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A Stylised Game Model

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Abstract

This paper presents an empirically-based game-theoretic model of the exploitation of the Norwegian Spring Spawning Herring stock, also known as the Atlanto-Scandian herring stock. The model involves five exploiters; Norway, Iceland, the Faroe Islands, the EU and Russia and an explicit, stochastic migratory behaviour of the stock. Under these conditions *Markov Perfect* (*Nash*) equilibrium game strategies are calculated and compared to the jointly optimal exploitation pattern. Not surprisingly, it turns out that the solution to the competitive game is hugely inefficient leading very quickly to the virtual exhaustion of the resource. The scope for co-operative agreements involving the calculation of *Shapley* values is investigated. It turns out that although the grand coalition of all players maximizes overall benefits such a coalition can hardly be stable over time unless side payments are possible.

Keywords: Fisheries economics, migratory fish stocks, fisheries game theory, multi-nation fisheries games, high seas fishing, natural resource extraction games

1. Introduction

The Norwegian spring-spawning (Atlanto-Scandian) herring stock is potentially one of the largest and biologically most productive fish stocks in the world. During the early 1950s its total biomass ranged between 15 and 20 million metric tonnes and its spawning stock averaged 10 million metric tonnes (Patterson 1998, Bjorndal et al. 1998). Although annual catches during the 1950s were in excess of 1 million metric tonnes, average fishing mortality was usually less than 0,1.

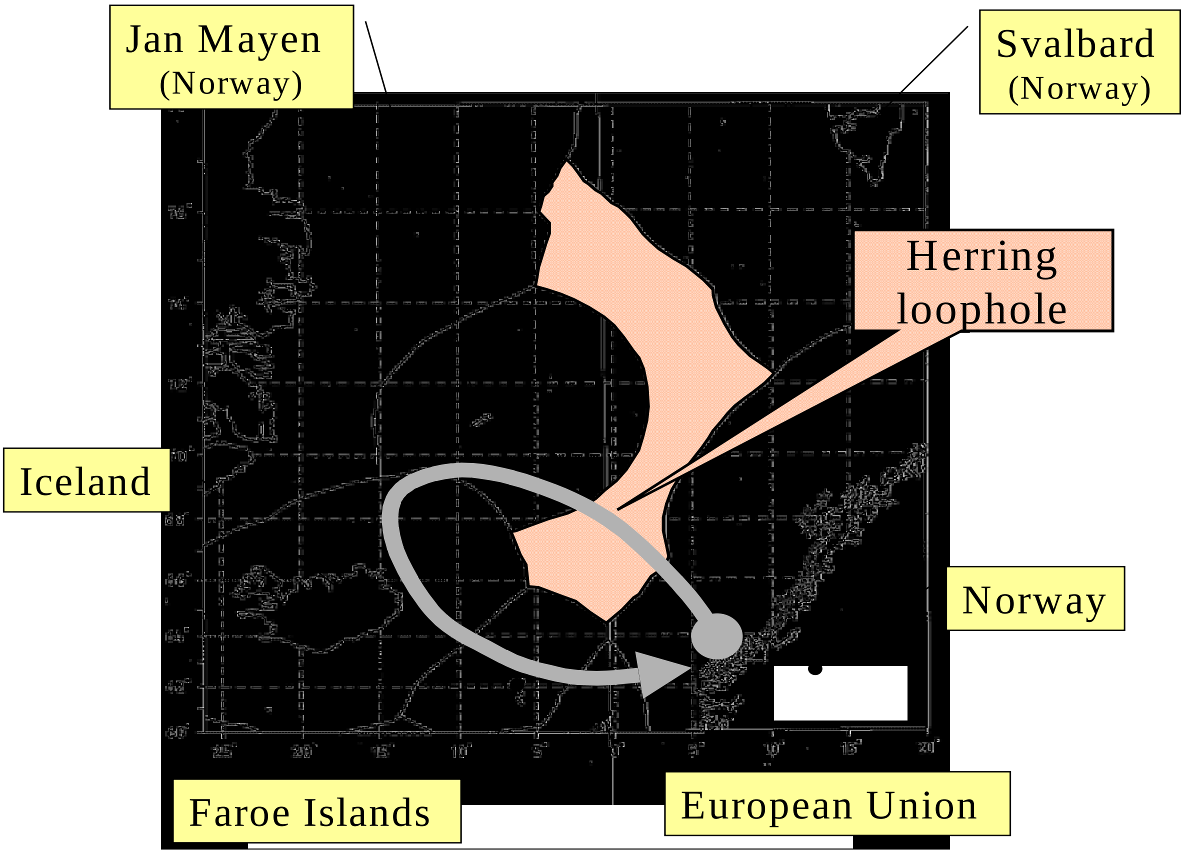
In the 1960s, new harvesting technology led to greatly increased exploitation of the stock.[1] Several European fishing nations participated in the fishery with Norway, Iceland and the USSR being the most prominent. In the late 1960s, the stock suffered a collapse apparently due to a combination of overfishing and deteriorating environmental conditions. In spite of a moratorium on fishing from the spawning stock imposed in 1969, the stock continued declining reaching a nadir of 71.000 metric tonnes and a spawning stock of 2.000 metric tonnes in 1972 (Patterson, 1998). Since then, the stock has recovered and the current spawning stock is now close to its previous size of 10 million metric tonnes.

The Atlanto-Scandian herring is highly migratory. The adult stock spawns off western Norway in February to April (see map in Figure 1). After spawning the adult stock embarks on feeding migrations westward and northward following the zooplankton blooms across the North Atlantic. The feeding period normally ends in September at which time the stock commences migrations to its wintering area. There the adult stock stays until January each year when it migrates to the spawning grounds off western Norway.

Although the above describes the essential features of the Atlanto-Scandian herring's migratory pattern, the exact migratory routes and distances have been somewhat variable. Although not fully understood, it appears that this migratory variability depends primarily on two factors: (i) spawning stock size and (ii) environmental conditions especially the availability of feed and ocean thermoclines. A stylized migratory pattern based on the migratory behaviour for a sizeable spawning stock is illustrated in Figure 1.

[1] Including the introduction of the sonar and the powerblock.

Figure 1
The Atlanto-Scandian Migratory Routes: National EEZs and the Herring Loophole



It is primarily during the feeding migrations from May to September each year[2] that the Atlanto-Scandian herring becomes subject to international fishing pressure. On leaving the Norwegian EEZ, the herring enters international waters (the herring loophole, see Figure 1). It then enters one or more of the EEZs of the Faroe Islands, Jan Mayen (Norway) and Iceland. During this period, the herring tends to form dense schools that are particularly suitable for purse-seine fishing. In the herring loophole, access to the stock is basically open to all. This is followed by sequential but somewhat stochastic exclusive national access by the three countries with adjacent EEZs, Iceland, the Faroe Islands and Norway.

This obviously defines a fairly intricate game-theoretic situation. First of all, the game is dynamic or evolutionary, in the sense that the opportunities (or moves) available to each player depend on the size of the stock and, consequently, his moves and those of the other players' in previous time periods. Secondly, over the course of the year, the set of moves available to each player depends on the location of the stock. Thus, if the stock is located within a country's EEZ, the other players do not have access to the stock and are reduced to the role of observers. Thirdly, any co-operative agreement the players may manage to arrange is potentially threatened by

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[2] Possibly also in the wintering area, from October to December each year.

(i) the entry of new players wanting to take advantage of a growing stock and (ii) altered migratory behaviour of the herring which will change the respective national threat-points and may render the existing co-operative sharing untenable.

In recent years, a number of fishing nations have participated in the Atlanto-Scandian herring fishery. The most important of these are Norway (about 60% of the total harvest), Iceland (about 15%), Russia (about 11%), EU nations[3] (about 8%) and the Faroe Islands (about 5%). A few years ago, these nations agreed on setting and sharing an overall quota in this fishery. The agreed quota shares are roughly in conformance with recent historical catch shares. This agreement, however, is not intended to be permanent, in particular the quota shares are periodically renegotiated. Given the high likelihood of altered migratory behaviour of the stock and the possibility of new entrants, it is unclear how stable this agreement can be.

Our intention in this paper is to study the fisheries game situation in which the exploiters of Atlanto-Scandian herring fishery find themselves. Our approach is to devise a simple model of the situation based on the measurable realities of the fishery. Since the model is quite simple and its key relationships imperfectly estimated we prefer to refer to this model as a stylized portrayal rather than an empirical model of the fishery. Subsequently, on the basis of this stylized model, we seek equilibrium strategies for each of the players under a variety of competitive and co-operative situations and study the implications for the fishery. Although designed for the Atlanto-Scandian herring fishery, our modelling framework is in fact quite general and can with little modifications be used to study multi-player, migratory fisheries games in general.

The structure of the paper is as follows. In section 1 we provide an overview of our game-theoretical framework for studying multi-player, migratory fishery games and describe the numerical solution methods we employ. In section 2, we outline the empirical content of our model. In section 3, we present our results from simulating the Atlanto-Scandian herring fisheries game involving the current five exploiters (e.g. Norway, Iceland, the Faroe Islands, the EU and Russia). Finally, in section 4 we briefly discuss the main results of the paper.

2. Theory

Considerable research has been conducted into the strategic aspects of the exploitation of fish stocks (Clark 1976, Levhari and Mirman 1980, Hannesson 1993). Kaitala (1986) provides a survey of the use of game theory to analyze the exploitation of fish stocks prior to 1986. This paper studies the special situation of strategic interaction where the fish stocks are strongly migratory.

We regard the situation as a game between various fishing agents, each of whom is trying to maximize the present value of their net returns. We describe the evolution of the game in terms of *Markov perfect equilibria* and utilize recently developed methods for analyzing such equilibria, example of which can be found in Ericson and Pakes (1995), Pakes and McGuire (1994), Pakes (1994) and Rust (1994

[3] Especially Denmark, Scotland, Sweden and the Netherlands.

and 1996). According to these methods, the agents select decision rules that prescribe their reaction to changes in the state variables, in this case the size of the fish stock and its location. Furthermore, each decision rule gives a best response to the decision rule of all the other agents. Agents' controls are usually either fishing effort or the amount of biomass caught. The setup is general enough to allow for more state variables such as several species and cohorts and more than one control per agent. However, computational limitations may prevent the implementation of these extensions. The Markov perfect equilibrium assumption means that agents cannot commit themselves for extended periods.[4] When coalitions are introduced it will be assumed that coalitions do not co-operate with each other or with single players. Coalition agreements are assumed to be binding.[5]

Our particular setup focuses on the importance of the migratory behaviour of fish stocks and in particular whether a fish stock, at a point of time, is located within the EEZ of a particular country or in high seas. Authors that have introduced EEZs or other ways of ensuring the excludability of potential exploiters include Fischer and Mirman (1994), Kennedy (1987), Kennedy and Pasternak (1991), Krawczyk and Tolwinsky (1993) and Naito and Polasky (1997).

In addition to finding the (competitive) Markov perfect equilibrium, we also calculate the jointly optimal solution. No attempt is made to model how the jointly optimal solution could be implemented, except by calculating Shapley values (Shapley, 1953). Several authors, including Kaitala and Pohjola (1988), have looked at the possibility of side payments to support a solution that is a Pareto improvement on the competitive outcome.

1.1 The Basic Model

We are concerned with modelling the harvesting from a migratory fish stock by more than one exploiter (nation).[6] Compared to the usual bioeconomic fisheries models, this implies two additional features; (i) variable catchability depending on the location of the stock at each point of time and (ii) strategic behaviour by each of the exploiters of the stock.

The following equations represent the essential structure of our model:

Biomass growth:

(1) $$x_t - x_{t-1} = G(x_{t-1}) - \sum_i y_t^i ,$$

where x represents the size (biomass) of the fish stock, y is the catch, t denotes time and the index i refers to the different exploiters. The function $G(.)$, of course,

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4 Reinganum and Stokey (1985) look at the importance of the period of commitment when extracting a common resource in an oligopolistic setting.

5 The stability of coalitions is briefly discussed in section 3.4.

6 It is possible to set up a model where players are individual vessel owners instead of nations. This was not done for several reasons. One reason is practical; the solution algorithm will quickly bog down if the number of players is too high. More importantly it is more natural to think of nations as players in a game like this where EEZ’s are of paramount importance.

represents the natural growth of the biomass.[7]

Harvesting costs:

The generic form of the harvesting cost function employed is:

$$(2) \qquad c_t^i\left(y_t^i, x_t, d_t^i\right),$$

where d_t represents the distance from the base of the exploiter to the centre of the fish stock at time t. More specific assumptions on the effect of the three variables, catches, stock size and distance on cost will be introduced later.

Migrations and the location of fish stock:

Several modelling assumptions are possible, but to keep the presentation reasonably simple let us initially assume that the fish migrate in a deterministic fashion, so that location in each period is a function of the location in the previous period. A more general stochastic type of migrations is discussed in section 1.3 below.

Let $l_t = (l^x{}_t, l^y{}_t)$ represent the location of the stock at time t, where x denotes the x-coordinate and y denotes the y-coordinate of the location. Then a simple deterministic presentation of migrations is given by the differential equation:

$$(3) \qquad l_{t+1} = L(l_t).$$

Location of exploiters:

It seems plausible to assume that the exploiters operate from a number of fixed ports or locations $\hat{l}_i$. Note that in principle each country may have fleets operating out of different ports so that the number of these locations may exceed the number of national exploiters. The exploitation pattern may and presumably will shift over time as the fleets embarking from each exploitation point vary between zero and a positive number over time.

Distance from exploiter to centre of fish stock:

Ignoring the curvature of the globe (which is reasonable for relatively short distances) we represent the distance between the ports of exploiter i and the location of the stocks by the expression:

$$d_t^i = \sqrt{\left(\hat{l}_i^x - l_t^x\right)^2 + \left(\hat{l}_i^y - l_t^y\right)^2}\ .$$

---

7 In principle it is possible to employ cohort disaggregated growth functions. This, however, is computationally much more demanding.

Prices:

We provisionally assume that all prices including the price of landed fish, *p*, and the discount factor, β,[8] are constant. This assumption is easy to relax.

Profits each period:

$$\Pi_t^i = p \cdot y_t^i - c_t^i\left(y_t^i, x_t, d_t^i\right).$$

Net present value of future profits:

$$\tilde{\Pi}_i = \sum_{t=1}^{\infty} \beta^{t-1} \cdot \Pi_t^i .$$

1.2 Solution method

In order to facilitate the appreciation of the method we employ to obtain explicit numerical solutions to the migratory fisheries game it is useful to consider first relatively simple game situations. In section 1.3 below we extend the model to include stochastic migrations and the restrictions imposed by exclusive economic zones.

Case 1: One exploiter

First we will consider the situation of one exploiter referred to as exploiter *i*. In this situation, presumably, the exploitation of the stock will be optimal (given the location of this exploiter).

The problem for one exploiter is easily solved using dynamic programming. In particular, note that the net present value of future profits can be split into two parts, the profits this year and the present value of all future profits, as follows:

$$\tilde{\Pi}_i\left(x_t, l_t\right) = \Pi_t^i + \beta \cdot \tilde{\Pi}_i\left(x_{t+1}, l_{t+1}\right).$$

It is important to notice that this system has two state variables; the size of the fish stock and its location. Profits will be a function of these two variables. To maximize the net present value of profits, exploiters will have to find the optimal catch, given the size of the fish stock and its location. Mathematically:

$$\tilde{\Pi}_i\left(x_t, l_t\right) = \sup_{x_t \geq y_t^i \geq 0}\left[\Pi_t^i\left(y_t^i, x_t, l_t\right) + \beta \cdot \tilde{\Pi}_i\left(X\left(x_t, y_t^i\right), l\left(l_t\right)\right)\right].$$

This is a straightforward contraction mapping that can be solved numerically with the help of a computer. The form of Π is known, given the above equations for cost, distance and the price of fish. The forms of the *X* and *l* functions are also known. The only unknown is thus $\tilde{\Pi}$. This can be found by iterative techniques. We start with a

8 $\beta \equiv (1+r)^{-1}$, where *r* is the rate of discount.

guess for $\tilde{\Pi}$ on the right hand side and use that to compute the $\tilde{\Pi}$ on the left hand side. The guess for the left hand side $\tilde{\Pi}$ thus found is then used as a guess for the right hand side $\tilde{\Pi}$ and a new guess for the left hand side $\tilde{\Pi}$ found. This is repeated until the $\tilde{\Pi}$'s on the left and right hand side are deemed sufficiently similar. A Fortran program has been written that performs these calculations.[9]

Having found $\tilde{\Pi}$ we have implicitly derived the decision rule for the exploiter:

$$y_t^i = \Gamma(x_t, l_t),$$

where

$$\Gamma(x_t, l_t) = \arg\max_{x_t \geq y_t^i \geq 0} \left[\Pi_t^i\left(y_t^i, x_t, l_t\right) + \beta \cdot \tilde{\Pi}_i\left(X\left(x_t, y_t^i\right), l(l_t)\right)\right].$$

To maximize profits, the harvesting activity should be concentrated on the period when the stock is closest to the home port of the exploiter. This rule is in general modified by capacity constraints (in this paper no capacity constraints are assumed) and the rate of discount.

Case 2: Two or more exploiters that cooperate

This is a straightforward extension of case 1. The only change is that the relevant profit function is now the sum of the two exploiters´ individual profit functions and there are two locations and harvests to maximize over. Consequently, essentially the same method as in the single exploiter case can be used to solve this problem. Having gone through that exercise we find the individual and total exploitation rule each period as:

$$y_t^i = \Gamma^i\left(x_t, l_t\right), \text{ all } i.$$

$$y_t \equiv \sum_{i=1}^{I} y_t^i = \Gamma(x_t, l_t).$$

Case 3: Two or more exploiters that compete

The simplest assumption is that each exploiter takes the decision rule ($\Gamma^i(x_t, l_t)$, i.e. catch as a function of stock size and the location of the stock) of his opponents as given and chooses his decision rule without taking into account that his choice of decision rule may affect the choice of a decision rule by the other exploiter.[10] In effect, this means that exploiter 1 behaves as if the growth function for the stock is:

(4) $$X_t\left(x_{t-1}, y_t, l_t\right) = (1+a) \cdot x_{t-1} - b \cdot x_{t-1}^2 - y_t^1 - \sum_{i=2}^{I} \Gamma^i\left(x_t, l_t\right).$$

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[9] The program is available from the authors upon request. Contact gylfimag@hi.is for details.

[10] The *decision rule* is sometimes referred to as the *reaction function*. The assumption that players take the decision rules of other players as given is fairly widely used but one could also attempt to model players that try to affect the decision rules of each other.

Exploiter 1 then finds his optimal decision rule, Γ^1, given this "growth" function. We have found an equilibrium if each Γ^i's is the best response to all the other decision rules (Γ^j's). This is referred to as a Nash equilibrium of the competitive game (Nash 1951).

To calculate this, we need a somewhat more complicated process than in cases 1 and 2. For the two exploiter game, we start with any decision rule for exploiter 2. One possibility might be the decision rule for exploiter 2 if he were the sole exploiter. Given this, we solve the problem for exploiter 1 in the same way as in case 1 but using the new "growth function", i.e. equation (4), given above. This yields his decision rule, i.e. $\Gamma^1(x_t, l_t)$. Then we use this decision rule to find the optimal decision rule for exploiter 2 and so on. This process is repeated until it converges, i.e. the changes in the two decision rules between iterations are deemed sufficiently small. This then represents the Nash equilibrium of the game.

With more than two exploiters, n, say, we start with any set of n-1 decision rules. On this basis we find the decision rule for the n-th exploiter, then the decision rule for exploiter number n-1, given the initial guess for the first n-2 exploiters and the one calculated for exploiter n. This is repeated until we have found a decision rule for all exploiters. Then we start with the n-th exploiter again and repeat the process until it converges in the sense that the changes in each exploiter's decision rule between iterations is arbitrarily small.

The computational requirements of the problem obviously increase very fast with the number of competing exploiters. Several exploiters also make it much more difficult to analyze and explain the outcome. The computer program that has been developed is however quite general and will in theory work for any number of exploiters. The computational requirements, however, limit the number of exploiters that can be practically deal with.

Case 4: Coalitions that compete

This case is a straight-forward combination of case 2 (co-operation) and case 3 (competition). From the viewpoint of the other players (single players or coalitions), each coalition acts as a single player. The only change is in the cost function, a coalition has a cost function that is based on the cost functions of all its members as in case 2. Having found the cost functions for the various coalitions, the game is played and simulated in the same way as in case 3 (for any number of coalitions and single players).

The establishment of coalitions, decisions whether to join one or not and whether to join a coalition and not adhering to the strategy of the coalition are, of course, games in and of themselves. This paper is not concerned with modelling this aspect of the strategy of high seas fisheries.

1.3 Model Extensions

The basic migratory model described above may be extended in various ways. For the purposes of describing the Atlanto-Scandian herring fishery the following additions have been adopted:

Stochastic migrations

The actual migrations of the Atlanto-Scandian herring are not very regular. They are more properly regarded as stochastic movements around an expected path. Stochastic migrations only call for a relatively minor change in the theoretical setup described above, at least if we assume that the set of points that the fish can swim to is bounded. The computational requirements, however, increase drastically.

Under uncertainty, it is natural to assume that exploiters will want to maximize the *expected* value of future profits.[11] We need to model the migrations of the stock, i.e. we need some function that describes the probability distribution over the stocks location next period as a function of the location this period (and perhaps other factors, such as the stock size). More precisely we seek:

$$p\left(l_{t+1} = l^* \middle| l_t\right),$$

where

$$\int_{l^* \in L} p\left(l_{t+1} = l^* \middle| l_t\right) dl^* = 1,$$

and

$$1 \geq p\left(l_{t+1} = l^* \middle| l_t\right) \geq 0 .$$

The changes stochastic migrations require for the profit maximization setup in case 1 above are given by the following expression. The changes needed for the other cases are analogous:

$$\tilde{\Pi}_i\left(x_t, l_t\right) = \sup_{x_t \geq y_t^i \geq 0}\left[\Pi_t^i\left(y_t^i, x_t, l_t\right) + \beta \cdot \int_{l^* \in L} \tilde{\Pi}_i\left(X\left(x_t, y_t^i\right), l^*\right) p\left(l_{t+1} = l^* \middle| l_t\right) dl^*\right].$$

So, clearly, the solution method does not change in principle, but the computational burden (involving integration over probabilities) may be considerably greater.

The simulations for the Atlanto-Scandian herring game that are described in section 3 below are based on stochastic migrations along these lines. The transition function that is used for the simulations reported in that section generates stochastic migration within the boundaries of a box but with a tendency to move from one quadrant of the box to another quadrant in a somewhat circular fashion. The function was also designed so that points near the centre of the box are chosen with a higher probability than points close to the boundaries.

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[11] Taking risk aversion into account is also possible.

Exclusive economic zones

The existence of exclusive economic zones (EEZs) means that some fishig areas may be off bounds for a particular exploiter. This does not call for major alterations to the theoretical setup, only the choice set of the exploiters changes. Theoretically, this is of minor importance (provided of course the opportunity set does not become too convoluted) although it may render the numerical search for a maximum more difficult. Below we provide the appropriate maximization set up for the case of one exploiter, i.e. case 1 above. The changes in the maximization set up for the other cases are analogous:

$$\tilde{\Pi}_i(x_t, l_t) = \sup_{y_t^i \in \Omega(x_t, l_t)} \left[\Pi_t^i(y_t^i, x_t, l_t) + \beta \cdot \tilde{\Pi}_i\left(X(x_t, y_t^i), l(l_t)\right) \right]$$

where

$$\Omega_i(x_t, l_t) = \begin{cases} \{0\} \text{if } l_t \notin E_i \\ (0, x_t) \text{if } l_t \in E_i \end{cases}$$

where E_i represents what we refer to as accessible zone for exploiter *i*. The accessible zone normally includes the exploiter's EEZ and the high seas. In some cases the accessible zone may include parts or all of another exploiter's EEZ. Note that accessible zones generally overlap. Thus the high seas would normally be within the accessible zones of all exploiters. The Ω function simply says that if the stock is located within the accessible zone of a player, he can catch anything between zero and the whole stock but if the stock is not located in the economic zone of a player, the player cannot catch at all.

2. Empirics

In addition to the migrations of the herring, described above, the empirical content of the model consists of the specification and estimation of the biomass growth and cost functions specified in equations (1) and (2) above.

A simple specification of biomass growth corresponding to (1) is given by:

(5) $$(x_t - x_{t-1}) + y_t = r \cdot x_{t-1}(1 - \frac{1}{K} x_{t-1}^{\gamma}),$$

where x_t denotes the biomass of the resource at time *t* and y_t the total harvest and *r*, *K* and γ are parameters. When γ=1, this equation represents the well known logistic growth function in which case *r* and *K* represent the so-called intrinsic growth rate and carrying capacity of the stock, respectively (Clark 1976).

Using annual data on spawning stock size and harvest for the Norwegian spring spawning herring during the period 1950-1995, equation (5) was estimated. The estimation equation is:

$$(x_t - x_{t-1}) + y_t = \beta_1 x_{t-1} + \beta_2 x_{t-1}^{\beta_3},$$

where, obviously, $\beta_1 = r$, $\beta_2 = \frac{r}{K}$ and $\beta_3 = \gamma + 1$.

Table 1
Estimates of the biomass growth function, equation (5), for the Norwegian spring-spawning herring.
(Dependent variable measured in 1000 metric tonnes, Standard errors in parenthesis)

	NL1	NL2	IV-1	IV-2
β_1	0,45387	0,47093*	0,29910	0,48549*
	(0,40377)	(0,11499)	(0,39100)	(0,15566)
β_2	-0,00003	-0,00005*	-0,00002	-0,00006*
	(0,00033)	(0,00001)	(0,00006)	(0,00002)
β_3	2,06884	2	2	2
	(1,26294)			
(Implied) K	15129	9418,6	14955	8091.5
$\bar{R}^2$	0,146	0,163	0,073	0,296
BG	4,528	1,600	0,301	13,868*
White	11,528 *	6,779*	31,707*	2,129
Jarque-Bera	19,159 *	19,108*	31,341*	20,736*

$\bar{R}^2$ is the adjusted R^2, BG represents the Breusch-Godfrey Lagrange multiplier test for serial correlation, here second-order correlation, White the White test for an unknown form of heteroskedasticity and Jarque-Bera represents the Jarque-Bera test for normally distributed residuals. * denotes that the parameters or tests are significant at the 1% level of significance.

Results from estimating the parameters of equation (5) are presented in Table 1. Column two presents the results of a nonlinear least squares estimation of all three parameters simultaneously. This procedure yields an estimate of β_3=2,07 (γ=1,07). As this value is very close to and seemingly statistically indistinguishable from 2, the parameter β_3 is restricted to be equal to 2 in the subsequent regressions reported in the next three columns.

According to the results reported in column three in Table 1 (headed NL2), restricting β_3=2 does not appear to be contradicted by the data. In fact, the two estimated parameters, β_1 and β_2, now seem to be statistically more significant than before. The corresponding intrinsic growth rate of the biomass, r, is now about 0,47 (47%) and the implied carrying capacity of the biomass (spawning stock) about 9,4 million metric tonnes.

It may be noted that lagged values of the herring stock appear both as a part of the dependent variable and as explanatory variables on the right-hand-side of expression (5). Moreover, estimates of the herring stock are subject to measurement errors. Both may lead to inconsistent estimates of the parameters reported in columns 2 and 3 of Table 1. These problems may be bypassed by using suitable instruments for the two herring stock variables. The results of doing this are reported in columns 4 and 5 in Table 1. In column 4, headed IV-1, lagged values of the annual catch were used. In column 5, headed IV-2, second lags of the herring stock were used as instruments.

None of the procedures employed to estimate (5) yields a seemingly valid statistical description of the data generating process. All fail one or more of the diagnostic checks reported. In particular, according to the Jarque-Bera test the assumption of normally distributed error terms is consistently rejected. Similarly, according to the White test, three of the estimates appear to be plagued by heteroskedasticity. Both of these results may be regarded as an indication of functional misspecification. This is not surprising as it is well known that the aggregative biomass growth function can only be regarded as an approximation to the real population growth process. One of the implications is that the parameter estimates reported and the usual tests for their significance are unreliable. In spite of this, estimates of (5) may be acceptable for forecasting purposes. For this purpose we have chosen to use the NL2 estimation results

In addition to the biomass growth function, we require estimates of the harvesting cost functions $c_t^i\left(y_t^i, x_t, d_t^i\right)$ for the different players. The available data consist of annual observations on the operations, costs and harvests of several Icelandic and Norwegian herring fishing vessels during the 1990s. Since this data set does not include distances the fishing grounds and is in any case on an annual basis, it is of limited help in this study which is concerned with the annual cycle of migrations and the consequent variable distance from port to the fishing grounds within the year. Our recourse is to construct what may be called a technical or engineering type of a costs function for this fishery that at the same time is consistent with the available data.

Examination of the available cost data suggests that vessel costs may be divided into four main categories:

- (i) The crew share and similar costs that are broadly speaking a fraction of the value of landings.
- (ii) Vessel sailing costs to and from the fishing grounds depending primarily on the distance travelled.
- (iii) The flow of fixed costs which depend on the length of the period in question.
- (iv) Other fixed costs (a sort of set-up costs) which are independent of the length of the period.

On this basis we may write the cost function as:

(6) $$c_i\,(y,T,d) = \kappa \cdot p \cdot y + \Delta \cdot T + \lambda \cdot 2 \cdot d \cdot h + \Phi$$

In this expression the variables are as follows. y is the volume and p the price of landings, so that $p{\cdot}y$ represents the gross value of landings. T is the length of the fishing season. d is the distance to the fishing grounds and h is the number of fishing trips, so that $2 \cdot d \cdot h$ is the total distance travelled. Φ represents fixed costs. The parameters are κ, Δ, λ and Φ. κ is the fraction of the value of landings that represents costs to the operation. The crew share is normally by far the largest part of this cost. Δ is the (more or less) fixed cost per vessel per day at sea. This consists of various items of which vessel and crew maintenance, crew salary, vessel insurance, fishing operational costs are among the most significant. λ is the cost per mile of distance travelled. The most prominent of this cost is fuel consumption. Finally, Φ represents the fixed costs not attributable to any of the variables of expression (6).

Now, the number of trips, h, during a season of length T depends on a number of factors. Analysis of this issue (see the Appendix) suggests the following expression for h:

(7) $$h = \frac{T(1-b)a}{\bar{y} + a\left[2\frac{d}{s} + e\right]},$$

where a is the daily rate of harvest when the vessel is on the fishing grounds, b is the proportion of each season spent in harbour due to repairs, bad weather, etc., $\bar{y}$ is the hold capacity of the vessel, s is the sailing speed (in miles/day) of the vessel and e is the landing time per trip. T and d, it will be recalled, represent the season length and the distance respectively.

Combining (6) and (7) yields the vessel cost function as:

(8) $$c_i(y,T,d) = \kappa \cdot p \cdot y + \Delta \cdot T + \lambda \cdot 2 \cdot \left[\frac{T(1-b)\cdot a}{\bar{y} + a(2\frac{d}{s} + e)}\right] \cdot d + \Phi$$

It is important to realize that this cost function, (8), does not explicitly include the biomass of the stock, x.[12] This is in conformance with empirical results (Bjorndal, 1987 and Agnarsson et al. 1999) and, of course, reflects the fact, that herring is an extreme schooling species so that the harvest is largely independent of the stock size.

Now, the fishing technology of all five players engaged in the Atlanto-Scandian herring fishery is similar. They all use standard, large boat purse seine fishing technology.[13] Hence, it stands to reason that the technological parameters of (8) be very similar. On the basis of technical information the following values for the parameters were assumed:

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[12] It could of course be included as one of the arguments determining a, the rate of harvest (see the appendix).

[13] This does not apply to the Norwegian inshore fishing of immature herring. But that fishery is not included in our international spawning herring fishery game anyway.

Table 2 **Technical parameters**		
Parameters	*Units*	*Values*
Catch rate, *a*	Metric tonnes per day	500
Maintenance time, *b*	Fraction	0,1
Hold capacity, $\bar{y}$,	Metric tonnes	1000
Vessel speed, *s*	Miles per day	240
Landing time per trip, *e*	Days	0,5

Obviously, inserting these technical parameters values in (8) yields a linear cost function in three variables, $p{\cdot}y$,*T* and *d*, and four unknown parameters, κ, Δ, λ and Φ. This equation is, in principle, estimable. The problem, however, is that the available data has *T* of one year and no observations on *d*, the distance, at all. Therefore, with our data set it is not possible to estimate (8) directly. Our approach, therefore, was to select values for the parameters of (8) on technical and accounting grounds. The following values were employed.

Table 3 **Economic parameters**		
Parameters	*Units*	*Values*
Crew share and similar, κ	Fraction	0,35
Operating time cost, Δ	M.ISK/day	0,1
Distance costs, λ	M.ISK/mile	0,0001
Annual fixed costs, Φ	M. ISK	150

While this approach is somewhat arbitrary, it may be indicative of its appropriateness that by setting the season length at 360 days and selecting values for the distance, *d*, from within a plausible interval, it was possible to obtain a very good fit to the available vessel cost data.[14] It should be noted, however, that this is not much of a test because varying *d* within plausible bounds allows us to span quite a wide cost range. Basically, it just shows, that this constructed cost function is not contradicted by the data.

A cost function based on (8) is a bit too cumbersome to be practical in simulations. Therefore, we elected to use this function to generate cost data for each quarterly season (91 days) and a wide range of distances and harvests. More precisely, we generated the data on the basis of (8) as follows:

[14] When *d* was allowed to vary within reasonable range for each individual vessel, the fit was virtually perfect (R^2=0,99999). With identical *d* for all the Icelandic and another one for all the Norwegian vessels the fit was still very good (R^2=0,96),

$$c_i\,(y,T,d) = \kappa \cdot p \cdot y + \Delta \cdot T + \lambda \cdot 2 \cdot \left[\frac{T(1-b)\cdot a}{\bar{y} + a(2\frac{d}{s} + e)} \right] \cdot d + \Phi$$

For T=91 and y and d in the range $y \in [1000{,}50000]$, $d \in [10{,}1500]$.

The resulting data series, 1155 data points, were used to estimate by OLS a cost function of the following form:

(9) $$c(y,d) = \alpha_1 \cdot (y)^{\alpha_2} \cdot (d)^{\alpha_3}$$

It turned out that this function provided a very good fit to these generated data[15] Hence we conclude that we may employ (9) as a reasonable approximation to the theoretically more appropriate cost function defined by (8).

Now, this cost function applies to individual vessels but our players in the Atlantic-Scandian fisheries game are nations. These players make their moves by selecting national harvest quantities. Therefore we have to establish a relationship between the number of vessels and the national harvest quantity. Catch per vessel is defined by the identity:

$$y = aT_f\,,$$

where T_f represents the time fishing and a, it will be recalled, is the rate of harvest. As shown in the appendix fishing is given by:

$$T_f = \frac{T(1-b)\cdot \bar{y}}{\bar{y} + a\left[2\frac{d}{s} + e\right]}.$$

Hence, denoting the national harvest by Y, the number of vessels needed to take that harvest is given by the ratio:

$$Y/y = Y \cdot \left[\frac{\bar{y} + a\left[2\frac{d}{s} + e\right]}{a \cdot T(1-b)\cdot \bar{y}} \right].$$

Multiplying (9) by this number of vessels finally yields the aggregate national costs.

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[15] R^2 =0,99997.

3. Games: Simulating the exploitation of the Atlanto-Scandian herring

In this section we employ the model outlined in section 1 and 2 to explore the possible outcomes of the harvesting game for the Atlanto-Scandian herring fishery. A further description can be found in Arnason et al. (2000).

3.1 Extreme schooling and optimal equilibrium

Before proceeding, it may be helpful to briefly consider a somewhat peculiar aspect of this model compared to more conventional fisheries models.This is the feature that the stock of fish does not enter the player's profit functions. This is in accordance with the theory of extreme schooling species (Clark, 1976, Bjorndal, 1987). An extreme schooling species forms schools of roughly equal density irrespective of the size of the stock. Hence the size of the stock only affects the number of schools and perhaps their average size. With modern technology, schools of pelagic species such as herring are releatively easy to locate. Moreover, purse seiners usually harvest a small part of one school. It follows immediately that the catchability of an extreme schooling species is largely independent of the stock size, provided, of course, the stock is large enough to form schools of reasonable size. This means that the elasticity of output with respect to stock size is zero or at least close to negligible as long as catches are (considerably) smaller than the stock size.

Now, the Atlanto-Scandian herring is an extreme schooling species. Hence, it is to be expected that the stock size does not play a role in the profit function of the harvesting process (provided the stock is big enough to form schools). Indeed, empirical investigations (Agnarsson 1999, Agnarsson et al. 1999 and Bjorndal 1987) broadly support this hypothesis.

Optimal harvesting programs for extreme schooling species are particularly simple. For instance, provided the harvesting capacity is sufficiently high, it is easy to show that a profit maximizing equilibrium is given by the simple expression:

$$G_x(x) = r$$

where $G(x)$ is the biomass growth function. In our case, using the biomass growth parameters of section 2 and a rate of discount of 5% per annum, the optimal equilibrium biomass of the Atlanto-Scandian herring stock is found to be approximately 4,209 million metric tons. This is presumably the equilibrium biomass level to which a cooperative game solution would converge. Of course, with variable distance, full equilibrium is not attainable. So in that case, we would expect the optimum biomass path to converge to a regular cyclical pattern with an average in the neighbourhood of 4,209 million metric tons.

3.2 The game setting

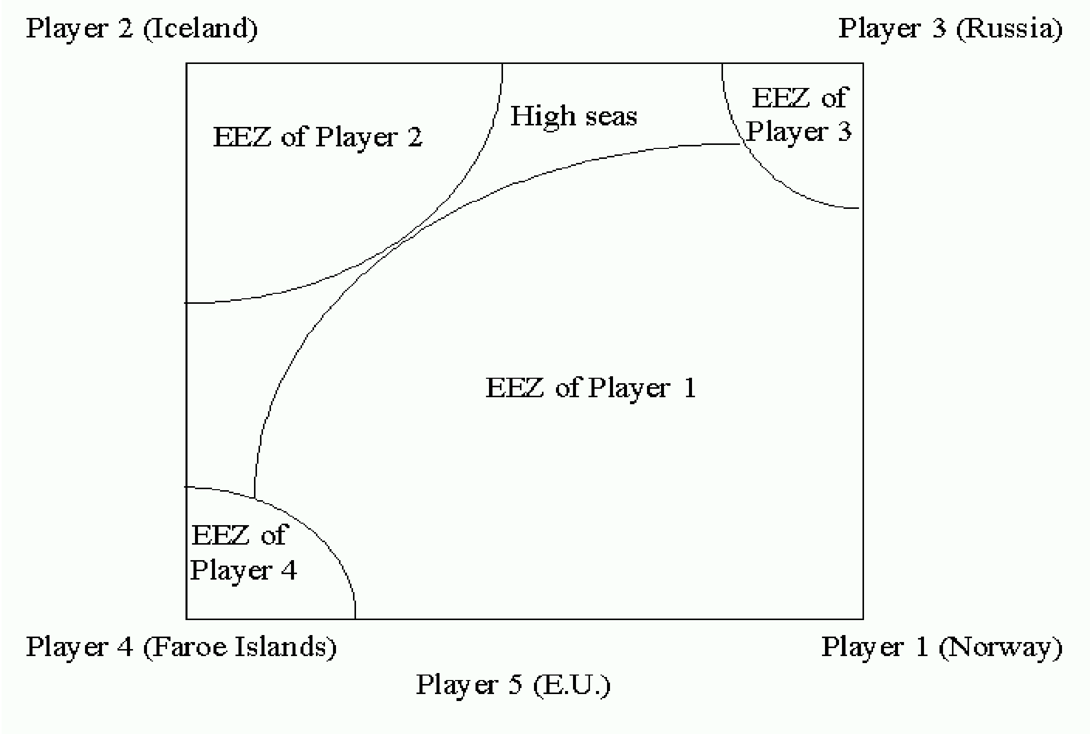
We will consider five different players of the game as follows:

- Player 1, Norway
- Player 2, Iceland

- Player 3, Russia
- Player 4, the Faroe Islands
- Player 5, EU countries

We take it for granted that each of these players seeks to maximize his expected economic returns (expected present value of profits) from the fishery. The stragegy space open to each player is his harvesting quantity. More precisely he can choose any positive level of harvesting bounded only by availability of fish. The game is a quarterly game. This means that each player makes his harvesting choice once every quarter. The players are assumed to have identical profit functions (defined in section 2).[16] They differ, however, in terms of their location and the section of the herring's possible migratory routes covered by their EEZs. The relative location and EEZs of the five players is illustrated in Figure 2.

Figure 2
Relative Location and EEZs of the Four Players (stylised)



In Figure 2, the herring fishing area is drawn as a rectangle (box), with each of the players located at the edges of the box. Note that the exclusive fishing areas (EEZs) of the players are of different sizes with far the largest one belonging to Norway. This is not supposed to be geographically accurate[17] but is believed to provide a reasonable approximation to each player's actual access to the stock. In the simulations, it is assumed that a player can not fish from another player's EEZs unless they are members of the same coalition. All players can fish from the high seas.

16 Simulations were also run assuming that one of the players was more efficient than the others. The results are noted below.

17 For instance, mature NSS herring never enters the Russian EEZ

As discussed above, the migrations of the stock are modelled as a stochastic process where the stock moves quarterly from one area of the box to another in a roughly circular fashion. Each simulation represents one realization of this stochastic process. Averaging over a number of simulations produces a migratory pattern similar to the one that has been observed.

3.3 Playing the Game

The game simulations assume, as discussed above, that the players choose their harvest volume once every quarter. The game solution algorithm was as described in section 1, so that all moves are consistent with Markov perfect equilibria. The game solution defines a decision rule for each agent — an agent being either a single nation or a coalition of nations. Thus, obviously, the game has different solutions depending on the extent of coalitions. Each decision rule prescribes the amount to be caught by a given agent as a function of the fish stock and its location — the state variables of the game. Although, the stock size does not enter each the players' profit functions explicitly, it imposes an upper bound on the harvest and thus determines whether the fishery can be profitable. Consequently, for each player this is a constraint that will have to be taken into account. Since this is a dynamic game, it follows that the biomass growth constraint has to be taken into account as well. We take the initial (at the beginning of the game) biomass to be the virgin stock equilibrium of some 9,4 million metric tons. The initial location of the stock is taken to be within the EEZ of player 1, Norway.

Having found Markov perfect equilibrium decision rules, the game was simulated for a period of 500 quarters (125 years). These simulations were then repeated 25 times each time using a different seed for the pseudo-random number generator that generates the migration patterns. The results reported below constitutes averages over these 25 runs. It should be pointed out that this averaging obscures how the game might evolve in reality because for some coalition and parameter scenarios outcomes varied significantly between runs.[18] This variation was generated by different migration patterns only since the rest of the model is deterministic.[19]

3.4 Game outcomes

The results of the game simulations were generally as expected. The most crucial outcomes are:

(1) Player co-operation is needed to save the stock from (near) extinction since the competitive game always resulted in the stock being (almost) fully depleted.
(2) Co-operation offers substantially more overall profits than competition.
(3) The more extensive the co-operation the higher the profits.

We will now study these outcomes in a little more detail.

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[18] The standard deviation of the net present value of the fisheries to an agent across runs was usually on the order of 5-20% of the average.

[19] Introducing other sources of stochasticity, namely in growth or in catches as a function of effort is actually relatively straight-forward.

The competitive game

In spite of its inefficient nature, under our specifications the competitive game yielded substantial present value of profits to the players. The reason for this is that the game starts at the virgin stock equilibrium and good profits can be made by the initially good catches (see Figure 3) as the stock is run down to bio-economic equilibrium where annual profits are virtually zero. Some pertinent numerical outcomes for the competitive game are listed in Table 4.

Table 4
The competitive game: Some outcomes

Rate of discount 5% Landings price, *p* =0,006 M.ISK/tonne	
Present value of profits (B.ISK.)	3,972
Average long run stock (million metric tons)	Negligible
Total catch in first two years, million metric tons	10,167
Average long run catch (million metric tons)	Negligible

The cooperative game (full co-operation)

Figure 3 compares the harvesting and biomass paths for competition and co-operation repectively. As expected, full co-operation generated considerably (over three times) higher net present value of profits than competition. However, even the fully co-operative solution had the stock being harvested intensively at the outset and quickly reduced to the long run optimal level of approximately 4,4 million metric tons. After that, the harvesting continued at approximately the level needed to maintain the stock, with some variability due to migration. The most pertinent outcomes of the co-operative game are listed in Table 5.

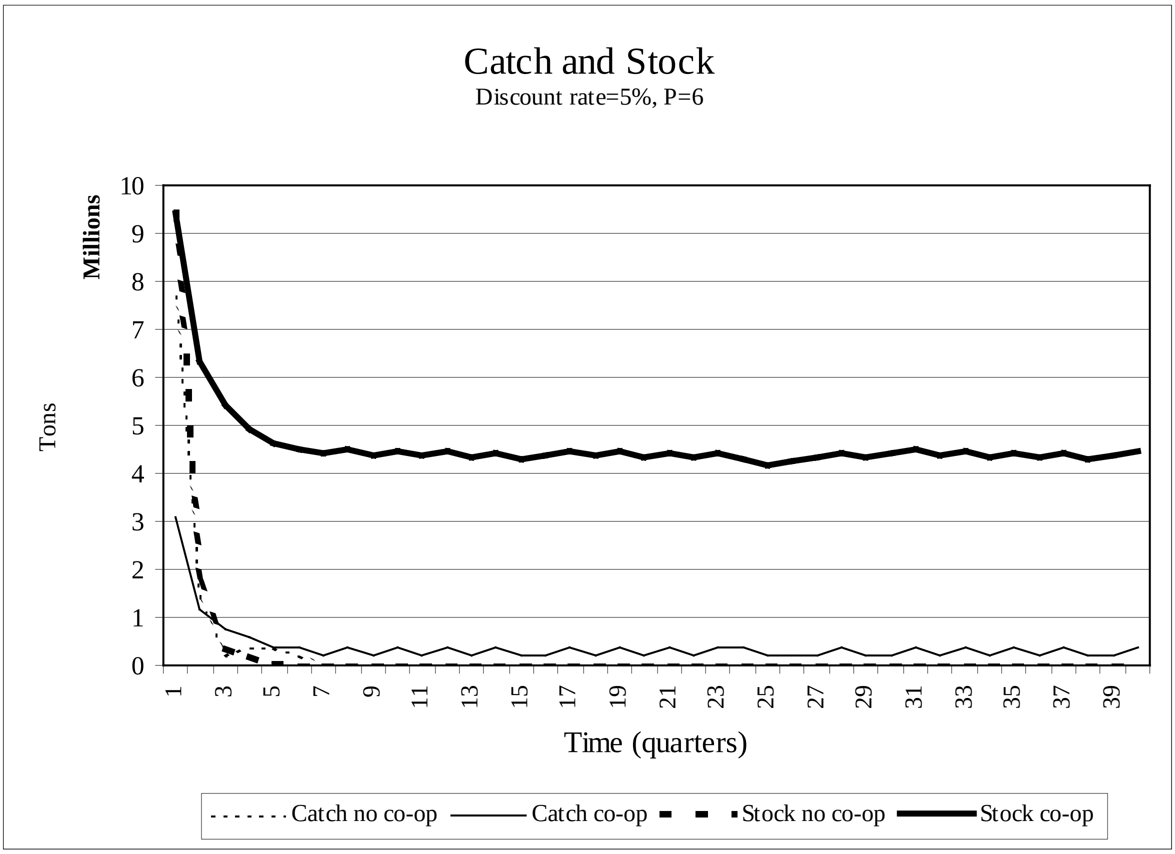
Table 5
The co-operative game: Some outcomes

Rate of discount 5% Landings price, *p* =0,006 M.ISK/tonne	
Present value of profits (B.ISK.)	12,604
Average long run stock (million metric tons)	4,384
Total catch in first two years, million metric tons	6,906
Average long run catch (million metric tons), per year	1,137

It is worth noting that even in the long run, harvest rates and stock levels fluctuate quite a bit under co-operation as illustrated in Figure 3. This is caused by the stock migrations. This does two things. First it affects the profitability of fishing since distances affect costs. Second, it prevents full equilibrium from being established. Since the migrations are stochastic, the fluctuations are also stochastic.

Figure 3

The Development of Stock and Catches Under Competitive and Co-operative Games



It may be noticed that average long run stock level under the co-operative solution is close to the optimal theoretical equilibrium of some 4,2 million metric tonnes. The difference is due to the averaging over 25 stochastically generated migratory paths.

Figure 3 illustrates that under the competitive game, the herring stock is reduced must faster than under co-operation. In the long run the stock becomes extinct under competition.

Finally, we should note that the very high initial level of fishing (millions of metric tonnes per quarter) in both the competitive and the co-operative game requires harvesting and processing capacity which may be in excess of what is actually available. Aggregate capacity constraints were not included in the model. Therefore, these rapid approach paths to equibrium may not be feasible. What would more realistically happen is full utilization of capacity until the neighbourhood of equilibrium levels is reached.[20]

[20] It is of course not easy to get rid of excess capacity so the transition to long term equilibrium may be far from smooth in practice.

Co-operation: Pay-off to different coalitions

For our five players there is a great variety of different coalitions that can be formed. Excluding the coalition of one, i.e. the competitive case, 26 different coalitions possible — ten two player coalitions, ten three player coalitions, five four player coalitions and one five player coalition.[21] Game simulations were run for all of these possible coalitions for rates of discount of 5% and 10% and the price of the output of 4 ISK/kg and 6 ISK/kg. For each case, the return (present value of profits) to each player was calulated as well as the Shapley values[22], each player's gain from full co-operation (according to the Shapley values) and the transfer payment needed to make that gain possible. Some of these results are summarized in Table 6 below.

Shapley values represent but one possible distribution of the total net profits available when all agents co-operate to maximize profits. However, the Shapley values represent a distribution of the benefits that is fair according to quite reasonable criteria (Shapley 1953) and, thus, may be regarded as more acceptable to the players than some other distribution. The Shapley values, however, should not be interpreted as the only possible distribution of profits or in any sense a 'solution' to the game.

Table 6 lists the calculated pay-off (in million ISK) to the players from all possible (single) coalitions games assuming a landings price of 6 ISK per kg and a rate of discount of 5% per annum. Also in the Table we report the relevant Shapley values (for the fully co-operative game) and the necessary transfer payment needed to give each player his Shapley value. under full co-operation. The last column of the table gives the aggregate pay-off to the coalition specified. This, as it stands, is not very informative. It has to be compared to some alternative. One relevant alternative (but by no means the only one) is the pay-off the coalition members would get under the competitive game, i.e. the 'none' coalition in Table 6.

Table 6
Results of game simulations: Pay-offs
(Rate of discount 5%, Price = 6)

	Pay-off to individual participants (M.ISK)						
	Player no.						**Payoff to**
Coalitions	**1**	**2**	**3**	**4**	**5**	**Total**	**Coalition**
None (competitive game)	3.407	50	140	373	4	3.972	0
(2,3)	3.408	71	120	373	4	3.976	191
(1,4)	2.117	148	156	1.949	4	4.374	4.066
(1,3)	1.698	135	1.980	361	8	4.182	3.678
(2,4)	3.408	145	140	284	4	3.981	429

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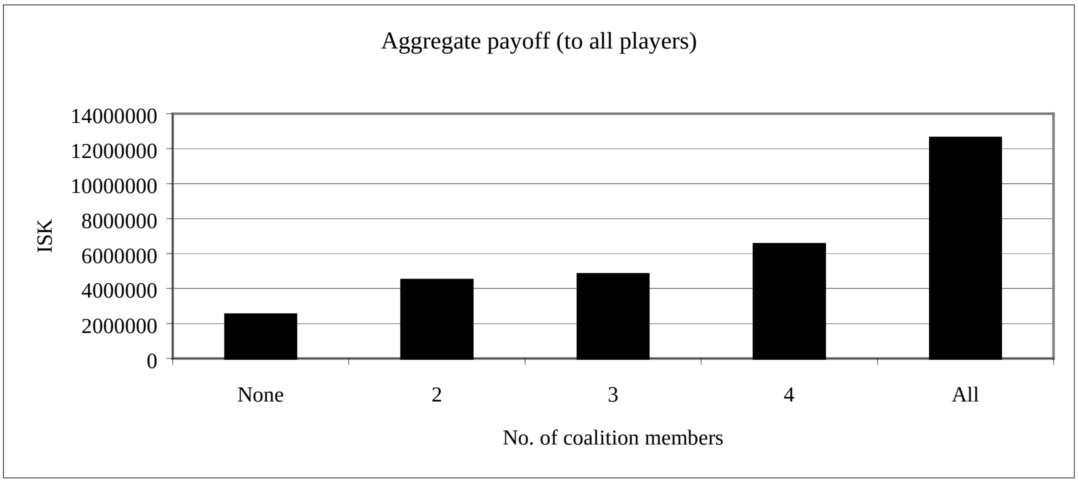
21 The general equation for the number of possible coalitions of any size r from a number of players n is $\sum_r \frac{n!}{r!(n-r)!}$. However this includes coalitions with a single member and ignores the possibility of two or more coalitions.

22 See Shapley (1953). A description of how Shapley values are calculated can be found in many advanced textbooks on Microeconomics or Game Theory. The underlying idea is to find a way to distribute gains from co-operation equally. The (marginal) contribution of each player to all possible coalitions is calculated. The average of this contribution for each player is his or her Shapley value.

(3,4)	3.624	263	271	444	46	4.647	715
(1,2,4)	1.737	1.198	170	1.481	12	4.599	4.417
(2,3,4)	3.656	293	270	407	62	4.688	970
(1,2,3,4)	2.392	2.185	2.306	2.420	1.963	11.266	9.303
(1,2)	1.623	2.001	118	413	3	4.157	3.624
(1,3,4)	1.768	359	1.527	1.482	99	5.235	4.777
(1,2,3)	1.082	1.590	1.282	409	14	4.377	3.954
(2,3,5)	3.742	191	200	577	147	4.857	538
(1,4,5)	2.028	309	203	1.690	1.122	5.352	4.840
(1,3,5)	1.414	437	1.460	498	1.262	5.072	4.136
(2,4,5)	3.742	276	234	424	192	4.868	892
(3,4,5)	3.743	308	241	406	160	4.858	807
(1,2,4,5)	1.875	1.080	332	1.391	901	5.578	5.246
(2,3,4,5)	3.754	275	255	394	208	4.886	1.132
(1,2,3,4,5)	2.701	2.583	2.645	2.607	2.069	12.605	12.605
(1,2,5)	1.623	2.001	118	413	3	4.158	3.627
(1,3,4,5)	1.633	360	1.370	1.249	961	5.572	5.213
(1,2,3,5)	935	1.554	1.125	613	1.171	5.399	4.786
(1,5)	2.074	295	234	565	1.818	4.985	3.892
(2,5)	3.742	184	234	564	121	4.845	305
(3,5)	3.743	295	167	564	72	4.841	239
(4,5)	3.743	296	234	445	127	4.844	572
Shapley values	5.554	1.856	1.958	2.339	897		
Transfer payments needed	2.853	-727	-687	-268	-1.172		
Total gain from co-operation	2.148	1.806	1.819	1.966	894		

As shown in Table 6, the overall benefit of the fishery increases with the size of the coalitions. This is further illustrated in Figure 4 which gives the average (over all possible coalitions of a given size) total payoff to the game.

Figure 4
Aggregate pay-offs as a function of coalitions



Stability of coalitions

Without side payments, relatively few coalitions seem to be stable in the sense that each player benefits from participating compared to what he could expect in the competitive case. More precisely, for the case in Table 6, (β=0,95 and price= 6 ISK/kg), only 10 out of 26 coalitions have this property.

It is particularly interesting to note that Norway can not be induced to enter a coalition without side payments. This also implies that without side payments the grand coalition, the coalition of all players, is not stable. If side payments are possible, the picture changes drastically. In that case the grand coalition seems quite stable. On average it yields almost three times the aggregate benefits of the competitive case and about 12% more than the best alternative coalition (1,2,3,4). If the benefits from the grand coalition are allocated according to the Shapley value criterion, the country that gains least in percentage terms compared to the competitive case, i.e. Norway, still increases its net benefits by over 60%. All the other nations receive several times more than they could expect under competition. More importantly, perhaps, all countries receive much more than they would be able to obtain from any other stable coalition without side payments. Thus, assuming the appropriate side payments, it is to the advantage of no-one to block the grand coalition.

For achieving of economic efficiency in the Atlanto Scandian herring fishery, the participation of Norway in an co-operative utilization arrangement seems to be crucial. This, however, does not seem to be possible without side payments. Hence, the possibility of side payments seems to be the key to efficiency in this fishery.

3.5 Altered conditions

Several simulations were run with some of the conditions of the game altered. In particular we investigated the effect of varying the relative economic efficiency of the national fishing fleets and altering the relative size of the national EEZs. It may be noted that the latter may also be taken to represent a shift in the migratory pattern of the Atlanto-Scandian herring.

Although the outcomes of these different cases vary in detail, they exhibit the same qualitative characteristics as described above. Most importantly, the more extensive co-operation between the players, the higher the aggregate present value of profits and the equilibrium stock level. What changes, however, is the stability of particular coalitions and the distribution of benefits of co-operation between the various players.

An extensive account of these additional runs is outside the scope of this paper. Therefore we only provide a few sample results pertaining to the grand coalition. These results, listed in Table 7 should be compared to the grand coalition base case reported in Table 6.

The results in Table 7 list the individual and aggregate pay-offs before and after side payments (transfer payments) under the grand coalition for conditions altered in three different ways. The first section of the table reports on the pay-offs assuming player 1, Norway, is 20% more efficient (20% higher net profits per unit of harvest) than the other players. This leads, as shown in Table 7, to an increase both in the aggregate payoff and the gain from co-operation compared to the base case. At the same time, according to the Shapley value calculations, most, but not all, of the added benefits go to the more efficient operator, Norway.

The second case reports on the aggregate payoffs assuming that the EEZs of players 1 and 2 are equal. All the other EEZs and the extent of the high seas are unchanged. This means, that the EEZ of player 2, Iceland, is increased at the cost of player 1, Norway. This is equivalent to assuming that on its migratory routes, the herring now spend the same amount of time in the Icelandic as the Norwegian EEZs as seems to have been the case in the 1950s and 1960s. In this case, the aggregate pay-off to the grand coalition is unchanged, but the distribution of the benefits according to the Shapley values tilts substantially toward Iceland compared to the base case.

The third case in Table 7 reports on the case where the landings price is reduced by a third (from 6 ISK/kg) to (4 ISK/kg). The main impact of this is to reduce the aggregate pay-off from the grand coalition by about 58% and the individual pay-offs proportionately.

Table 7
Altered conditions: Simulation results
(Amounts in M. ISK)

Case 1		Direct profit	Transfer payment	Shapley value	Gain from cooperation
Player 1 20% more efficient					
	Player 1	4.035	2.025	6.061	1.939
	Player 2	2.286	-388	1.898	1.898
	Player 3	2.501	-529	1.971	1.971
	Player 4	2.545	-110	2.434	2.434
	Player 5	1.887	-997	890	890
	Sum	**13.254**	**0**	**13.254**	**9.132**
Case 2					
EEZ of Players 1 and 2 equal					
	Player 1	2.709	-107	2.601	1.862
	Player 2	2.582	31	2.613	1.858
	Player 3	2.648	-244	2.404	1.658
	Player 4	2.597	-270	2.327	1.581
	Player 5	2.069	591	2.659	1.915
	Sum	**12.605**	**0**	**12.605**	**8.874**
Case 3					
Price of landings 4 ISK/kg					
	Player 1	1.710	1.506	3.216	1.238
	Player 2	1.479	-409	1.070	1.049
	Player 3	1.516	-371	1.146	1.058
	Player 4	1.610	-256	1.354	1.143
	Player 5	987	-470	517	515
	Sum	**7.303**	**0**	**7.303**	**5.002**

Finally, we may mention that altering the discount rate, just as altering the price of landings, primarily affects the aggregate and individual pay-offs but does not affect the overall tenor of results under the grand coalitions or the distribution of the benefits.

4. Discussion

The above analysis of the Atlanto-Scandian herring fishery is based on quite a simple empirical description of the fishery — a description that is more properly regarded as a stylized portrayal rather than an empirical model. For this reason, the numerical results reported should be regarded as indicative only. The qualitative nature of the results, on the other hand, is probably more reliable. They are first of all very much along the lines predicted by theory. Secondly, they are in good conformance with the game as it seems to have been played hitherto by the nations involved.

Perhaps the most striking result of the paper is the difficulty in establishing stable coalitions for this fishing game unless side payments between the players are possible. There are ample incentives to reach agreement however, since the co-operative solution generates far higher aggregate profits than other solutions. Side payments may take various forms. Monetary payments will of course do the trick and it is implicitly assumed in this paper that side payments are monetary. A perhaps more acceptable method is to allow certain players selective access to other player's EEZs. As is well known, such agreements are often seen in practice.

The game simulations reported in this paper do not cover some pertinent aspects of the actual game situation. Among the more interesting aspects of the game omitted in the paper, but perfectly feasible to analyze within the model that has been developed, are (i) the possibility of entry by new players and (ii) the question of time consistency of whatever cooperative agreement reached.

Under the UN agreement on high seas fishing (United Nations 1995), interested fishing nations must be included in regional fisheries agreements. This potentially opens the door for new nations to enter a fishery once co-operation between the current fishing nations has rebuilt the stocks and enhanced the profitability of the fishery. Clearly, this threat will affect the optimal game strategies of the existing players. A way to model this within the framework of the current model is to define a less efficient additional player that can enter profitably once the stock has exceeded a certain size or the migratory behaviour of the stock has become sufficiently favourable.

To be dynamically stable or time consistent, any co-operative agreement must at all times provide the parties with an expected present value in excess of what he could get by leaving the coalition. In the case of the Atlanto-Scandian herring fishery, the evolution of the stock variables over time will generally alter the players' threat points and thus potentially destabilize a previously stable co-operative agreement. This aspect of the game can also be analyzed within the framework of the model. What is needed is essentially a calculation of the necessary side payments or Shapley values over time. With significantly variable conditions, it may be that a necessary component of a stable cooperative agreement is dynamic sharing of the aggregate pay-off depending on the state of the fishery.

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Appendix
Derivation of the fishing time and fishing trips equations

Consider a fishing vessel. Its instantaneous rate of harvest may be written as

(A1) $y(t) = F(x(t),k(t))\cdot\phi(t)$,

where $y(t)$ represents the rate of harvest, $x(t)$ fish stock biomass and $k(t)$ vessel characteristics (i.e. capital) all at time t. $\phi(t)$ is a shift variable for fishing with $\phi(t)=1$ when fishing takes place and $\phi(t)=0$ otherwise. (A1) is essentially the standard form a harvesting function used in fisheries economics (Clark, 1975). The only modification of that theory is the explicit inclusion of the shift parameter $\phi(t)$.

Over a period of time, e.g. a fishing trip, the accumulated harvest may be written as:

(A2) $y = \int_0^T F(x(t),k(t))\cdot\phi(t)\, dt = F(x(t),k(t))\cdot t_f$,

where t_f represents the fishing time during the period and $x(t)$ and $k(t)$ must be regarded as representing their average values during $[0,T]$. Alternatively, the time period may be regarded as short enough so that $x(t)$ and $k(t)$ may be regarded as constant during the period. For simplicity, we may write (A2) as:

(A3) $y = a\cdot t_f$,

where $a \equiv F(x(t),k(t))$.

In pelagic purse seine fisheries, such as the Atlanto-Scandian herring fishery, the harvest during the fishing trip is typically only limited by the hold capacity of the vessel, $\bar{y}$, say. Clearly in this case:

(A4) $t_f = \bar{y}/a$.

Now, consider a longish period of fishing operations, a month, quarter of a year or even a year. Let the length of this period be represented by T. Let the actual fishing time during the period be T_f. Also, let the ineffective time, i.e. the time for sailing from port to the fishing grounds and back, landing the catches and re-supplying the vessel etc. be represented by T_t. Finally, let delays due major maintenance of the vessel, bad weather etc. be a constant fraction of the overall period, b where $0< b <1$. Thus,

(A5) $T = T_f + T_t + b\cdot T$

Note that $T\text{-}b\cdot T$ represents what may be called *vessel operating time* (sometimes measured as days at sea), a statistic that is frequently recorded by fisheries authorities. For later reference write this as:

(A6) $T^o = T - b\cdot T = T_f + T_t$.

Let the ineffective time depend on the number of trips, h, as follows:

(A7) $T_t = h\cdot(t_s + e)$

where t_s is the sailing time to and from the fishing grounds and the harbour and e is the landing and re-supplying time each trip.

The sailing time clearly depends on the distance to the fishing grounds, d. I.e.,

(A8) $t_s = 2\cdot(d/s)$,

where s represents the sailing speed of the vessel.

The number of trips, on the other hand, is:

(A9) $h = T\cdot(1\text{-}b)/(t_f + t_s + e)$.

Combining (A7) and (A9) yields:

(A10) $T_t = T\cdot(1\text{-}b)\cdot(t_s + e)/(t_f + t_s + e)$.

Therefore, in view of (A10), (A5) and (A5), the overall fishing time is given by:

(A11) $T_f = T^o\cdot[1\text{-}(t_s + e)/(t_f + t_s + e)] = T^o\cdot[t_f/(t_f + t_s + e)]$

Now, substituting in for t_f, T^o and t_s from (A4), (A6) and (A8), respectively, we find:

(A12) $T_f = T\cdot(1\text{-}b)\cdot[\bar{y}/a/(\bar{y}/a+2\cdot d/s+e)] = T\cdot(1\text{-}b)\cdot[\bar{y}/(\bar{y}+a\cdot(2\cdot d/s+e))]$.

Obviously, according to this equation, total fishing time is a declining function of distance, and the catch rate, a, increasing in vessel speed, s, and vessel hold capacity, $\bar{y}$. Moreover, in accordance with intuition, as $\bar{y}$ approaches infinity, there is only one fishing trip and fishing time reaches an upper limit of $T\cdot(1\text{-}b)$. The same applies when the rate of catch, a, goes to zero. If distance to the fishing grounds, d, is zero, fishing time is $T_f = T\cdot(1\text{-}\beta)\cdot[\bar{y}/(\bar{y}+a\cdot e)]$. However when distance goes to infinity, fishing time converges to zero as intuition also suggests.

Finally, the number of trips, h, is obviously given by $h = T_f/t_f$. Hence, by (A4):

(A13) $h = T_f\cdot a/\bar{y}$.

Therefore, it follows from (A12) and (A13) that

(A14) $h = T\cdot(1\text{-}b)\cdot[a/(\bar{y}+a\cdot(2\cdot d/s+e))]$.

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