in the second stage. Then deriving the first order condition from (10.5) and isolation the effort subsidy parameter, leads to the reaction function for country i depending on the effort subsidy size in country j.

$$d_i = \left(\frac{1 - n_i - n_j}{2n_i}\right)\left(\frac{1 - b - n_j d_j}{1 + n_j}\right) \tag{10.6}$$

The reaction curve for country i describes the optimal level of effort subsidy parameter given the effort subsidy parameter in country j.

Finding the intersections between the two counties reaction curves can derive the equilibrium size of the effort subsidy parameter. The effort subsidy parameter depends on the size of the fleet, why they not necessary are equal in the two countries.

$$d_i = \left(\frac{1 - n_i + n_j}{n_i}\right)\left(\frac{1 - b}{3 + n_i + n_j}\right) \tag{10.7}$$

If the fleet in country i is larger then the $j^{th}$ fleet plus one, that is $n_i > 1 + n_j$, then country i uses an effort tax to reduce the excessive effort arising from competition between the in its fleet to the strategically optimal rent-shifting level. Otherwise the $i^{th}$ country uses an effort subsidy to raise the effort level. That is, whether it is an effort subsidy or an effort tax depends on the relative firm size.

The total welfare or the rent dissipation when a country changes its effort subsidy (or tax) parameter can be described by the following equation.

$$\frac{\partial (W_i + W_j)}{\partial d_i} = \frac{rpn_i K \lfloor (1 - n_i - n_j)(1 - b) - 2n_i d_i - 2n_j d_j \rfloor}{(1 + n_i + n_j)} < 0 \qquad (10.8)$$

If both countries have a positive effort subsidy, only possible according to (10.8) when the two countries have the same fleet size, then the total welfare decreases as the effort subsidy parameter increases.

Consider the special case where the stock is exclusively owned by one of the countries, the other fleet size is zero. This leads to an effort tax if there is more then one firm in the fleet, if there is only one agent in the fleet there will be no intervention from the regulator, as this firm by itself will maximize profit and thereby social welfare. Another special case is, when the two fleets have equal size ($n_i$=$n_j$), in this case the first stage equilibrium is characterized by a positive effort subsidy in each country. It can be shown that the total welfare in this case decreases when the effort subsidy increases. This equilibrium is therefore compared to the prisoners' dilemma, that in the non-co-operative equilibrium no one has the incentive to deviate even though they by co-operation both could be better of.[24] This can be summarized in the following conclusion.

For every level of fleet management costs the symmetric non-cooperative solution results in a positive level of effort subsidy in both countries and incomplete rent dissipation in the international fishery.

## *10.2 Concluding Remarks*

The effort subsidy model shows that an increase in the effort subsidy in one country increases the rent in this country while it decreases rent in the other and the steady-state level of the fish stock decreases. If the countries are symmetric (e.g. have the same fleet size) the non-cooperative equilibrium results in a prisoner's dilemma where both countries subsidize fleets but rent is incomplete dissipated and the steady-state stock size decreases. The model provides an explanation for persistence of subsidized national fleets that exploit depleted fish resources. The model aims at explaining a practical problem with subsidizing fleets exploiting depleted resources but it has some crucial assumptions. First and mostly the assumption of no discount factor. With no

24 The total welfare for both countries increases, but one country should probably make a transfer in order to cope with the loss from the decrease in the effort subsidy in the other country.

discount factor in the model is interpreted as present rent having same value as future rent. This assumption is crucial because the economic rent usually is the measure for returns in resource economics. Among other assumptions that could be loosened are to be mentioned the missing discussion of technological advantages seen by equal catchability coefficient, equal marginal cost on effort and no threat of potential entrants. Usually new entrants apply to straddling stocks. The biological externality caused by multispecies is also not considered.

# 11. Conclusion and Perspectives

This paper is a survey of game-theoretic literature modeling renewable resources. The paper starts by introducing different underlying biological models. Then game-theoretic methods for solving fishery models are briefly introduced and different features of fishery models are discussed. Fishery models also include some special features as externalities, locked-up capital and uncertainty, which is discussed in section 5 and 6. The following section introduces some of the classic examples of fishery models using game-theoretic concepts. Section 8 discusses the management concepts and the use of management in game-theoretic fishery models. The models are fitted into the game-theoretic frame defined in section 3.

Models for a sole-owner ship and open access are quite well defined, so are the shared stock in discrete time settings. But many challenges in using game theory for fishing models still remain. Models for the conservation and management of high sea fisheries need to be fully developed, especially with respect to determining viable cooperative solution outcomes. This includes the sequential move games, which in particular are used for the transboundary resource stocks. Also, application of analytical tools to many actual cases of jointly owned renewable resources presented by the regime of 200-mile Exclusive Economic Zones needs development. Further are sequential-move game-theoretic models, defined in another perspective, a challenge for further research. Further promising research areas are sequential games discussing the legislative problems of European Union (EU) policy contra third part countries. Models in continuous time also need further development.

Other EU topics for further research are the strategic behavior among fleets and asymmetric information partly among agents in fleets and partly among those to enforce regulation and those who harvest. Also the compliance and enforcement of EU policy is of interest for further research. EU imposes regulations on the fleets' size of capacity (or capacity reductions) but with no enforcement the compliance to follow these regulations diminish, which is seen be countries in EU not following the demanded reductions in capacity. In addition it must be taken into account that the EU-policy is based on a cooperative connection. This leads to the discussion whether a cooperative equilibrium is stable or not. Both the EU and United Nations (UN) have made some agreements based on a cooperative solution, are these agreements good enough or strong enough to maintain a cooperative solution?

Among further work is to give a quantitative description of the common fishery policy (CFP) in the European Union (EU), then to discus whether the CFP can be implemented in a game-theoretic framework. The EU is based on co-operation between member states, but there is no punishment if the member states deviate from the settings. How does this theoretical and practical affect behavior of the member states? Further, is to develop a model on subsidizing fleet that fits to the Baltic Sea, which is exploited by several agents. The Baltic Sea may be subject to changes as EU enlarges towards east making the Baltic Sea only consisting of 2 agents namely the EU and Russia. The model to use for this is thought to be a refinement of the model presented in section 10, hopefully loosening some of the assumptions. The final issue, which the author finds of particular interest, is the market for the resource, which is taking the market externality into account. Is it possible to set up a game-theoretic model with regulations of the resource stock but also considering restructuring the market? See Brander *et al.*(1997) who show that an inefficient regulation or management of a natural resource can discourage free trade. Also, trade liberalization has an effect of the steady state level.

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