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NASH EQUILIBRIA FOR A COALITIONAL GAME OF ATLANTO-SCANDIAN HERRING

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Nash equilibria for a coalitional game of Atlanto-Scandian herring

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1 INTRODUCTION

The Atlanto-Scandian (Norwegian spring-spawning) herring is potentially one of the largest and most valuable fish stocks in the world. It is highly migratory in nature and therefore accessible to several fishing nations. During 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. However, since the early 1990's the stock has shown clear signs of a recovery and has recently begun to exhibit its previous migratory pattern across the North-Atlantic. During these migrations out of the Norwegian EEZ the stock has in addition to Norwegian fishing become subject to exploitation by several other countries.

Because history has taught that cooperation is extremely important in the exploitation of Atlanto-Scandian herring it is natural to analyse the problem in a cooperative game theory framework. Another aspect in favour of a cooperative point of view to the game is the Convention of Straddling and Highly Migratory Fish Stocks (United Nations 1995). This agreement stresses the importance of cooperation and requires cooperation among all members inside and outside regional fisheries management organisations.

The purpose of this paper is to extend previous coalitional game analysis in Lindroos (1999) by letting the fishing mortality vary along with the fleet size and consequently with costs. We calculate Nash equilibria for each coalition of our three-player game when the strategies of the countries are constant through time. The results differ from the previous ones since Nash strategies for two-player coalitions are not maximum fishing mortalities anymore. However, for single players the harvesting will continue at maximum in the Nash equilibrium in the case of efficient fleets. The simulation period is 50 years and the countries differ with respect to their harvesting costs. It is shown that if the fleets are efficient the two-player coalitions are stable but the grand coalition is not. In the case of inefficient fleets, however, grand coalition is stable so that full cooperation is attainable.

Shapley value and nucleolus are calculated for both cases in order to find the shares of cooperative benefits to the countries. It is shown that in the efficient case the Shapley value is not in the core. Furthermore, it is difficult to find any reasonable distribution mechanism because of the game structure. The inefficient case provides with a more promising prediction of cooperative behaviour and thus, Shapley value is in the core. However, the nucleolus does not give a stable solution to the problem.

Previous cooperative game models of fisheries include an early contribution by White and Mace (1988), Kaitala and Lindroos (1998) where cooperative game solutions have been calculated for a dynamic game, and Costa Duarte et. al. (2000) who calculate the characteristic function by comparing benefits of cooperation to open access strategies. In the current paper, however, Nash equilibria are calculated for the non-cooperative games between coalition members and outside fishing nations. Models of global climate change and transboundary pollution have applied the same methodology use in the current paper to various problems. For an overview of the issues see Tulkens

(1998). Nevertheless, there exists a strong need to analyse coalitional stability issues also in the context of fisheries.

The paper is organised as follows. Section 2 presents the bioeconomic model on which the coalitional game is based. Section 3 studies the coalitional game for efficient and inefficient fleet cases. In section 4, the new member problem is briefly discussed. Finally, section 5 concludes.

2 THE BIOECONOMIC MODEL

The model follows the specific biological model developed by Patterson (1998). The simulation model is based on Touzeau et. al. (1998) and (1999). We assume Beverton-Holt stock-recruitment, high juvenile natural mortality and the selectivity of fishing gear is 0 for age classes not harvested and 1 for the ages that are harvested. We assume that the first harvesting age is 1 throughout the paper.

Population dynamics is given as a discrete time and age-structured model:

$$\begin{aligned} & N_{0,y} = R_y && y > y_1 \\ & N_{a+1,y+1} = N_{a,y} e^{-m_a - S_a F_y} && a \in \{0,1, \dots ,15\} \qquad (1) \\ & N_{a,y_1} \text{ known} && a \in \{0,1, \dots ,16\}. \end{aligned}$$

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.

Population biomass in year y is given by:

$$B_y = \sum_{a=0}^{a=16} B_{a,y} = \sum_{a=0}^{a=16} SW_a N_{a,y}, \qquad (2)$$

where parameter SW_a is the the stock weights at age.

Spawning stock biomass (right after spawning) is given by:

$$SSB_y = \sum_{a=0}^{a=16} MO_a SW_a N_{a,y}, \qquad (3)$$

where parameter MO_a gives the proportion of mature individuals among age class a.

Beverton-Holt stock-recruitment function, which gives us the average recruitment (expected value) is the following:

$$R_y = \frac{aSSB_y}{1 + SSB_y / b} e^{\sigma / 2} \qquad (4)$$

The parameters of this stock-recruitment relationship as well as the natural mortalities are shown in table 1.

PARAMETER	VALUE	UNIT
	Mortality	
$m_{0,1,2}$	0.9	
$m_{3,\ldots 16}$	0.15	
	Stock-Recruitment	
a	32.459	1/kg
b	3044.867	million kg
σ	1.763	

Table 1: Biological parameters, estimated by Patterson (1998)

The catch in numbers for country *i* is given by

$$C^i_{a,y} = \frac{S_a f^i_y}{m_a + S_a f_y}(N_{a,y} - N_{a+1,y+1}). \qquad (5)$$

Inserting equation (1) to equation (5) gives the yield (or harvest) for country *i*:

$$Y^i_y = \sum_{a=1}^{a=16} Y^i_{a,y} = \sum_{a=1}^{a=16} CW_a N_{a,y} \frac{f^i_y}{m_a + f_y}(1 - e^{-m_a - f_y}), \qquad (6)$$

where parameter CW_a is the catch weights at age. Note that the term f_y denotes the total fishing mortality.

The economic part of the 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 which are identical for a given country. However, there are significant cost differences between countries.

The modification we make to Lindroos (1999) is the following. Fishing mortality and number of vessels in the country's fleet are linked linearly with one another:

$$\frac{f_i(t)}{Nv_i(t)} = \theta_i = \theta = 0.016 \quad or \;= 0.0016 \;\; (inefficient\;\; case)$$

Here *f* is fishing mortality for country *i* and *Nv* is the fleet size for country *i*. The proportion between *f* and *Nv* is kept constant through time and it is equal for each country. Thus, we assume that countries are equally efficient in their harvesting technology. However, we separate between two cases: the efficient case where the efficiency parameter θ is larger for all countries and inefficient case where the parameter is smaller for all countries. For each unit of fishing mortality the countries wish to have they have to acquire 62 (inefficient case: 620) vessels to their fleet, or the other way around each vessel produces 0.016 (0.0016) units of fishing mortality. The maximum values of fishing mortality for the countries are 1, 0.5, 0.3, respectively, which reflect the highest historical harvesting periods for the three most important countries.

The essence of linking fishing mortality and fleet size is to make fishing effort (*f*) costly. Otherwise, the countries could have a very high *f* with very low costs if the harvests are low.

Costs for country *i* are given by

$$Q_i(t) = Nv_i \, e^{q_{1,i}} \left(\frac{Y_i(t)/Q4}{Nv_i}\right)^{q_2} . \tag{7}$$

Here Q is total costs, q1, q2 and Q4 cost parameters and Y is the total catch (or yield) for country i. Note that the countries are identical with respect to the cost elasticities, q_2. This means that changing the harvest level costs equally much for each country. The other cost parameter q_1 is 15.04, 15.1, 15.4, for countries 1, 2, 3 respectively. This means that the same level of harvest is not equally expensive for the countries. Note that the cost specification is similar to Lindroos (1999). However, we restrict ourselves to first fishing age a_1 of 1. Table 2 compiles the harvesting and economic parameters.

PARAMETER	VALUE	UNIT
a_1	1	year
$S_{0,1,2}$	0	
$S_{3,\ldots16}$	1	
q_1^i	15.04, 15.1, 15.4	ln(NOK)
q_2	0.56	
h (price)	1.45	NOK/kg
Y_v	1.2449	million kg
$f^i_{\max}$	1, 0.5, 0.3	
N^i	changing with f	

Table 2: Harvesting and economic (see Bjørndal and Gordon 1998) parameters.

The countries 1, 2 and 3 could be understood as Norway (with Russia), Iceland (with Faeroes) and EU. Norway is clearly in a dominant position for the herring fishery since most of the spawning takes place within its jurisdiction.

The net present values of countries as functions of the control variables *F* and *N* are given by

$$J^i(f^i, N^i) = \sum_y P_y^i = \sum_y \frac{hY_y^i - Q_y^i}{\rho_y}, \tag{8}$$

where $\rho_y = (1+r)^{y-y_1}$ is the discount rate. Note, that we have 1997 as the starting point y_1 and 2046 as the end point of simulations. Discount rate is 2% throughout the analysis.

3 THE COALITIONAL GAME OF HERRING

In this section we calculate the net present values that each possible coalition is able to receive in the coalitional game setting. For this purpose it is necessary to 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, it is important to study the stability of coalitions, i.e., what 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 if the situation is such that the countries do not cooperate, all they can do is to maximise their own profits taking into account the strategies of the other players. Nash equilibrium where it is not optimal for any country to unilaterally change its strategy is calculated for both the efficient and inefficient cases.

For two-player coalitions we adopt the view taken for example 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 coalition and draw reaction curves to illustrate the strategic aspects of the model.

Finally, the full cooperation - the value of the grand coalition where all players are cooperating is given by maximising the sum of net revenues of the countries. In this model it turns out to be the case that the country with the lowest costs will act as a sole owner in exploiting the stock.

The Shapley value (1953) 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.

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

$$\begin{aligned} Z_1^S &= \left[v(M)-v(2,3)\right]/3+\left[v(1,2)-v(2)\right]/6+\left[v(1,3)-v(3)\right]/6+v(1)/3 \\ Z_2^S &= \left[v(M)-v(1,3)\right]/3+\left[v(1,2)-v(1)\right]/6+\left[v(2,3)-v(3)\right]/6+v(2)/3 \quad (9) \\ Z_3^S &= \left[v(M)-v(1,2)\right]/3+\left[v(2,3)-v(2)\right]/6+\left[v(1,3)-v(1)\right]/6+v(3)/3 \end{aligned}$$

The advantage of the nucleolus (Schmeidler 1969) 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 maximised.

3.1 Case of efficient fleets

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 f. The Net present values for singletons, respectively, are given (in Norwegian currency NOK) as
v(i) = (4.8779, 2.3128, 0.8958) 10^9.

These values are the individual values in the characteristic function. In this case the herring stock is driven almost to extinction rapidly. Note that the countries will receive negative rent from harvesting after 3 years. Having an exit condition would change the payoffs slightly but it would not affect our main results.

The two-player cases are given essentially as two-player games where the most efficient country of the two members within a 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 as v(1,2) = 19.562 10^9, v3 = 14.534 10^9, v(1,3) = 18.141 10^9,
v2 = 17.544 10^9, v(2,3)=17.544 10^9 , v1=18.141 10^9. Note that v*i* denotes the value for a country that is outside of the coalition (i,j).

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 stabilise with a relatively large positive value in all two-player coalition cases. However, the SSB is well below the safe minimum biological level 2.5 10^9 kg (see Patterson 1998) already after 5 years. The spawning stock at the end of simulations is 1.3 10^9 kg for coalitions (1,3) and (2,3), and 1.5 10^9 kg for coalition (1,2).

In figure 1 we see the Nash equilibrium of the game between coalition (1,3) and (2). The Nash equilibrium is very similar in the two other cases which is illustrated in figure 2 for the game coalition (1,2) against country 3.

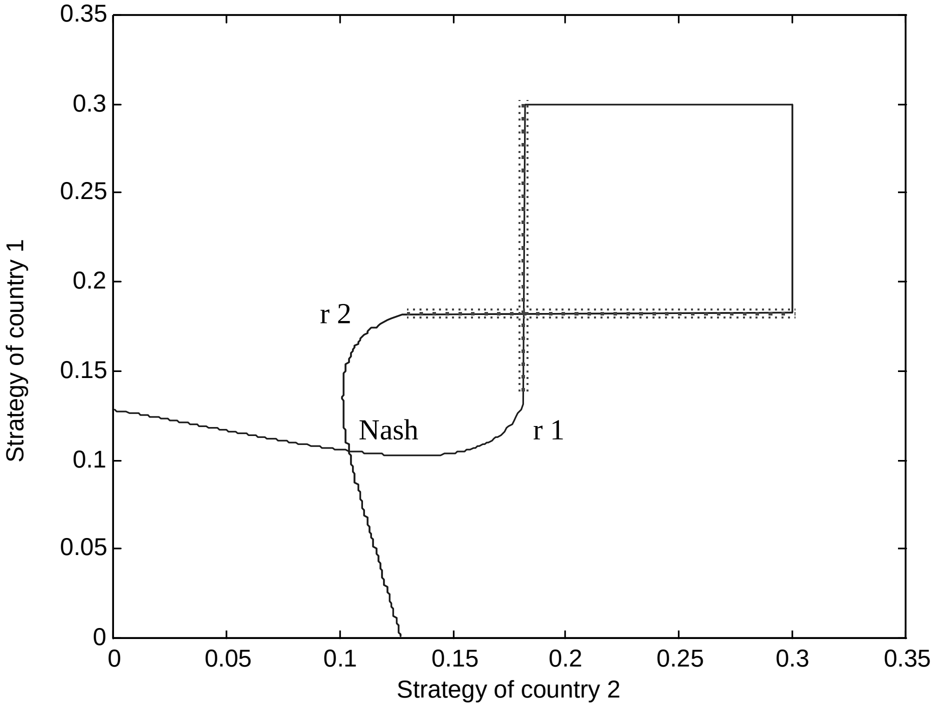

Figure 1: Reaction curves r1 and r2 of countries 1 and 2.

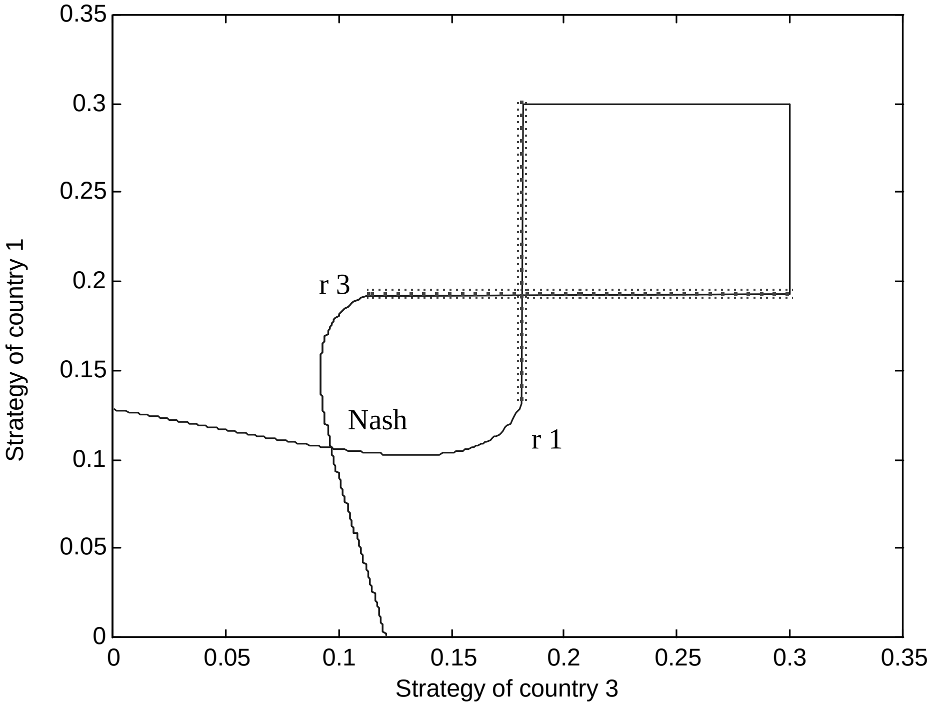

Figure 2: Reaction curves r1 and r3 of countries 1 and 3.

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 given as a dashed line. A similar story can be told for r2. Note that there exists another Nash equilibrium at the maximum fishing mortality values of the countries. However, this equilibrium is inferior to the one illustrated in the figures.

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 10^9 where M is the number of players. At the end of simulation period the spawning stock is 4.5 10^9 kg.

Thus, we see immediately that two-player coalitions are stable coalitions, 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 value gives: (16.35, 14.78, 13.36) 10^9. Thus, 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 Costa Duarte et. al. 1999 for similar results). Therefore, we need to construct a mechanism that creates incentives for the countries to cooperate since otherwise the stock will be depleted. Note that, without coalitional analysis this would be straightforward: there are huge benefits from cooperation (36 10^9 NOK). However, even if individual deviations are not profitable, free-riding with the expense of the other two makes deviations more likely.

Table 3 summarises the results:

COALITION	VALUE	STRATEGY	FREE-RIDER VALUE
1	4.88	1.00	
2	2.31	0.50	
3	0.90	0.30	
1,2	19.56	0.107	14.53 (country 3, f=0.096)
1,3	18.14	0.105	17.54 (country 2, f=0.104)
2,3	17.54	0.104	18.14 (country 1)
1,2,3 = M	44.49	0.13	50.21 (sum of the above)

Table 3: Characteristic function and free-riding in the efficient case (values in 10^9 NOK)

3.2 The case of inefficient fleets

Let us now turn to the case where the fishing fleets are inefficient. The efficiency parameter $\theta = 0.0016$ is one tenth from the previous section.

For the single player Nash equilibrium we have f_1 = 0.07, f_2 = 0.07 and f_3 = 0.01. The following payoffs are v(1) = 9.002 10^9 , v(2) = 7.984 10^9, v(3) = 0.1952 10^9. Comparing the values of singletons to the efficient fleet case of section 3.1 we notice that countries 1 and 2 are better off in the inefficient Nash equilibrium whereas country 3 is worse off. It is interesting to notice that some countries may actually have better payoffs with all countries have less efficient fleets. The spawning stock even in this non-cooperative case is 3.5 10^9 kg. Thus, well above the safe level. This is a remarkable difference to the previous case where the stock is depleted rapidly to extinction.

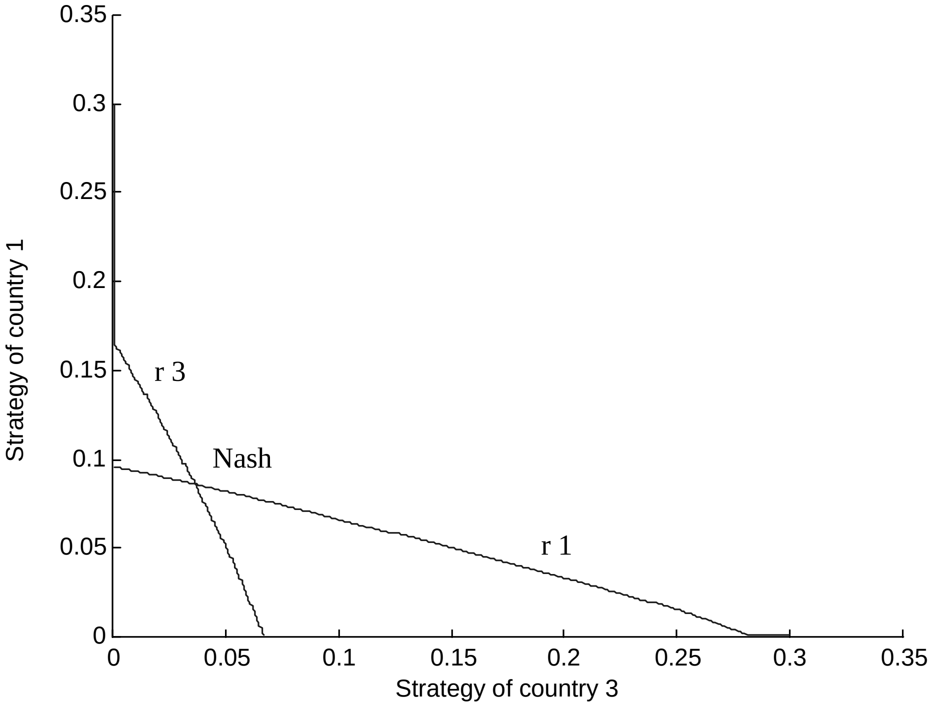

Figure 2:Nash equilibrium (coalition (1,2) against country 3) for the less efficient case

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 2). Thus, we see that now the relative difference between equilibrium strategies is greater. Also the reaction curves are different in shape. They are nearly linear for each country. The resulting payoffs are v(1,2) = 15.700 10^9, v3 = 2.1898 10^9. At the end of simulation period the spawning stock is 5 10^9 kg. Note that in this case there is only one Nash equilibrium, if the other chooses maximum fishing mortality 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 10^9 and v2 = 8.4617 10^9. At the end of simulation period the spawning stock is 3.7 10^9 kg. Thus, there is a significant biological difference between the two-player coalition Nash equilibria. Further, as compared to the previous efficient fleet case we notice that the spawning stock is always above the safe biological level whereas in the previous case it is always below the safe level when two-player coalitions are competing with the outside country.

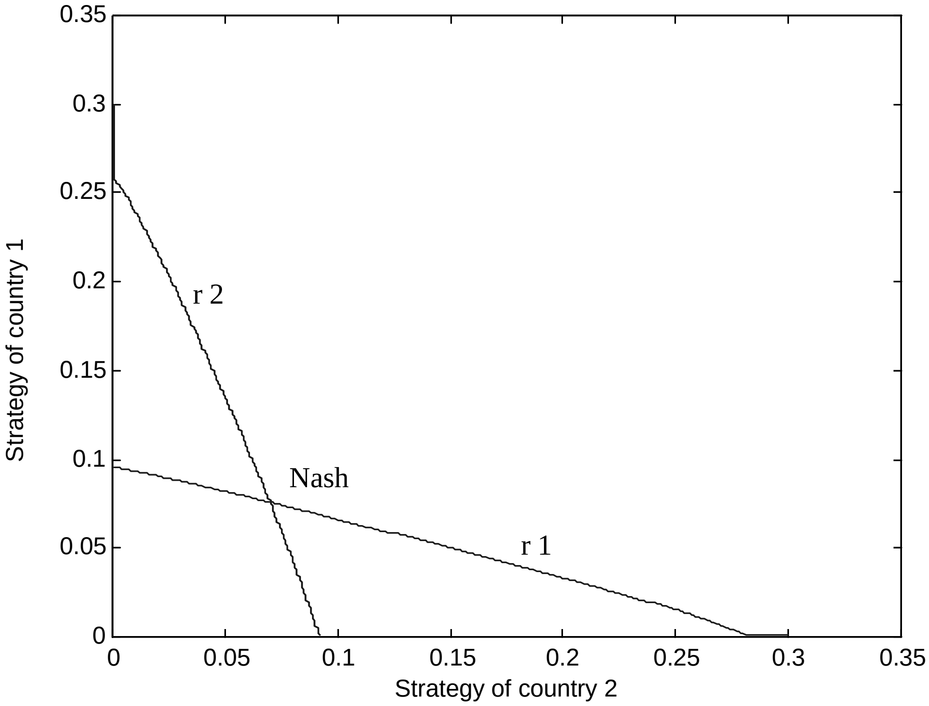

Figure 3:Nash equilibrium (coalition (1,3) against country 2) for the less efficient case

For coalition (2,3) again the equilibrium is similar to coalition (1,3) with values v(2,3) = 8.4617 10^9 and v1 = 10.310 10^9. For reaction curves r1 and r3 see figure 3.

Finally, the full cooperative outcome is f = 0.1, with v(M) = 23.3179 10^9. The spawning stock after 50 years is high, 6.5 10^9 kg.

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

Shapley value gives (10.92, 9.50, 2.90) 10^9 which lies in the core. Nucleolus gives (10.94, 9.92, 2.14) 10^9 which can be checked using Kohlberg's (1971) criterion. The idea 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 and thus the singletons are most dissatisfied coalitions. However, if we look at the proposed allocation we see that country 3 can not be satisfied with it since it would immediately get more by exiting from the regional fisheries management organisation. Thus, in the context of our game the nucleolus should be slightly modified.

Table 4 summarises the results:

COALITION	VALUE	STRATEGY	FREE-RIDER VALUE
1	9.00	0.07	
2	7.98	0.07	
3	0.20	0.01	
1,2	15.7	0.086	2.19 (country 3, f = 0.036)
1,3	10.31	0.08	8.46 (country 2)
2,3	8.46	0.07	10.31 (country 1)
1,2,3 = M	23.32	0.10	20.96 (sum of the above)

Table 4: Characteristic function and free-riding in the inefficient case (values in 10^9 NOK)

4 ON THE NEW MEMBER PROBLEM

Let us define the Charter members (original members) as players i,j and the new entrant as player k. Players i and j are making profits worth 44.49 billion (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 out. Then in the first case the new entrant has no incentive to join the regional organisation since it would be better off by playing Nash (staying out) against Charter members. However, the Charter members do 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 14.08 billion and still receiving 30.41 billion NOK, which is clearly better than their Nash equilbrium outcome of 18.83 billion NOK. Thus, in the case of efficient fleets there could exist countries that would gain from the fishery by simple threatening to enter. Although, it may be that the Convention on Straddling and Highly Migratory Stocks (1995) may prevent such actions, since a country should have real interest in the fishery. Further, there may be legal barriers for the distant water fishing nations to harvest as an outsider in a given fishery.

However, the situation where no regional fisheries organisation 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 1999). Thus, it may be that cooperation will never take place.

For the second case, however, the situation is more promising since the new entrant does have an incentive to join the cooperative organisation. This is due to the fact that the grand coalition is now stable. In the case of inefficient fleets it is therefore the case that the threat of non-cooperative behaviour by the new entrant is not credible in the sense that it is not individually rational. Note that even if country 1 would be the new entrant the cooperative benefits would still be large enough to sustain cooperation and a stable grand coalition.

5 CONCLUSIONS

We have calculated Nash equilibria for harvesting Atlanto-Scandian Herring for three player coalitional game. We have shown that the possibilities for cooperation crucially depend on the efficiency parameter. If the countries are very efficient 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 are less efficient is ecologically more promising since the spawning stock biomass level is always above the safe minimum biological level. In the Nash equilibria of the efficient case the spawning stock is always below the safe level.

With respect to the new member problem the two cases studied are also very different. In the efficient fleet case the new entrants do not have any incentive to join the existing regional fisheries management organisation. However, the existing members may exclude the new entrants 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 is may be dangerous, however, since there could be a number of countries demanding their share and the result could be that the existing members of the regional fisheries management organisation would find it optimal to switch to non-cooperation instead which would a disaster to the ecosystem and economies that depend on the fishery.

The inefficient case seems more promising since the new entrants do have an incentive to enter cooperative arrangement and their threats of non-cooperative behaviour are not individually rational. Thus, the countries might wish to seek an agreement of reducing efficiency or allowing only small scale fishing vessels in order to improve stability of the cooperative regime.

The model studied in the current paper could be extended to the case of more than three players. This would give more insights on the coalition formation issues. Further, 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 this way there may be several changes to the negotiation positions of countries as well as to stability of coalitions. Finally, the results could be analysed with different parameter values in order to see how for example the discount rate or asymmetries in the efficiency parameter affect the results.

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