Nash Equilibria in a Coalition Game of the Norwegian Spring-spawning Herring Fishery

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Abstract The purpose of this paper is to study the coalition game between the potential fishing nations of Norwegian spring-spawning herring. We study a three-player cooperative game using Shapley value and nucleolus as solution concepts. We show that full cooperation between all fishing nations is not stable when the fishing fleets have a high-catchability coefficient. Further, the potential new members of the regional fisheries management organization do not have an incentive to join in this case. However, the case of lower catchability coefficient of the fleets gives opposite results, providing us with more promising expectations for cooperation.

Key words Cooperative games, fisheries, new member problem, Norwegian spring-spawning herring.

Introduction

The Norwegian spring-spawning herring is potentially one of the largest and most valuable fish stocks in the world. It is straddling in nature and, therefore, accessible to several fishing nations. In the 1960s, the stock was subjected to heavy exploitation by several European nations employing new and substantially more effective fishing technology. As a consequence, the stock collapsed and a fishing moratorium was declared. Since the early 1990s the stock has shown clear signs of recovering and has also begun to exhibit its previous migratory pattern across the Norwegian Sea. In addition to Norwegian fishing, the stock has become accessible to several other countries during the migration out of the Norwegian Exclusive Economic Zone (EEZ).

The history of the utilization of marine resources has taught that cooperation is extremely important in the exploitation of Norwegian spring-spawning herring. Thus, a natural setting for the analysis of the exploitation of the herring stock is a cooperative game theory framework. Another aspect in favor of a cooperative point of view to the fisheries game is the United Nations Agreement of Straddling Fish

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Stocks and Highly Migratory Fish Stocks (United Nations 1995). The UN agreement stresses the importance of cooperation and requires that stocks are managed by Regional Fisheries Management Organizations (RFMOs), consisting of countries that have been harvesting fish stocks within a given region. The RFMOs are responsible for managing the resources both within EEZs of coastal states and in the relevant high-seas areas. Further, the analysis of coalitions is important since bilateral agreements between countries have played an important role in herring fishery negotiations.

Kaitala and Munro (1993) were the first to detect a potential problem in the management of the RFMOs. Since the UN Agreement allows any fishing nation with a “real” interest in the fishery to enter such an organization, achieving sustainable cooperation may be very difficult or even impossible. The charter or original members of the organization might be dissatisfied with the cooperative agreement at some point in time since new entrants could extract a part of the resource rent from the fishery. On the other hand, new members should make a contribution to conservation and management, data collection, and research on the stocks (see Article 11 of the UN Agreement). Further, when participatory rights to new members are considered, the RFMO should take into account existing fishing patterns and fishing practices of both new and existing members. Thus, Article 11 of the UN Agreement sheds some light on what is meant by “real” interest.

Our aim here is to analyze the possibilities and likelihood for cooperative harvesting of the Norwegian spring-spawning herring stock. The current study analyzes explicitly Nash equilibria in the spring-spawning herring case when coalition formation is allowed; e.g., by means of reaction curves for the countries. The present paper also analyzes the difficult problem of new entrants in the herring case. These two contributions are essential for finding out whether successful cooperative agreements can be established and maintained in the future for this fishery. At present, the situation is such that all major exploiters have been able to negotiate an agreement. However, in the past, the herring fishery has had long periods of non-cooperative harvesting.

The countries of our three-player game are given as follows: Country 1, Norway (with Russia); Country 2, Iceland (with Faroes); and Country 3, the EU. Norway is clearly in a dominant position for the herring fishery, since most of the spawning takes place within its jurisdiction. These three countries are assumed to capture all fundamental strategic differences in the herring fishery, since Iceland and the Faroes have had historical records of cooperation, as is also the case with Russia and Norway. Further, the EU acts as one agent when negotiating international fisheries agreements. Similar specifications are found in Lindroos (2000) and Bjørndal et al. (2000). Arnason, Magnusson, and Agnarsson (2000) consider four countries in the spring-spawning herring negotiations, with Russia separated from Norway.

We extend the previous coalition game analysis of spring-spawning herring by Arnason, Magnusson, and Agnarsson (2000) and Lindroos (2000) by letting the fishing mortality vary along with fleet size and, consequently, costs. By introducing a catchability coefficient parameter, it is possible to study cases where the grand coalition (full cooperation including all countries) is not stable. For this purpose, we examine two cases where the catchability coefficient is either high or low. In both cases, the coefficient is equal to the countries, but harvesting costs are different. Our results suggest that the catchability coefficient plays an important strategic role when negotiating fisheries agreements. We calculate Nash equilibria for each coalition of our three-player game when the strategies of the countries are constant through time. Further, we extend previous literature by analyzing whether it is optimal for new entrants to enter an RFMO in the context of Norwegian spring-spawning herring fishery.

We use two solution concepts of cooperative game theory. Shapley value and
nucleolus are calculated to evaluate the shares of cooperative benefits to the countries (Shapley 1953; Schmeidler 1969). The Shapley value is based on the marginal contributions of the country to each possible coalition, whereas the nucleolus maximizes the benefits of the least-satisfied coalition.

We study the stability of the cooperative solutions using two stability conditions. These indicate which coalitions or groups of countries are likely to cooperate. First, the core conditions include individual and group rationality—all countries should be better off with cooperation to guarantee stability of a given solution. Second, we check whether any countries are better off by leaving the coalition (internal stability).

Previous cooperative game models of fisheries include an early contribution by White and Mace (1988) and Kaitala and Lindroos (1998), where cooperative game solutions have been calculated for a dynamic game, and Duarte, Brasão, and Pintassilgo (2000), who calculate the characteristic function by comparing benefits of cooperation to open-access strategies. Bjørndal et al. (2000) studied the effects of various international management strategies for the spring-spawning herring fishery, including open access. In the current paper, Nash equilibria are calculated for the non-cooperative games between coalition members and outside fishing nations. Comparable approaches can be found in the economics of global climate change and transboundary pollution (for an overview, see Tulkens 1998).

The Norwegian Spring-spawning Herring Fishery

Norwegian spring-spawning herring (Clupea harengus) is one of the most valuable fish stocks in the world. It is harvested by vessels from Norway, Iceland, the Faroe Islands, Russia, and several European nations. During the 1950s, the fishable component of the Norwegian spring-spawning herring stock is believed to have measured about 10 million metric tons (MT). In the late 1950s and the 1960s, the stock was subjected to heavy exploitation by several countries, employing new and more effective fishing technology. By 1966, the stock was in serious decline, and a complete stock collapse occurred by the end of the decade. Finally, with catch levels declining to practically zero, a fishing moratorium was declared in 1970.

In the 1950s and early 1960s, adults would spawn off the south-central coast of western Norway from February through March. The adults would migrate west and southwest through international waters toward Iceland (April and May), spending the summer (June through August) in an area north of Iceland. In September, the adults would migrate south to a wintering area east of Iceland before returning to western Norway to spawn. Juveniles, including the recently spawned or “zero cohort,” would migrate north.

In the mid-1960s, a second, more northerly stock component appeared. This component would spawn south of the Lofoten Islands, with the adults migrating northwest into the north Norwegian Sea, then northeast into the Barents Sea, and finally south to the wintering grounds west of the Lofoten Islands before moving south to spawn. By 1966, the northern component was the largest of the two major herring stocks. Because of overfishing and poor recruitment, the spawning biomass of both components fell precipitously in 1968 and 1969, leading to near extinction by 1972. In its depleted state, the adult population ceased migration, and both adults and juveniles remained in Norwegian waters yearround.

1 For an overview of the biology of and the fishery for Norwegian spring-spawning herring, see Bjørndal et al. (1998).
Recruitment remained weak throughout the 1970s, and it was not until the strong year class of 1983 that the stock began to recover. From the mid 1990s, after spawning, the adult herring began a westerly migration passing through the EEZs of the EU, the Faroe Islands, Iceland, and through international waters called the “Ocean Loop” on their way to the summer feeding area near Jan Mayen Island.

The migration pattern of the Norwegian spring-spawning herring takes on importance since, as a “straddling stock,” they are exposed to territorial and possibly distant water fleets with strong incentives to harvest the population before it moves elsewhere (Bjørndal et al. 1998). If a cooperative management policy, with an equitable distribution of harvest cannot be agreed upon, Norway, Iceland, the Faroe Islands, countries of the EU, Russia, and possibly distant water vessels fishing in the Ocean Loop, may resort to strategic overfishing that could jeopardize continued recovery of the stock.

Until recently, the situation was quite chaotic. There was no comprehensive regional agreement about the utilization of the stock. It followed that Norway, Russia, Iceland, and the Faroe Islands were able to harvest the stock at will within their own jurisdictions. Moreover, in international waters the stock could be harvested legally by any interested fishing nation.

In 1995, the Advisory Committee on Fishery Management (ACFM) recommended a total allowable catch (TAC) for the Norwegian spring spawning herring of 513,000 MT. Norway, however, announced an individual TAC of 650,000 MT, of which 100,000 MT would be allocated to Russian vessels. Iceland and the Faroe Islands followed suit and announced their own combined TAC of 250,000 MT. In total, the collective harvest of Norway, Russia, Iceland, the Faroe Islands, and the EU was approximately 902,000 MT, almost twice the quantity recommended by ACFM (Bjørndal et al. 1998). Nevertheless, in spite of these high catch levels, the herring spawning stock continued to increase.

There was, however, some progress towards cooperation. In 1996, Norway, Russia, Iceland, and the Faroe Islands reached an agreement for a combined TAC. The agreement was reached by increasing the quota levels for each country and setting a total maximum limit of 1,267,000 MT. The EU did not take part in a TAC commitment and continued fishing at near capacity. In 1997, the EU became a signatory to an agreement limiting the maximum total catch to 1,498,000 MT. The significance of this agreement is that the EU, in a commitment to international fisheries cooperation, agreed to reduce their total catch levels from the previous period, whereas the four other member countries again increased individual TACs (Bjørndal et al. 1998). Notwithstanding, the stock of spring-spawning herring showed great robustness and continued to increase.

The countries involved agreed to continue cooperation with a TAC of 1.3 million MT in 1998 and 1999, while the TAC was set at 1.25 million MT in 2000. There are also bilateral arrangements that allow harvesting in the EEZ of other member countries. For example, for fishing spring-spawning herring Russia, the EU, Iceland, and the Faroe Islands are all granted limited access to Norwegian fishing waters and vice versa.

In an international context, the intergovernmental UN Conference on Highly Migratory and Straddling Stocks (1993–95) dealt with the management of fishery resources found both within the EEZs of coastal states and the adjacent high seas. The Ocean Loop is an important example of this problem. According to the UN Agreement, the management of straddling and highly migratory fish stocks is to be carried out through RFMOs. It seems reasonable that the members in a regional fishery organization are the nations or their representatives that currently manage and exploit the fishery. For Norwegian spring-spawning herring, management takes place through the North East Atlantic Fishery Commission, which represents the RFMO for this fishery.
The recovery of the Norwegian spring-spawning stock offers the opportunity for substantial, annual harvests on a sustainable basis for the benefit of all nations involved. It is clear that if the current cooperative arrangement among the countries fails, and there is a return to the non-cooperation conditions of the early 1990s, this will result in increased international competition for harvest shares that will be biologically, economically, and politically damaging. Eventually, this could threaten a new stock collapse for the fishery and result in substantial economic damage for all nations concerned in terms of lost revenue and employment as catch levels decline.

The Bioeconomic Model

The simulation model is based on the previous works by Patterson (1998) and Touzeau, Kaitala, and Lindroos (1998) and Touzeau et al. (2000). The population dynamics are given as a discrete time, age-structured model as follows:

\[
\begin{align*}
N_{0,y} &= R_y, \quad y > y_1 \\
N_{a+1,y+1} &= N_{a,y} e^{1 - m - S - F}, \quad a \in \{0, 1, \ldots, 15\} \\
N_{a,y}, & \text{ known} \quad a \in \{0, 1, \ldots, 16\}. 
\end{align*}
\]

Thus, we have 17 age classes, from age 0 to age 16. Parameter \(y_1\) is the initial year, for which we assume that all abundances at age \(N_{a,y_1}\) are known. Parameter \(R\) is the recruitment into the stock, \(m\) is natural mortality, \(S\) is selectivity of the fishing gear, and finally, \(F\) is fishing mortality; i.e., mortality caused by human activities. We assume high juvenile natural mortality. The selectivity of the fishing gear is 0 for age classes not harvested and 1 for the ages that are harvested. Here, the first harvesting age is 1.

Population biomass in year \(y\) is given as the sum over all age classes, where the number of fish is multiplied by their weight for each age class:

\[
B_y = \sum_{a=0}^{a=16} B_{a,y} = \sum_{a=0}^{a=16} SW_a N_{a,y}
\]

where parameter \(SW_a\) is the stock weights at age.

Spawning stock biomass (right after spawning) is given as the sum of mature fish over all age classes:

\[
SSB_y = \sum_{a=0}^{a=16} MO_a SW_a N_{a,y}
\]

where parameter \(MO_a\) gives the proportion of mature individuals among age class \(a\). We assume that the older component of the population (from age 7) is fully mature, whereas the younger fish (ages 0–3) do not spawn. The intermediate age classes are only partially mature.

We assume Beverton-Holt stock-recruitment relationship, which gives the average recruitment (expected value of the recruitment where we have a log-normal error term with mean zero and variance \(\sigma\)) as follows:

\[
R_y = \frac{aSSB_y}{1 + SSB_y/b} e^{\sigma/2}
\]
The parameters of this stock-recruitment relationship, as well as the natural mortalities, are shown in table 1. These parameters are used in the simulations later in the paper. Note that as SSB approaches infinity, expression (4) for recruits approaches $abe^{\alpha/2}$. That is,

$$\lim_{SSB \to \infty} = abe^{\alpha/2}.$$ 

The catch in numbers for country $i$ and for a specific cohort is given by:

$$C_{a,y}^i = \frac{S_a f_x^i}{m_a + S_a f_y}(N_{a,y} - N_{a+1,y+1}). \quad (5)$$

Here $S_a$ is the selectivity of the fishing gear (see table 2). Inserting equation (1) into equation (5) gives the yield (or harvest) for country $i$:

$$Y_y^i = \sum_{a=1}^{a=16} Y_{a,y}^i = \sum_{a=1}^{a=16} CW_a N_{a,y} \frac{S_a f_x^i}{m_a + S_a f_y}(1 - e^{-m_a-S_f_y}) \quad (6)$$

where parameter $CW_a$ is the catch weights at age. Note that the term $f_y$ denotes the total fishing mortality; i.e., the sum over the three countries involved in the fishery.

We next introduce the catchability coefficient, which is constant and allows for a linear transformation of the fleet size into fishing mortality. We assume that fishing mortality is directly proportional to the number of vessels, and the catchability coefficient is equal for all countries in the fishery (see Hilborn and Walters [1992] for a similar formulation):

$$f_y^i = \theta \ N_v^i \quad (7)$$

Here, $f_y$ is fishing mortality for country $i$, and $N_v$ is the fleet size for country $i$. Thus, inserting equation (7) into equation (6) yields our catch equation:

$$Y_y^i = \sum_{a=1}^{a=16} CW_a N_{a,y} \frac{S_a \theta \ N_v^i}{m_a + S_a \theta \ N_v_y}(1 - e^{-m_a-S_f_y \theta \ N_v}) \quad (8)$$

Table 1
Biological Parameters, Estimated by Patterson (1998)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mortality</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{0,1,2}$</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>$m_{3\ldots16}$</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>Stock-recruitment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a$</td>
<td>32.459</td>
<td>1/kg</td>
</tr>
<tr>
<td>$b$</td>
<td>3.044867</td>
<td>million tons</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>1.763</td>
<td></td>
</tr>
</tbody>
</table>
Again, note that $N_v_y$ denotes the total number of vessels in the herring fishery in year $y$. Below we show that the analysis of Nash equilibria in coalition games depends upon the ability of the fleet to take catch relative to the ability of the stock to reproduce itself over the range of outputs where fishing is profitable. We do this by focusing on the catchability coefficient, although any of the biological or economic parameters could have been used. Specifically, we show that for a given set of values for the biological and economic parameters, there is a critical value of $\theta$ above and below by which the coalition games may be strategically different. To demonstrate this, we study two cases: the high-catchability case $\theta_{\text{high}} = 0.016$, and the low-catchability case $\theta_{\text{low}} = 0.0016$. We will return to a discussion of the critical value and other related points in the summary. It must be remembered that what is high and low can only be interpreted relative the other parameter values.

The maximum values of fishing mortality for the countries are 1, 0.5, and 0.3, respectively, which reflect the highest historical harvesting periods for the three most important countries (Patterson 1998). Recall that the countries of our three-player game are given as follows: Country 1, Norway (with Russia), Country 2, Iceland (with the Faroes), and Country 3, the EU. Changing this specification to include all five players would not change our main results, but would unnecessarily complicate the analysis.

Before analyzing the coalition games of herring, we need to discuss the economic parameters that we use in the model. The economic model is based on constant unit price of herring/kg and a cost function for an average vessel. We assume that each country has a fleet of vessels that are identical for a given country. However, there are cost differences between countries due to varying engine sizes, input prices of the factors of production, and finally, the distance to the fishing grounds.

Costs for country $i$ are given by a log-linear cost function:

$$Q_i(t) = N_v e^{q_1} \left( \frac{Y_i(t) / Q_4}{N_v_i} \right)^{q_2}. \quad (9)$$

Here, $Q$ is total costs; $q_1$, $q_2$, and $Q_4$ cost parameters; and $Y$ is the total catch (or yield) for country $i$. The term $q_1$ is the intercept term in the cost estimations, $q_2$ is the cost elasticity, and $Q_4$ is a scaling term that gives the average catch of the vessels in the data. Note that the countries are identical with respect to the cost elasticities, $q_2 = 0.56$. This means that changing the harvest level costs the same for each country. The cost parameter, $q_1$, is 15.04, 15.1, and 15.4, for countries 1, 2, and 3, respectively. This means that the same level of harvest is not equally costly for the countries. Norway (country 1) has lowest costs, and the EU (country 3), the highest. When harvests are low, $e^{q_1}$ gives the total costs of the vessels. Thus, $q_1$ is close to the fixed costs of the vessels. The scaling term $Q_4 = 0.0012449$ million tons, represents how much an average vessel actually harvests.

We see from equation (9) that harvesting costs also depend indirectly on the catchability coefficient. To achieve a given level of fishing mortality, a country needs to have a certain number of vessels. The required fleet size is defined by equation (7); that is, the catchability coefficient. Since we assume that for all countries the catchability coefficient is equal, all economic differences between the countries are captured by the cost function difference. Nevertheless, the high and low-catchability cases produce different costs for the countries, since they need more vessels in the low-catchability coefficient case and vice versa.

Note that the cost specification is similar to Lindroos (2000). However, we restrict ourselves to first fishing age $a_1$ of 1. Note further that the main results of the present paper are not sensitive to the choice of cost function. Thus, the approach is
easily applicable to many other fisheries. Table 2 compiles the harvesting and economic parameters.

The net present values of countries as functions of the control variables $f$ and $N$ are given by:

$$J^i(f^i, N^i) = \sum_y p_y = \sum_y \frac{p Y^i_y - Q^i_y}{\rho_y}$$

(10)

where $\rho_y = (1 + r)^{y-1}$ is the discount factor and $r$ the discount rate. Note, that we have 1997 as the starting point, $y_1$, and 2.046 as the end point of simulations. The discount rate is 2% throughout the analysis.

### Coalition Game of Herring

In this section, we calculate the net present values for each possible coalition in the coalition game setting. For this purpose, we construct the characteristic function of the game that assigns a value to each such coalition or union of countries. When the characteristic function is complete, we shall calculate cooperative solutions: Shapley value and nucleolus. In addition, we study the stability of coalitions, which helps us to predict which countries are expected to join together.

For the single-player coalitions (hereafter singletons) we assume that the countries play a non-cooperative game. This means that when a country does not belong to any coalition, it does not cooperate, and all it can do is maximize its own profit, taking into account the strategies of the other players. Nash equilibrium, at which it is not optimal for any country to unilaterally change its strategy, is calculated for both the high and low-catchability coefficient cases (see below).

For two-player coalitions, we adopt the view taken by Chander and Tulkens (1995) that the country outside the coalition will play non-cooperatively against the coalition members. Thus, the members of the coalition will try to do their best, taking into account the actions of the outsider country and vice versa. We shall calculate Nash equilibria for these two-player coalitions and draw reaction curves to illustrate the strategic aspects of the model.

Finally, full cooperation—the value of the grand coalition where all players are cooperating—is given by maximizing the sum of net revenues of the countries.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_i$</td>
<td>1</td>
<td>year</td>
</tr>
<tr>
<td>$S_{0}$</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>$S_{1,...16}$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$q_1$</td>
<td>15.04, 15.1, 15.4</td>
<td>ln(NOK)</td>
</tr>
<tr>
<td>$q_2$</td>
<td>0.56</td>
<td></td>
</tr>
<tr>
<td>$p$ (price)</td>
<td>1.45</td>
<td>NOK/kg</td>
</tr>
<tr>
<td>$Q4$</td>
<td>0.0012449</td>
<td>million tons</td>
</tr>
<tr>
<td>$f^\text{max}$</td>
<td>1, 0.5, 0.3</td>
<td></td>
</tr>
<tr>
<td>$N^i$</td>
<td>Changing with $f$</td>
<td></td>
</tr>
</tbody>
</table>

The Shapley value is a solution concept producing a single point. It has several intuitive interpretations that make it a widely used solution concept: possible orders of coalition formation are equally likely; each player is treated equally; all the benefits are shared among players; it is seen as an average outcome of the negotiations; it measures the marginal contributions of countries to each coalition; and finally, it gives the sum of dividends that each coalition pays to its members (Shapley 1953).

The characteristic function of the game is the following:

\[
v(i) = J^i(F_N^i)
v(i, j) = J^{i,j}(F_N^{i,j}, F_N^k)
v(M) = J^i(F^*)
\]

where \(v(i)\) is the value of a single-player coalition; \(v(i,j)\) the value of a two-player coalition; and \(v(M)\) is the value of the grand coalition, which contains all the players. Term \(F_N^i\) denotes the strategy chosen in Nash equilibrium by coalition \(I\), and \(F^*\) denotes the optimal full-cooperative strategy that maximizes the value of the grand coalition.

The Shapley value for our three-player game can be calculated from the following equation:

\[
Z^i = \frac{v(M) - v(2,3)}{3} + \frac{v(1,2) - v(2)}{6} + \frac{v(1,3) - v(3)}{6} + \frac{v(1)}{3}
Z^j = \frac{v(M) - v(1,3)}{3} + \frac{v(1,2) - v(1)}{6} + \frac{v(2,3) - v(3)}{6} + \frac{v(2)}{3}
Z^k = \frac{v(M) - v(1,2)}{3} + \frac{v(2,3) - v(2)}{6} + \frac{v(1,3) - v(1)}{6} + \frac{v(3)}{3}
\]

Equation (12) calculates the average of the marginal contributions of the three countries to every coalition they can join. In our three-player case, we see that the countries have four possible coalitions they can join: the grand coalition, two 2-player coalitions, and a coalition within itself.

The second cooperative solution concept that we apply is the nucleolus, which maximizes the value of the most dissatisfied coalition towards a given solution (Schmeidler 1969). Since we do not know the stability properties of cooperative solutions to a given problem beforehand, we wish to have an alternative solution when we study the outcome of the negotiations for herring fishery. The advantage of the nucleolus is that it has just one point, which always lies in the core. For example, when calculating the Shapley value, one must always check that the solution is in the core. The idea of the nucleolus is to find a payoff vector whose excesses for all coalitions are as large as possible. This means that the benefit of the least satisfied coalition is maximized.

**Negotiations Between Countries with High-catchability Coefficient**

When each country acts on its own, we can formulate the game as a three-player game. We calculate Nash equilibrium for the case, and it turns out to be the maximum effort case where each country harvests at maximum fishing mortality. The net present values for singletons, respectively, are given (in million Norwegian kroner NOK) as \(v(i) = (4,877.9, 2,312.8, \text{and } 895.8)\).

The values \(v(i)\) are the individual values in the characteristic function. In this case, we see from figure 1 that the herring stock is rapidly driven almost to extinc-
tion. Figure 2 shows that the countries will receive negative rent from harvesting after 3 years, since harvesting is so intensive that the stock collapses very rapidly. After a few years catches are almost zero (see figure 3). Having an exit condition would change the payoffs slightly, but it would not affect our main results. Table 3 summarizes the results for all coalitions, that is, it gives the complete characteristic function of the game.

The two-player coalition cases essentially represent two-player games where the most efficient country of that coalition plays against the country outside the coalition. This is due to the formulation of cost functions (equal cost countries could also be found to have symmetric equilibria). Values of two-player coalitions are given in million NOK as:

\[
\begin{align*}
  v(1, 2) &= 19,562, \quad v_3 = 14,534 \\
  v(1, 3) &= 18,141, \quad v_2 = 17,544 \\
  v(2, 3) &= 17,544, \quad v_1 = 18,141.
\end{align*}
\]

Note that \( v_k \) denotes the value for a country that is outside of the coalition \((i, j)\), that is their free rider value.

In the cases of coalitions \((1, 3)\) and \((2, 3)\), the total fishing mortality is \( f = 0.209 \) (13 vessels), and in the case of coalition \((1, 2)\), total \( f = 0.203 \). The stock will stabilize at a relatively large positive value in all two-player coalition cases. However, the spawning stock biomass (SSB) is well below the safe minimum biological level of 2.5 million tons after five years (Patterson 1998). The spawning stock at the end of simulations is 1.3 million tons for coalitions \((1, 3)\) and \((2, 3)\), and 1.5 million tons for coalition \((1, 2)\).

![Figure 1](image.png)

**Figure 1.** Spawning Stock Biomass (SSB) in Non-cooperation of the High-catchability Coefficient Case
Figure 2. Profits of Countries in Non-cooperation of the High-catchability Coefficient Case

Figure 3. Harvests of Countries in Non-cooperation of the High-catchability Coefficient Case
In figure 4, we see the Nash equilibrium of the game between coalition (1,3) and (2); that is, Norway against Iceland. The Nash equilibrium is very similar in the two other cases. This is illustrated in figure 5 for the game coalition (1,2) against country 3; that is, Norway against the EU.

Let us take a look at the reaction curve of country 1. As the fishing mortality of country 2 increases, country 1 finds it initially optimal to lower its fishing mortality. However, after the fishing mortality of country 2 becomes higher than 0.15, the reaction curve of country 1 begins to rise rapidly. In fact, there is even a discontinuous point at $f_2 = 0.18$, where the optimal response of country 1 jumps up to the maximum strategy and stays there for any higher values of $f_2$. Discontinuity in the figures is

<table>
<thead>
<tr>
<th>Coalition</th>
<th>Value</th>
<th>Strategy ($f$)</th>
<th>Free Rider Value ($v_k$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4,878</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2,313</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>896</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>1,2</td>
<td>19,562</td>
<td>0.107</td>
<td>14,534 (country 3, $f = 0.096$)</td>
</tr>
<tr>
<td>1,3</td>
<td>18,141</td>
<td>0.105</td>
<td>17,544 (country 2, $f = 0.104$)</td>
</tr>
<tr>
<td>2,3</td>
<td>17,544</td>
<td>0.104</td>
<td>18,141 (country 1, $f = 0.105$)</td>
</tr>
<tr>
<td>1,2,3 = $M$</td>
<td>44,494</td>
<td>0.13</td>
<td>50,219 (sum of the above)</td>
</tr>
</tbody>
</table>

Note: Values are in million NOK.

Figure 4. Reaction Curves $r_1$ and $r_2$ of Countries 1 and 2 for the Case of High-catchability Coefficient
The reason why the reaction curves begin to rise rapidly, is that the change from both coalitions having $f = 0.15$, to both having $f = 0.2$ leads to a considerable change in the profitability of harvesting. With $f = 0.15$, the countries are able to harvest with profits considerably longer. Therefore, there is a discontinuous jump when it is optimal to harvest at maximum effort.

Finally, the full cooperative situation is given by $f = 0.13$ and the first harvesting age, $a_1 = 1$. The value of this grand coalition is $v(M) = 44,494$ million NOK, where $M$ is the number of players. At the end of simulation period, the spawning stock is $4.5$ million tons.

We see immediately from the characteristic function of table 3 that two-player coalitions are stable, but others are not. Even the grand coalition is not stable, since there are not enough cooperative benefits to be shared. If we sum up the outside values of each country, we see that the sum is greater than $v(M)$ (see table 3). Thus, we are not able to find any reasonable imputation (allocation) that would satisfy all the fishing nations.

Shapley values are $16,350$, $14,780$, and $13,360$ million NOK. Thus, the Shapley value is not in the core. Nucleolus would be in the core, but calculating it is not reasonable since the equilibrium cooperation structures are two-player coalitions (see Duarte, Brasão, and Pintassilgo [2000] for similar results). Therefore, we need to
construct a mechanism that creates incentives for the countries to cooperate, since the stock will be depleted otherwise. Note that without coalition analysis, this would be straightforward; there are huge benefits from cooperation (36,407 million NOK). However, even if individual deviations are not profitable, free riding at the expense of the other two countries makes deviations more likely.

Table 3 shows that the sum of free rider values (countries outside RFMOs) is larger than the value of full cooperation (coalition $M$). We also see the strategies (fishing mortalities) of the countries in all possible coalition games.

**Cooperation with Low-catchability Coefficient**

Let us now turn to the case where the fishing fleets have a low-catchability coefficient. The catchability coefficient $\theta_{\text{low}} = 0.0016$ is one tenth of the case of high-catchability coefficient.

For the single player Nash equilibrium, $f_1 = 0.07$, $f_2 = 0.07$ and $f_3 = 0.01$. The following payoffs are in million NOK: $v(1) = 9,002$, $v(2) = 7,984$, and $v(3) = 195$ (see table 4). Comparing the values of singletons to the high-catchability coefficient case of the previous section, we notice that countries 1 and 2 are better off in the low-catchability coefficient Nash equilibrium, whereas country 3 is worse off. It is interesting to note that some countries may actually have better payoffs when all countries have fleets with a low-catchability coefficient. The spawning stock in this non-cooperative case is 3.5 million tons, which is well above the safe level. This is a remarkable difference to the previous case where the stock is depleted rapidly to extinction due to dependence of harvesting costs on stock size. Table 4 summarizes the results for all coalitions; that is, gives the complete characteristic function of the game with a low-catchability coefficient.

The Nash equilibrium for two-player coalition $(1,2)$ against country 3 is given by strategies $f_1 = 0.086$ and $f_3 = 0.036$ (see figure 6). Thus, we see that now the relative difference between equilibrium strategies is greater. Also, the reaction curves are different in shape as compared to the case with a high-catchability coefficient. They are nearly linear for each country. The resulting payoffs are in million NOK: $v(1,2) = 15,700$, and $v(3) = 2,190$. At the end of the simulation period, the spawning stock is 5 million tons.

Note that in this case, there is only one Nash equilibrium. If the other chooses maximum fishing mortality, the optimal policy for the other country is to exit the fishery.

The Nash equilibrium for coalition $(1,3)$ is $f_1 = 0.076$ and $f_2 = 0.07$. Values of coalitions are $v(1,3) = 10,310$ and $v(2) = 8,462$. At the end of the simulation period,

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<td>195</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1,2</td>
<td>15,700</td>
<td>0.086</td>
<td>2,190 (country 3, $f = 0.036$)</td>
</tr>
<tr>
<td>1,3</td>
<td>10,310</td>
<td>0.08</td>
<td>8,462 (country 2, $f = 0.07$)</td>
</tr>
<tr>
<td>2,3</td>
<td>8,462</td>
<td>0.07</td>
<td>10,310 (country 1, $f = 0.08$)</td>
</tr>
<tr>
<td>1,2,3 = M</td>
<td>23,318</td>
<td>0.10</td>
<td>20,962 (sum of the above)</td>
</tr>
</tbody>
</table>

Note: Values are in million NOK.
the spawning stock is 3.7 million tons. Thus, there is a significant biological difference between the two-player coalition Nash equilibria. Further, as compared to the previous high-catchability coefficient case, we notice that the spawning stock is always above the safe biological level; whereas, in the high-catchability coefficient case, it is always below the safe level when two-player coalitions are competing with the outside country. Again, this is because harvesting costs depend on stock size.

For coalition (2,3) the equilibrium is, again, similar to coalition (1,3), with values \( v(2,3) = 8,462 \) and \( v_1 = 10,310 \). Reaction curves \( r_1 \) and \( r_2 \) are of the same form as in figure 6. The equilibrium fishing mortalities are, however, different (0.076, 0.07).

Finally, the full cooperative outcome is \( f = 0.1 \), with \( v(M) = 23,318 \). The spawning stock after 50 years is high, 6.5 million tons.

Clearly, in this case there are better chances for cooperation, since the sum of the outside coalition net present values (free rider values) is smaller than benefits from full cooperation (see table 4). Furthermore, it is important to note that in all the cases of this section, the SSB is well above the safe biological level.

Shapley values are: (10,920, 9,500, and 2,900), which lie in the core. Nucleolus gives (10,940, 9,920, 2,140), which can be checked using Kohlberg’s (1971) criterion. The idea of the criterion is to have equal excesses for a balanced set of coalitions. In this case, it turns out that the excesses of the singletons are the lowest; thus the singletons are the most dissatisfied coalitions. However, if we look at the proposed allocation, we see that country 3 cannot be satisfied with it, since it would immediately get more by exiting the RFMO. Therefore, in the context of our game, the nucleolus should be slightly modified. Table 4 summarizes the results.

Table 4 shows that the sum of free rider values is smaller than the value of full cooperation. We also see the strategies (fishing mortalities) of the countries in all possible coalition games.
On the New Member Problem

The first contributions on economic analysis of the UN Agreement are by Kaitala and Munro (1993; 1995a; 1995b). They were the first to note the new entrant problem. Article 8 of the UN Agreement states that any country having real interest in a high-seas fishery must be allowed entrance to the RFMO managing the fishery. However, if a country refuses to abide by the management regime, then membership may be denied. On the other hand, coastal states have a right to harvest within their own EEZ, since the Law of the Sea Convention of 1982 is in force. Kaitala and Munro (1993) predict that the likelihood of achieving stable cooperation will be very low if the new member problem is mishandled. In addition, Datta and Mirman (1999) have shown that with an increasing number of countries, the inefficiency of the non-cooperative equilibrium generated by the common access feature of high seas dominates, and overharvesting increases.

Let us define the charter (or original members) of the RFMO as players $i$ and $j$ and the new entrant as player $k$. Players $i$ and $j$ are making profits worth 44,494 million NOK in the high-catchability coefficient case (assuming that one of them is country 1) before there exists any potential new entrants. However, if a potential new member $k$ appears, then this country $k$ can either enter the existing cooperative arrangement or stay outside. Then, in the high-catchability coefficient case, the new entrant has no incentive to join the regional organization, since it would be better off by playing Nash (staying out) against charter members. However, the charter members still find it optimal to keep cooperating with one another. Thus, if there already exists a two-player coalition, it will not be changed, since it is a stable coalition both externally and internally.

The charter members may succeed in keeping the new entrant from fishing at all by paying the new entrant its free-rider value. In this way, they could be much better off than having to compete with the new entrant in a non-cooperative game. For example, charter coalition (1,2) could keep country 3 out by paying 14,534 million NOK and still receiving 29,960 million NOK, which is clearly better than their Nash equilibrium outcome of 18,141 million NOK. Thus, in the case of efficient fleets, there could exist countries that would gain from the fishery by simply threatening to enter. However, the UN Agreement may prevent such actions, since a country should have “real” interest in the fishery. Further, according to the UN Agreement, there are legal barriers for the distant water fishing nations to harvest as an outsider in a given fishery.

The situation where no RFMO exists is more problematic, since in that case it might be optimal for some countries to wait before signing the agreement, since the outside player makes the highest profits (see Kaitala and Lindroos 2000). Thus, it may be that cooperation will never take place.

For the low-catchability coefficient case, the situation is more promising, since in that case it might be optimal for some countries to wait before signing the agreement, since the outside player makes the highest profits (see Kaitala and Lindroos 2000). Thus, it may be that cooperation will never take place.

Discussion and Conclusions

We have calculated Nash equilibria for harvesting Norwegian spring-spawning herring for a three-player coalition game. We have shown that the possibilities for cooperation crucially depend on the catchability coefficient. If the countries have
high-catchability coefficients, in the sense that a small number of vessels is required for harvesting, a cooperative arrangement would be difficult to achieve. In addition, the case where countries have low-catchability coefficients is ecologically more promising, since the spawning stock biomass level is always above the safe minimum biological level. In the Nash equilibria of the high-catchability coefficient case, the spawning stock is always below the safe level.

With respect to the new member problem, the two cases studied also appear very different. In the case of the high-catchability coefficient, the new entrants do not have any incentive to join the existing RFMO. However, the existing members may exclude the new entrant from harvesting by paying them off. This kind of policy, where a country may receive benefits from a fishery by merely threatening to enter and starting non-cooperative harvesting, may be dangerous. However, since there could be a number of countries demanding their share, the result could be that the existing members of the RFMO would find it optimal to switch to non-cooperation, which would be a disaster to the ecosystem and economies that depend on the fishery. It is uncertain at the present time whether the UN Agreement is sufficient in handling the new member problem and, consequently, the high-seas fisheries. The demand for “serious interest” of the UN Agreement may or may not prevent unauthorized fishing. The case of low-catchability coefficients seems more promising, since the new entrants do have an incentive to enter the cooperative arrangement and their threats of non-cooperative behavior are not individually rational. Thus, the countries might wish to seek an agreement that would reduce the catchability coefficient, if possible.

In the current paper, we have studied two cases where the catchability coefficient may be either high or low. However, there exists a continuum of these values and a critical value above which full cooperation is not stable, and new members do not have an incentive to join the RFMO, and below which full cooperation is stable, and new members would find it optimal to join the organization. In our model the critical value is 0.0049.

Different economic and biological parameters obviously affect this critical value and thus, the likelihood of stable cooperation. We find that a higher price tends to lower the critical value of theta, thereby reducing the probability of cooperation. In addition, higher discount rate, shorter simulation period, and lower costs result in a lower value of theta, and, consequently, a less probable cooperative management of herring. Having a higher first fishing age, however, tends to increase the critical value of theta. Therefore, harvesting the older part of the stock increases the likelihood of cooperation.

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

The result of more stable cooperation structure in the case of the low-catchability coefficient is also related to Hardin’s (1968) tragedy of the commons. He sees freedom of the seas, or open access to a resource, justifiable only under
conditions of low population density. It is appealing to extend this argument to the case of low-catchability coefficient. The risk of overexploitation when fleets have a low-catchability coefficient is obviously reduced, since depletion of the stock is not economically feasible.

In real world fisheries, the countries could have objectives other than profit maximization. They may wish to attempt to achieve a given stock size or maximize employment. However, the constant strategies that the countries employ in our model do imply that the countries have constant, desirable stock and catches in equilibrium. Duarte, Brasão, and Pintassilgo (2000) have studied open-access strategies, such as non-cooperative options, for the North Atlantic bluefin tuna fishery. Future research would also be needed to address the issue of multiple objectives in the case of the herring fishery.

The model studied here could be extended to the case of more than three players. This would give more insight on the coalition formation issues, but it would not change our main results on strategic importance of catchability coefficients or the results on the new member problem. Further, the dynamic aspect of the model could be given more detailed emphasis, since the stock level is changing on its way to the equilibrium value. On the transient, there may be several changes in the negotiation positions of countries, as well as in the stability properties of coalitions. Finally, the results could be analyzed applying different parameter values in order to see how asymmetries in the catchability coefficients, for example, affect the results and how likely cooperation is in other fisheries.

References


