An Enforcement-Coalition Model: Fishermen and Authorities forming Coalitions

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Abstract

The paper sets up a four-stage enforcement model of fish quotas. The purpose of the paper is to show how the level of enforcement set by the authorities affects the way fishermen form coalitions. We show that a high level of control effort yields less cooperation among fishermen, while in the case of low control effort, coalitions are somewhat self-enforcing. The paper further discusses how the optimal enforcement level changes when the coalition formation among authorities changes: centralised, partly centralised and decentralised authorities. We show that decentralised authorities set a lower level of control effort compared to the centralised authorities. The theoretical results are illustrated by simulations of the Baltic Sea cod fishery.

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Key words Coalition formation, Fisheries management, Quota enforcement, Self-enforcing policy

JEL Codes C70, Q22, Q28

Table of contents

1. Introduction

It is a general problem that management measures in fisheries decided at the regional level often have to be implemented on the national level; hence, a centrally determined policy is enforced on a decentralised level. This is termed by Holden (1994), the Achilles heal of the Common Fisheries Policy in EU. It is also known from earlier studies (e.g. Jensen 2001), that the enforcement of regulations at the national level may differ tremendously among countries, if there is any enforcement at all. The essence of the problem is that the individual states joining the agreement have no incentive to employ costs for monitoring and enforcement. The problem is also present in the Baltic Sea. The International Baltic Sea Fishery Commission (IBSFC) was established pursuant to the Gdansk Convention (IBSFC 2003). On signing this Convention, the Contracting Parties undertook to

> *"co-operate closely with a view to preserving and increasing the living resources of the Baltic Sea and the Belts and obtaining the optimum yield, and, in particular to expanding and co-ordinating studies towards these ends,..."*[1]

To comply with the Convention, the IBSFC introduced the first total allowable catch (TAC) on cod in the Baltic Sea in 1977. Until that time the fishery was subject to access based on bilateral agreement, where countries agreed to share territories in return for satisfying some technical conservation measures. In 1977 the exclusive economic zones (EEZ) were also increased to 200 nautical miles, dividing the sea according to the centre line, which created some disputes over the islands of Bornholm and Gotland. In particular, the dispute between Sweden and the Soviet Union over Gotland Island gave rise to an area frequently called the ‘White Zone’, in which there existed open access until 1987 when Sweden and the Soviet Union finally came to an agreement. Comparing the TAC with actual harvests indicates that the TAC has often been exceeded, see table I.

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1 Source: Article 1 of the Gdansk Convention, IBSFC (2003), www.ibsfc.org.

Table I. TAC for Cod in the Baltic Sea and the actual Catches

Year	TAC Tonnes	Catch Tonnes	Excess Catch Tonnes	Excess catch % of TAC
1977	185	211.1	26.1	14.11%
1978	174	194.6	20.6	11.85%
1979	175	272.7	97.7	55.85%
1980	235	389.6	154.6	65.78%
1981	227	384.4	157.4	69.33%
1982	No TAC	363.6		
1983	No TAC	380.8		
1984	No TAC	441.4		
1985	No TAC	355.2		
1986	No TAC	279.3		
1987	No TAC	235.6		
1988	No TAC	223.9		
1989	220	197.7	-22.3	-10.14%
1990	211	171.3	-39.7	-18.80%
1991	171	139.2	-31.8	-18.59%
1992	100	72.9	-27.1	-27.12%
1993	40	66.4	26.4	66.03%
1994	60	124.0	64.0	106.75%
1995	120	141.6	21.6	18.01%
1996	165	172.7	7.7	4.69%
1997	180	132.2	-47.8	-26.54%
1998	145	101.5	-43.5	-29.97%

Source: ACFM (2000) and own calculations.

Neither before the establishment of the IBSFC, nor after has there been any effective enforcement and the fishery is considered to be *de facto* open access. Furthermore, it is pointed out in Kronbak (2002) that the cod fishery, from 1982-1999, seems to fit a dynamic open access model rather well. This, again, is an example of the general enforcement problem. Coalitions among fishermen do exist in some real world settings, for instance in the form of producer organizations (POs).[2] Producer organisations are, however, not very common in the Baltic Sea, particularly not in the Eastern European countries. This paper sets up a model to discuss the effects of fishermen forming a coalition and the effect of having a decentralised versus a centralised enforcement policy. The model is inspired by the actual situation in the Baltic Sea, but it is a general model with relevance to all regulated fisheries where management measures are decided centrally but implemented on the decentralised level.

In the existing literature there are models where part of the control is at the centralised level and part is at the decentralised level (Caplan & Silva 1999). Our model contributes to the literature by modelling coalitions on the enforcement level taking into account coalitions at the regulated level. In addition, it opens up for discussing the question of how centralised, decentralised or partly centralised enforcement can affect the way fishermen form coalitions.

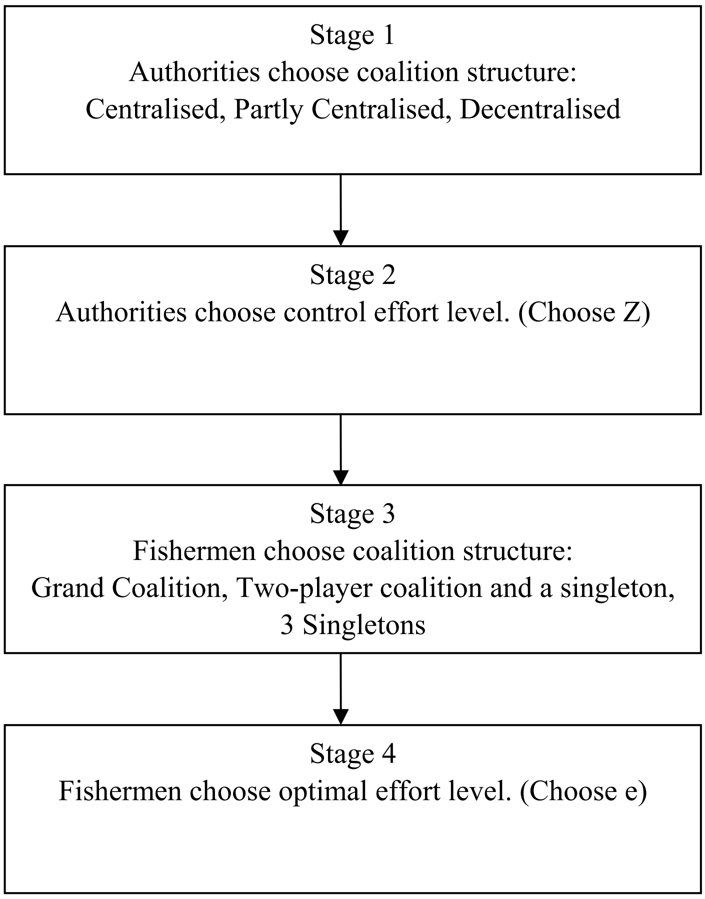
Previous fisheries enforcement studies include Sutinen & Andersen (1985) who examined the enforcement of fish quotas in a single-player model, Jensen & Lindroos (2002) who studied enforcement of fish quotas in a two-player model and Jensen & Vestergaard (2002a) who investigated the moral hazard problem when individual catches are unobservable to society. These studies have not considered the possibility of forming coalitions. There exist studies that have addressed coalition formation, mainly on the international level, such as Lindroos (2002), Duarte *et al.* (2000) and Pintassilgo (2003). However, these studies do not consider the enforcement problem. The present study integrates these

2 In Denmark there are 3 POs; the Danish Fishermen's Producer Organisation, Denmark's Pelagic Producer Organisation, and Skagen Fishermen's Producer's Organisation.

two types of models by introducing coalition formation to both the authorities (international) and the fishermen.

The purpose of the paper is to show the effects of fishermen forming coalitions and authorities forming coalitions given the authority undertakes a certain level of quota enforcement. The paper discusses the effects of authorities being centralised, partly centralised or decentralised. The paper sets up a four stage static model. The four stages of the model are illustrated in figure 1.

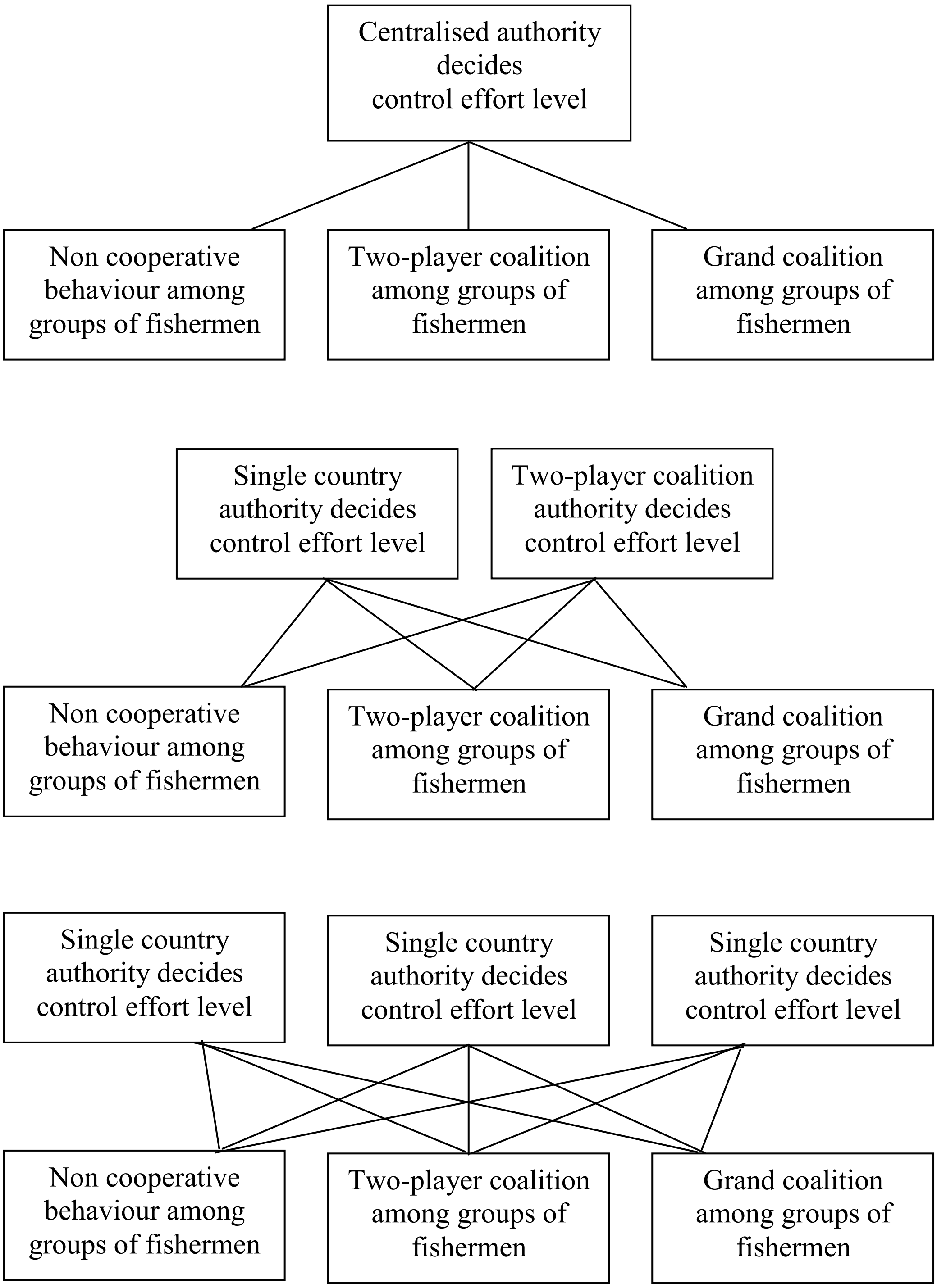
Figure 1. The four stages of the model



The first two stages of the model belong to the authorities. In stage one; the authorities decide their level of coalition formation. There are three defined levels of centralisation among authorities; centralised (a grand coalition among authorities), decentralised (no coalition among authorities) or partly centralised (a two-player coalition and a singleton). Given the level of centralisation decided by authorities, they then decide their level of enforcement in stage two. The last two stages belong to the three groups of fishermen. They also start out by deciding which coalition to belong to in stage three. The fishermen also have three possible coalition structures, namely, three singletons playing Nash against each other, a two-player coalition and a singleton or a grand coalition. In stage four they maximise the expected profits by deciding the employed effort level. As with the authorities, the fishermen also have the choice of joining three different coalition formations. This yields nine different scenarios to analyse.[3] These nine scenarios are illustrated in figure 2.

3 We ignore that there are three possible two-player coalitions among authorities since we later assume that the authorities are identical. We also ignore that there are three possible two-player coalitions among fishermen, in this case we simply choose the most efficient coalition.

Figure 2. Illustration of nine different scenarios



In our paper we analyse analytically six of the nine scenarios; those where authorities are either completely centralised or completely decentralised, leaving the three scenarios in-between, where authorities are partly centralised for discussion only.

At present, there are six contracting parties in the Baltic Sea: Estonia, the European Community, Latvia, Lithuania, Poland and the Russian Federation. We can fit the six parties into our coalition model by grouping the contracting parties into 3 authorities. These 3 authorities are represented by; the European Community, which is the largest agent, catching between 50-70% of the total catch of cod, Poland, which is the second largest agent, catching some 20-30% of the total catch of cod and the former Soviet Union (now Russia) and the three Baltic countries (Estonia, Latvia and Lithuania) catching some 10-20% of the total catch of cod. We can also group the fishermen exploiting the cod stock into three groups represented by the technology they apply. The three main technologies for harvesting cod are demersal trawls, high opening trawls and gillnets, where gillnets catch up to 50% of the total catch, all three technologies are represented in each country group. Currently, there is no formalized cooperation among the authorities and there is only little cooperation among the fishermen in the Baltic Sea in the form of POs. This model seeks to explain the gains from cooperation on both the authorities and the fishermen levels.

The paper is organised as follows. First a basic theoretical model is set up. The model is discussed theoretically for centralised and decentralised authorities. Then how enforcement can affect the way fishermen form coalitions is discussed. Simulations follow the theoretical model. Finally, the main results are discussed together with the scope for future research.

2. The Basic Model

The model follows the basic two-stage structure used by Ruseski (1998) and Lindroos (2002). However, our model does differ, since we allow the players in each stage to make two decisions; first, which coalition to belong to and second, which effort level to decide on. This explains the four stages of our one-shot model.

The Gordon-Schaefer model sets out the biological and production related characteristics of the fishery considered in the paper. With three players, or groups of asymmetric fishermen, $\{1,2,3\}$, the dynamic equation looks as follows:

$$\frac{dx}{dt} = G(x) - \sum_{i=1}^{3} h_i \ , \tag{1}$$

where x is a single fish stock and h_i is the harvest of the single group of fishermen. In this one shot model the discount rate is equal to zero for all groups of fishermen. It is assumed throughout that the fish stock is a common property of the fishermen and there are no potential new entrants. The natural growth of the fish stock is given by the logistic growth function:

$$G(x) = rx\left(1 - \frac{x}{K}\right), \tag{2}$$

where r is the intrinsic rate of growth of fish and K is the carrying capacity of the fishing ground. The harvest function for a group of fishermen following technology i is assumed to be linear, following the Gordon-Schaefer type:

$$h_i = q_i e_i x, \tag{3}$$

where the term q_i is the catchability coefficient for technology i, and e_i is the effort employed by the group of fishermen applying technology i. We assume that the fishermen are asymmetric since they can differ in their catchability coefficients, q_i's. A higher catchability coefficient can be interpreted as a technological advantage. Without loss of generality we assume i is the most efficient technology and k is the least efficient technology, e.g. $q_i > q_j > q_k$.

The steady state stock can be derived, using the equations (1) to (3), where harvesting equals growth:

$$x = \frac{K}{r}\left(r - \sum_{i=1}^{3} q_i e_i\right), \qquad x > 0 \,. \tag{4}$$

Hence, for each level of fishing effort, given the catchability coefficients, there is a sustainable steady state stock level.

The authorities are able to act as Stackelberg leaders against the groups of fishermen. Therefore, the problem is solved backwards. In the fourth stage, fishermen choose the effort that maximises the individual expected steady-state rents given their choosen coalition structure and the enforcement level. The individual group of fishermen further takes the effort level by rival group(s) as given. The fishermen, or coalitions, are playing a Nash game against each other. In the third stage the fishermen decide coalition formation. In the second stage, each authority unilaterally chooses the level of control effort in its region, taking into account full knowledge of how control effort influences the third and fourth stage equilibrium and taking the foreign control effort level as given, in the case of decentralised control authorities. In the first stage the authorities decide which coalition structure to belong too. Each authority plays a Stackelberg game in the effort level against the fishermen and a Nash game in control effort policies against the foreign authority. The authorities' problem is to set a level of enforcement, given that control is costly. This type of authority problem is discussed in Jensen and Lindroos (2002). We contribute to the literature by allowing for asymmetry among fishermen and also by allowing fishermen to form coalitions. This is relevant for the society since coalitions on both levels might result in more compliance with TACs even though less effort is employed for control.

The fishery is managed by a total allowable catch (TAC) and it is assumed that the TAC is set at a sufficiently low level, restricting the effort of the fishermen. Since control is costly it is not optimal for the authorities to choose perfect control. The authorities are assumed to maximise the economic surplus given by the difference between fishermen's profits and the control costs. Only fishermen having homeport in own country group are considered. The decision variable for the authorities is the level of control effort, *Z*. The maximisation problem for a single authority is as follows:

$$\underset{Z}{Max}\,\pi = \sum_{i=1}^{3} P_i(\Psi) - \frac{\gamma}{1-Z}, \qquad (5)$$
$$s.t. \quad 0 \le Z < 1$$

where $P_i(\Psi)$ describes the fishermen's profit facing probability Ψ of being detected applying technology *i*. γ is the unit cost of control effort. The second term on the RHS describes the total costs of control; we see that if the control effort is extensive, *Z* approaches one, then the costs of control go to infinity. On the other hand, if control effort approaches zero, there are still some fixed management costs.

The fishermen choose their level of fishing effort based on expected profit maximisation according to the following formula:

$$\underset{e_i}{Max}\,E(P_i) = \begin{cases} \underset{e_i}{Max}\left((1-\Psi)ph_i - ce_i - \Psi\Omega \quad \middle| h_i > TAC_i\right) \\ \underset{e_i}{Max}\left(ph_i - ce_i \quad \middle| h_i \le TAC_i\right) \end{cases}. \qquad (6)$$

Assuming the TAC is set at a sufficiently low level then there is non-compliance.[4] The profit when not complying with the TAC is determined by the ordinary profit minus an expected lump-sum fine ($\Psi\Omega$) and an expected penalty depending on the value of the harvest (Ψph_i). Ψ is the probability of being caught. We assume there is a one-to-one linear relationship between the control effort and the probability of being caught, hence $Z=\Psi$.

4 Non-compliance is, of course, only true for some levels of control effort, but either by assuming an extremely low TAC or by assuming fishermen face some high fixed costs, we can 'force' the fishermen to non-compliance.

The remainder of the paper is organised as follows; First, we analyse the three scenarios resulting from the authorities agreeing on being completely centralised, second we analyse the three scenarios resulting from the authorities being completely decentralised. Third, we discuss what happens if the authorities are partly centralised. Finally, we discuss the stability of the coalition structures and illustrate some of the results using a simulation model.

3. A Centralised Authority

This section analyses the three scenarios resulting from the control authorities forming a grand coalition and acting as a single centralised authority. The fishermen can join three different coalitions; act as three singletons playing Nash against each other, a two-player coalition playing Nash against a singleton or a grand coalition. The fishermen maximise their profits after deciding which coalition structure to belong to. The fishermen's behaviour and the optimal control effort in three different coalition structures are evaluated.

3.1. Three Singletons among Fishermen

The non-cooperative equilibrium is determined where the groups of fishermen act as singletons playing Nash against each other. Since the control authority acts as a Stackelberg leader, the problem is solved by backwards induction. Inserting the steady state stock (equation (4)) and the harvest function (equation (3)) into the profit function for the fishermen (equation (6)) and maximising the expected profit for the groups of fishermen yields the following reaction functions for group i:

$$e_i = \frac{r\left(1-\dfrac{b}{q_i}\right) - q_j e_j - q_k e_k}{2q_i} \quad \forall i,\ i \neq j \neq k, \tag{7}$$

where $b = \frac{c}{(1-\Psi)pK} > 0$.The Nash equilibrium effort is derived by the intersections of the reaction functions for the groups of fishermen, which yields the best response for all fishermen given others best response. The optimal effort employed by a single group of fishermen where fishermen are playing a Nash game follows the following formula:

$$e_i^N = \frac{\left(1 - \frac{3b}{q_i} + \frac{b}{q_j} + \frac{b}{q_k}\right) r}{4q_i} \qquad \forall i, i \neq j \neq k. \tag{8}$$

It must be assumed that $-\frac{3b}{q_i} + \frac{b}{q_j} + \frac{b}{q_k} < 1$, to ensure that effort employed is positive. The Nash equilibrium effort depends on the risk of being caught, Ψ, since it is a part of b. If the risk of being caught increases, that is if b increases, then the Nash effort level decreases if it is assumed that $\frac{1}{3q_i} > \frac{1}{q_j} + \frac{1}{q_k}$ for all $i, j, k, i \neq j \neq k$. Since the resource is a shared stock among the three groups of fishermen, the effort employed by one group of fishermen has a negative effect on the level of effort employed by others. If, for instance, fishermen with technology i become more effective, that is the catchability coefficient, q_i, increases, then the effort of fishermen with technology j and k decreases. The change in the effort for fishermen applying technology i is, however, ambiguous. On the one hand there is an increase in the effort resulting from being more efficient, but on the other hand with a higher catchability, less effort is required to retain the same harvest level.

Solving backwards now allows us to solve the problem of the centralised authorities. The benefit function for the authorities is defined by (5), where the fishermen's profit function (6), the steady state stock (4) and the harvest function (3) are inserted. The authorities maximise their benefit function of harvesting minus the control costs written as follows:

$$\underset{Z}{Max}\,\pi_0 = \sum_{i=1}^{3}\left(pq_i e_i \left(K - \frac{K\sum_{j=1}^{3} q_j e_j}{r} \right) - ce_i \right) - \frac{\gamma}{1-Z}. \tag{9}$$

$$s.t.\;\; 0 \le Z < 1$$

Penalties paid by fishermen from exceeding the TAC are exactly offset by the income received by the authority.[5]

Inserting the optimal effort level employed by fishermen (7) and determining the first order condition for the centralised authority (*CA*) when fishermen are playing Nash (*N*) yields the optimal enforcement level, given that enforcement is costly:

$$Z_{CA}^{N} = 1 - \frac{rc^2}{8rc^2q^2\left(\frac{1}{q_i^2}+\frac{1}{q_j^2}+\frac{1}{q_k^2}\right) + 2rc^2 + Kpqrc - 8Kpq^2\gamma}, \tag{10}$$

where $\frac{1}{q} = \frac{1}{q_i} + \frac{1}{q_j} + \frac{1}{q_k}$. It is observed, that a higher level of control costs decreases the optimal control effort. The intuition behind this is that more expensive enforcement is less appropriate to apply (Becker 1968). Hence, if enforcement control is extremely expensive, it might imply less effort employed and thus more non-compliance. If compliance is the goal in such a case, it might be wise to consider subsidising the control policy. The effects of changes in other parameters are included in comparative statics later.

3.2. Coalitions among Fishermen

This section discusses the implications of fishermen forming either a two-player coalition or a grand coalition.

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5 We assume no double dividend exits; that is, tax revenues cannot be used to reduce other distorting taxes Jensen & Vestergaard (2002b).

Assume two groups of fishermen form a two-player coalition we assume i and k form a coalition, $\{i,k\}$. The two-player coalition plays a Nash game against the singleton. The coalition is assumed to apply the most efficient technology in the coalition, since the marginal benefits from applying the most efficient technology are always higher than the marginal benefits from applying a less efficient technology.[6,7] It is intuitively clear, that fishermen with the highest efficiency have to employ the lowest level of effort to reach a certain level of harvest. This implies that the benefits are highest from forming a coalition of heterogeneous fishermen compared to a coalition of homogeneous fishermen. Thus POs are most suitable across heterogeneous technologies. It is beyond the scope of this paper to deal with the question of how the benefits are distributed among the groups in a coalition.

The grand coalition is defined as full cooperation among all groups of fishermen. The grand coalition is also assumed to apply the most efficient technology in the coalition.

The optimal fishing effort and the optimal level of control effort when fishermen form coalitions are summarised in the appendix, table A.I and table A.II.

From the optimal level of control effort we can conclude, that in the scenario with a grand coalition among fishermen, self-regulation works and there is no need for government intervention. This conclusion is drawn from the fact, that only a corner solution, where $Z = 0$, satisfies $0 \leq Z < 1$.[8] The intuition behind this result is that fishermen forming a grand coalition maximise an objective function comparable to the objective function of the society except for the costs

6 We are analysing only the two-player coalition among i and k. This coalition is the most efficient coalition (together with the coalition between j and k) since the technology of the least efficient group of fishermen (k) is 'hidden' in a coalition and therefore not applied.

7 The reason that we do not have a reallocation of effort in the coalition but a corner solution, where the effort employed by the least efficient technology is zero, is that we assume marginal costs are constant.

8 We consider that the cases of having a zero biological growth rate (r=0) or zero harvesting costs (c=0) are too unrealistic.

of control. Thus, if the society observes that the fishermen are organising in one large PO, then the circumstances permit the control effort to be reduced to zero. Since we are not able to make further analytical conclusions, we use comparative statics on the level of control effort.

3.3. Comparative Statics on the Level of Control Effort

The effects of changes in economic parameters are determined by comparative statics analysis on the level of control effort in the case of fishermen playing Nash and in the two-player coalition.[9] The effects of changes in price and costs are summarised in table II and the effects of changes in the catchability measure are summarised in table III.

Table II. Comparative statics on optimal control effort w.r.t. price and cost parameters

	γ	c	p
Z_{CA}^{N}	-	- if $c > \frac{16 q_i q_j q_k \gamma}{r(q_i q_j + q_i q_k + q_j q_k)}$	+ if $c > \frac{8 q_i q_j q_k \gamma}{r(q_i q_j + q_i q_k + q_j q_k)}$
Z_{CA}^{2C}	-	- if $c > \frac{18 q_i q_j \gamma}{r(q_i + q_j)}$	+ if $c > \frac{9 q_i q_j \gamma}{r(q_i + q_j)}$

Note: - indicates a negative effect, + indicates a positive effect.

From table II we can conclude that the optimal level of control effort unambiguously decreases, if the costs of control increase. The result is, however, ambiguous when analysing the effect of changes in prices and costs of harvesting. The ambiguity is a result of control effort being dependent on prices and costs in an advanced fashion. The authorities should, therefore, not react to changes in prices and costs, unless they have accurate information about estimated pa-

9 Comparative statics in the scenario of a grand coalition among fishermen are omitted since it is a corner solution. Only zero costs of harvesting can make the corner solution move from the no control to the full control effort level. This is, however, not a realistic scenario.

rameter values, but instead accept a second best solution. If the unit cost of harvesting is sufficiently high, we can conclude that the optimal control effort increases if p is increased and decreases if harvesting costs are increased.

Table III. Comparative statics on optimal control effort w.r.t. catchability parameters

	q_i
Z_{CA}^{N}	+ if
	$q_i > \dfrac{crq_j q_k\left(16cq_j + 16cq_k - Kpq_j q_k\right)}{16c^2 r\left(q_j^2 + q_k^2\right) + crKpq_j q_k\left(q_j + q_k\right) - 16Kpq_j^2 q_k^2 \gamma}$ for $i, j, k = \{1,2,3\}, i \neq j \neq k$
$Z_{CA}^{\{i,k\}}$	+ if
	$q_i > \dfrac{crq_j\left(18c - Kpq_j\right)}{18c^2 r + crKpq_j - 18Kpq_j^2 \gamma}$ for $i, j, k = \{1,2,3\}, i \neq j \neq k$

Note: + indicates a positive effect.

From table III we can conclude that if the catchability coefficient in question is sufficiently high, then a further increase in the catchability coefficient implies an increase in the control effort level. This is true for the control effort level in both the Nash game among fishermen and the two-player coalition among fishermen. The intuition behind this is that one player, who is already efficient, becomes even more efficient and it is thus easier to not comply. An increase in control effort has the opposite effect. In the two-player coalition case there is an effect of an increase in q_k only when q_k exceeds q_i, otherwise the effect is zero. If the catchability for group k is increased such that $q_k > q_i$, then group k becomes the most efficient in the coalition, and a switch between technology k and i will take place.

4. A Decentralised Authority

Consider the authorities to be completely decentralised; e.g. there are three individual authorities each setting their own level of control effort based on a Nash game against other authorities and a Stackelberg game against the fishermen. The control effort in one country only affects fishermen from this country. In each country there are fishermen representing all three different technologies. Therefore, control effort levels set by all three authorities affect each group of fishermen. To simplify, it is assumed that the groups of fishermen consist of one-third from each country; hence the control policy from the countries has equal weight on each group of fishermen.[10] This assumption implies that we can maximise the profit of the groups of fishermen only considering the level of control effort corresponding to the sum of Z's applied in the three countries. We also assume that countries are symmetric, e.g. the lump-sum penalty for being caught is the same in all three countries and so are the unit costs of control.[11] We determine the optimal effort employed by fishermen and the optimal control effort by the authorities in the three scenarios resulting from fishermen forming coalitions.

4.1. Three Singletons among Fishermen

Denote the three authorities by 1, 2 and 3. The benefits for the fishermen applying technology i are now determined by the following formula:

$$\begin{aligned} P_i^N &= \frac{1}{3}(1-Z_1)ph_i^N + \frac{1}{3}(1-Z_2)ph_i^N + \frac{1}{3}(1-Z_3)ph_i^N - ce_i^N - \Omega(Z_1+Z_2+Z_3) \\ &= \frac{1}{3}(3-(Z_1+Z_2+Z_3))ph_i^N - ce_i^N - \Omega(Z_1+Z_2+Z_3) \end{aligned} . \tag{11}$$

Equation (11) is an extension of equation (5). It describes the fishermen's profit from applying technology i, but since this technology is represented in all three countries with 1/3 in each of them, then 1/3 of them face control effort Z_1, 1/3

10 This assumption does not change the general result since the control effort will always be interpreted by the fishermen as the sum of control efforts. If the shares of different technologies change, it only changes the weight the different levels of control effort have in the sum of control efforts.

11 Without symmetry among authorities the analysis becomes complicated, and it might not be possible to achieve an analytical solution.

face control effort Z_2 and 1/3 face control effort Z_3. The optimal effort employed in the fishery is determined and summarised in the appendix, table A.III.

The optimal effort employed by fishermen when the authorities are decentralised is equivalent to the effort level employed in the centralised authority scenario, except that the optimal control effort is now considered as an average control effort. Since the fishermen consider the control effort only as a single level, the way the authorities can affect the coalition structure is unchanged compared to the case with a centralised authority. What differs is, however, how to reach a certain level of control effort when the authorities play a Nash game against each other.

The three authorities each maximise their net present values of harvest minus the costs of control according to the following formula:

$$\underset{Z_{DA}}{Max}\,\pi = \sum_{i=1}^{3}\left(\frac{1}{3}pq_i e_i\left(K - \frac{K\sum_{j=1}^{3} q_j e_j}{r}\right) - ce_i\right) - \frac{\gamma}{1-Z_{DA}}. \tag{12}$$

Since the optimal effort employed in the fishery depends on the optimal control effort set by other authorities there is an externality in the control effort. The externality in control effort arises from the fact that, if one country increases its control effort, then it affects the optimal fishing effort and hereby influences the control effort level chosen by another country.

Assuming the authorities play Nash against each other we can solve for optimal Z in each country (the results are summarized in the appendix, table A.IV). We observe that the level of control effort for the centralised authorities resembles the level of optimal control effort in the case of centralised authorities (see table A.IV). The only difference is the negative factor in front of the control costs, γ, in the denominator. In the centralised case the factor is -8, in the decentralised case the factor is three times smaller, namely -24. A main explanation for this difference can be found in the fact that the decentralised authorities face three times the fixed costs faced by the centralised authorities. We can conclude that when fishermen are playing a Nash game against each other and other things are equal, then the single authority in the decentralised scenario has an optimal level of control effort that is lower than the optimal level of control for the centralised authority. The level of control effort is, however, identical for the centralised authorities and the single decentralised authority if the costs of control, γ, are zero. An increase in the costs of control implies that the gap between the control efforts in the two scenarios increases. Since we have assumed identical countries, the average control effort in the decentralised scenario is equivalent to the control effort set by a single authority in the decentralised case. Therefore, the fishermen face a lower level of control effort when the authorities are decentralised compared to a centralised authority. The levels of control efforts are, however, equivalent if there are no control costs. The reason the control efforts are lower in the decentralised scenario is that the control costs are considered to be an externality with high costs of control it is optimal for the single decentralised authority to choose a lower level of control effort since it plays Nash against other authorities. The authorities are free riding on each other. Holden (1994) and Jensen (2001) present some empirical studies of the EU emphasising that the control effort is lower when authorities are decentralised then when authorities are centralised. These studies and our analytical model suggest that, if society wants compliance, it might be easier to reach if authorities are centralised, given that this is a stable solution.

4.2. Two-Player Coalition among Fishermen

The optimal effort level employed in the fishery and the optimal control effort is determined when the fishermen form a two-player coalition playing Nash against the singleton. The optimal effort for group i is summarised in the appendix, table A.III. The optimal control effort in each country is found in the appendix, table A.IV.

When comparing the level of optimal control effort in the decentralised and the centralised scenarios (see table A.IV) the conclusion is exactly the same as in the case where fishermen play a Nash game. Namely, that the control effort only differs by the factor in front of the control effort costs. Hence, also in the two-player coalition among fishermen the level of control effort is also higher when authorities are centralised then when authorities are decentralised.

4.3. Grand Coalition among Fishermen

The optimal effort level for the grand coalition among fishermen and the corresponding level of optimal control are determined and the results are summarised in the appendix, tables A.III and A.IV. The optimal control effort is, again, a corner solution with Z=0. We can conclude that even if enforcement is decentralised, a grand coalition among fishermen is self-enforcing.

5. A Two-Player Coalition Authority

Authorities forming a two-player coalition playing Nash against a singleton complicates the analytics since the symmetry of the authorities disappears. The two-player coalition among authorities contains twice as many of fishermen as the singleton, but since the case is non-linear in Z, we cannot say anything about the relation between the optimal control effort for the coalition and the singleton.

The fishermen forming coalitions are, however, not very different from the other scenarios. The fishermen still view the control effort as a single level and therefore the optimal effort employed for harvest in the three scenarios resembles the scenarios where the authorities are centralised and decentralised.

We are not able to solve these three scenarios analytically, but can conclude that the asymmetry implies results that are not directly comparable to the other six scenarios. Numerical simulations do, however, suggest that there is only a corner solution, where Z=0 for both rivals, satisfying the constraints when fishermen form a grand coalition. This seems likely since it underlines the results achieved when authorities are centralised or decentralised.

To sum up; so far we have shown that the effort employed in the fishery is dependent on the average control effort level, but is otherwise independent of the coalition formation among authorities. Furthermore, we have shown that the control effort level is higher when the authorities are decentralised compared to the control effort level set by centralised authorities, and this holds no matter which coalition formation the fishermen choose.

6. Stability of Coalition Structures among Fishermen

This section analyses the stability of the different coalition formations among fishermen. For a coalition to be stable there must be no group of fishermen with incentives to leave the coalition. To determine the benefits for the group of fishermen it is assumed that fishermen are rational and apply the optimal effort level given the control effort and the coalition structure. Since we assume the TAC is set at a sufficiently low level, the benefits for the single group or a coalition of fishermen are determined by the following formula:

$$P_i(\Psi) = (1-\Psi)pq_ie_ix - ce_i - \Psi\Omega \,. \tag{13}$$

The total benefits for the groups of fishermen are derived when fishermen are singletons, form a two-player coalition and form a grand coalition. The sum of benefits from free riding is also derived to determine when the grand coalition is stable. The total benefits when the fishermen act as three singletons are as follows:

$$\begin{aligned}\sum_{i=1}^{3} P_i^N\left(Z^N\right) = &\left(\left(1-Z^N\right)pK - \frac{1}{4}\left(3-\frac{c}{q}\right)\right)\frac{r}{4}\left(3-\frac{c}{q\left(1-Z^N\right)pK}\right)\\ &- cr\left(\frac{1}{4q}+\frac{c}{4\left(1-Z^N\right)pKq^2}-\frac{c}{\left(1-Z^N\right)pK}\left(\frac{1}{q_i^2}+\frac{1}{q_j^2}+\frac{1}{q_k^2}\right)\right)-3Z^N\Omega\end{aligned} \,. \tag{14}$$

The benefits in the case of a two-player coalition $\{i,k\}$[12] are as follows:

$$\sum_{i=1}^{2} P_i^{\{i,k\}}\left(Z^{\{i,k\}}\right)=\left(1-Z^{2C}\right)p\left(q_i e_i^{\{i,k\}}K\left(1-\frac{1}{2}\left(2-\frac{b}{q_i+q_j}\right)\right)+q_j e_j^{\{i,k\}}K\left(1-\frac{1}{2}\left(2-\frac{b}{q_i+q_j}\right)\right)+\right)$$
$$-c\left(e_i^{\{i,k\}}+e_j^{\{i,k\}}\right)-2Z^{\{i,k\}}\Omega \quad . \quad (15)$$

The total benefits in the scenario of the grand coalition are as follows:

$$P^{GC}\left(Z^{GC}\right)=\left(1-Z^{GC}\right)pK\left(1-\frac{\left(1-c/\left(pKq_i\right)\right)}{2\left(1-Z^{GC}\right)}\right)\frac{r\left(1-c/\left(pKq_i\right)\right)}{2\left(1-Z^{GC}\right)}-c\frac{r\left(1-c/\left(pKq_i\right)\right)}{2\left(1-Z^{GC}\right)q_i}-Z^{GC}\Omega\,. \quad (16)$$

The sum of benefits from fishermen free riding is determined as follows:

$$\sum_{i=1}^{3} P_i^{F}\left(Z^{\{i,k\}}\right)=\left(1-Z^{\{i,k\}}\right)p\,*$$
$$\left(q_i e_i^{\{i,k\}}K\left(1-\frac{1}{3}\left(2-\frac{b}{q_i+q_j}\right)\right)+q_j e_j^{\{i,k\}}K\left(1-\frac{1}{3}\left(2-\frac{b}{q_i+q_j}\right)\right)+q_k e_k^{\{i,k\}}K\left(1-\frac{1}{3}\left(2-\frac{b}{q_i+q_k}\right)\right)\right) \quad (17)$$
$$-c\left(e_i^{\{i,k\}}+e_j^{\{i,k\}}+e_k^{\{i,k\}}\right)-3Z^{\{i,k\}}\Omega$$

The grand coalition is stable if and only if no group of fishermen has the incentive to leave the coalition. As discussed in Pintassilgo (2003), the benefits from the grand coalition must exceed the sum of benefits from free riding, otherwise the cooperative benefits cannot be distributed in a way that satisfies each country. Furthermore, the benefits from the grand coalition must exceed the sum of benefits from a non-cooperative game. The two-player coalition is stable if the sum of benefits from this scenario exceeds the benefits from a Nash game, which are equivalent to the benefits from free riding. Since we are not able to conclude further from these equations, we illustrate the stability by a simula-

12 There are two other possibilities for two-player coalitions, namely $\{i,j\}$ and $\{j,k\}$. The former implies that j will have no harvesting activity and k will act as a singleton, the latter does not change our results since k will continue to have no harvesting activity.

tion. The simulation model also discusses which solution is preferred by the authorities.

6.1. *Simulation*

A simulation model is set up to determine when the grand coalition among fishermen is stable and whether the government is able to affect the fishermen's coalition formation by its choice of control effort. It further determines which equilibrium coalition structure is preferred by the authorities. Parameter values inspired by the Baltic Sea cod fishery are applied. The costs of harvesting are determined as the average daily costs over the period 1995-1999 for a Danish vessel harvesting cod in the Baltic Sea. The price is determined as the average price per kilogram of cod over the same period. The cod stock is assumed to follow an intrinsic growth rate, r=0.4, which is an approximation for the growth rate from an OLS regression using data from 1966-1999. The OLS regression does, however, suggest an extremely high carrying capacity. This level of carrying capacity is, in our view, unrealistically high, since the exploited stock has not, even in extremely good years, been a third of the estimated carrying capacity. We therefore assume a more moderate carrying capacity level, and perform a sensitivity analysis w.r.t. the carrying capacity. The catchability coefficients are assumed to lie between 6 and 8, which are believed to be moderate values.[13] The parameter values are summarised in table IV.

Table IV. Parameter values applied in the simulation model

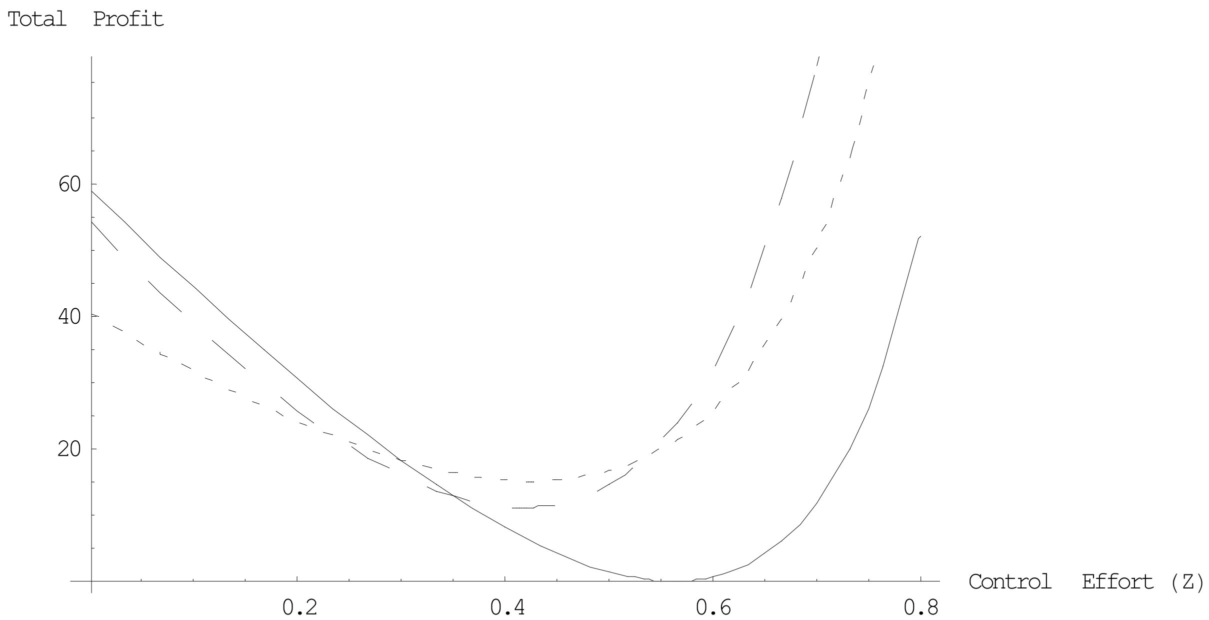
c	K	p	q_i	q_j	q_k	r
6492	230	8.07	8	6.5	6	0.4

The benefits of the different coalition structures among fishermen are determined as functions of the control effort applied by the authorities and are plotted in figure 3. The fishermen regard the level of control effort as an average

13 A sensitivity analysis w.r.t. the catchability coefficients, is possible but to save space we have omitted this.

and do not change their behaviour according to the authorities' coalition formation.

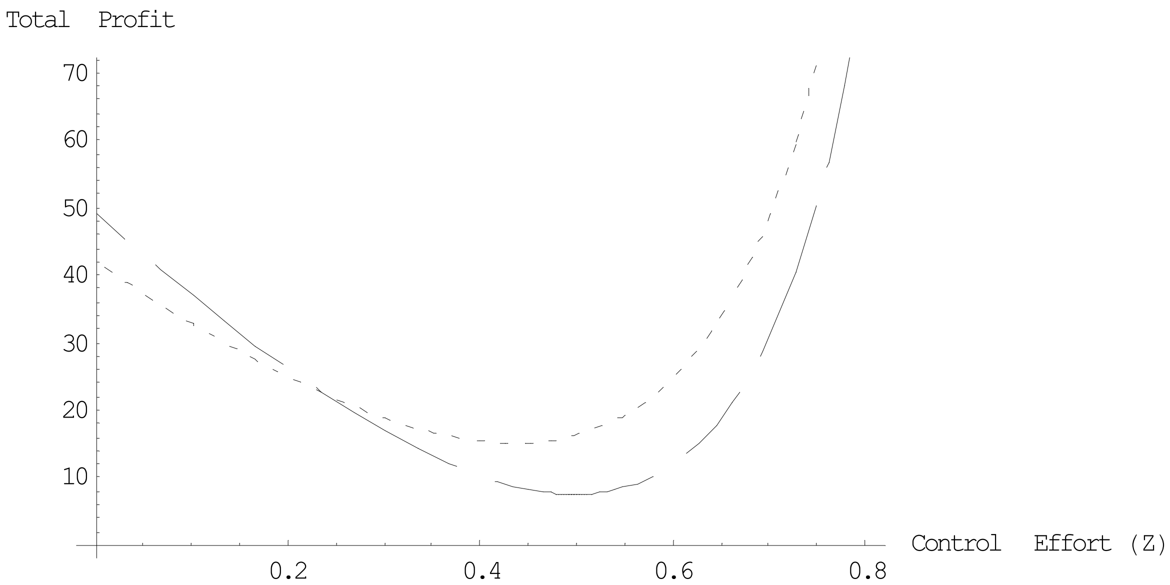
Figure 3. Benefits from the grand coalition, sum of benefits from free riding, sum of benefits from three singletons



Hence, for $0 \leq Z < 0.31$ the grand coalition is stable. For $0.31 \leq Z < 0.54$ the scenario with the three singletons yields the highest profit, and for $Z \geq 0.54$ the sum of free riding yields the highest profit. The scenario of all fishermen free riding is, however, not a possible solution. We, therefore, have to determine the profit of the three possible two-player scenarios to determine whether this profit exceeds the sum of profits for three singletons. The benefits from a two-player coalition are determined and plotted in figure 4 to determine when it is a stable scenario.[14]

14 We have only exploited the $\{i,k\}$ coalition, but since k is the least efficient technology, highest payoff results if this technology is avoided by including it in a coalition. Coalition $\{i,k\}$ and coalition $\{j,k\}$ do, however, yield the same pay-offs since both scenarios result in a Nash game amongst i and j.

Figure 4. Benefits from a two-player solution and benefits from a Nash game



From figure 4 we can conclude that the two-player coalition is stable only when the control effort level is sufficiently low ($Z \leq 0.24$). This conclusion is drawn from the fact that, here, the benefits of the two-player coalition exceed the benefits of the fishermen acting as three singletons playing a Nash game. The two-player coalition is, however, not in the core since the grand coalition is also stable for these values of Z, and the grand coalition yields higher benefits. Combining the results from figure 3 and figure 4 we can conclude that for $0 \leq Z < 0.31$, the grand coalition is stable,[15] for $0 \leq Z \leq 0.24$ the two-player coalition is stable, but since the grand coalition yields higher payoffs, we assume that the fishermen choose this coalition formation. For large Z only the scenario with three singletons is stable. Thus, when control effort is low, it is optimal to form coalitions, hence coalitions are somewhat self-enforcing. This means that a high level of control effort yields a Nash game among three singletons since the au-

15 The grand coalition among fishermen is only socially optimal for zero control effort.

thority does the job of controlling the fishermen. This result can be explained by the effect of free riding; the stock is harvested down since the punishment for exceeding the TAC is low, and a low stock implies a lower profit than can be achieved by cooperation. A higher control effort ensures a higher steady state stock level when thus making free riding more profitable and hence, more likely. This is some sort of self-regulation and might explain that cooperation is more likely when the control effort is low. Thus if society sets a low level of control effort, then one would expect more POs, which might explain why we see POs in real world settings. The uncertainty about carrying capacity emphasises that a discussion of the effects of changes in *K* is necessary. We have determined how the stability of the coalition formation among fishermen changes if *K* is decreased by 25% or increased by 25%, 75% or 500%, respectively.[16] The results are summarized in table V.

Table V. The effect of changes in K on the stability of the coalition formation among fishermen

	Low values of *Z*	**Low-Mid values of *Z***	**Mid-High values of *Z***	**High values of *Z***
25% decrease	grand coalition	3 singletons		3 singletons
Original K	*grand coalition*	*3 singletons*		*3 singletons*
25% increase	2-player coalition	grand coalition	3 singletons	3 singletons
75% increase	2-player coalition	grand coalition	3 singletons	3 singletons
500% increase	2-player coalition	2-player coalition	grand coalition → 3 singletons	3 singletons

Note: An arrow (→) indicates that as *Z* increases we are moving towards another solution.

16 We focus our discussion mainly on an increase in the carrying capacity since we are aware of having chosen *K* lower than suggested by regressions.

A decrease in the carrying capacity does not change the result. What does change our result is an increase in the carrying capacity. For low values of Z, the grand coalition is no longer stable since the sum of free riding yields a higher payoff and therefore benefits from the grand coalition cannot be distributed such that it satisfies all fishermen. The higher the carrying capacity becomes the broader becomes the area of Z where free riding gives the most beneficial outcomes. All fishermen free riding is, however, not an option; therefore the sum of benefits of three singletons and a two-player coalition playing Nash against a singleton is compared. Even with changes in the carrying capacity, the model illustrates a somewhat self-enforcing behaviour for low values of control effort. For large increases in the carrying capacity the grand coalition among fishermen is now also possible for higher levels of control effort, this is, however, not a socially optimal solution since authorities would prefer zero control effort if fishermen form a grand coalition. The general conclusion is that for low to mid values of Z, a two-player coalition or a grand coalition is preferred among fishermen, while for high values of Z, the non-cooperative behaviour with three singletons playing Nash against each other is preferred. The sensitivity analysis suggests that if the stock is low, which it is now, then it is likely that the POs will collapse, since the area with 3 singletons dominates.

Since we know from the comparative statics that there is an unambiguous negative relationship between control effort and control costs, we can conclude that inexpensive control effort leads to less cooperation, while an expensive control effort leads to more cooperation. When control costs are high and consequently control effort low, the fishermen have no choice but to organise adequate control themselves by joining together. In the opposite case the control effort of the authority ensures enough profits for the fishermen in the non-cooperative case. Hence, in our numerical example the authority can, by its desired level of control, affect the optimal coalition structure of the fishermen.

The coalition formation of the authorities indicates that the level of control effort is, on average, lower if the authorities are decentralised than if they are centralised.

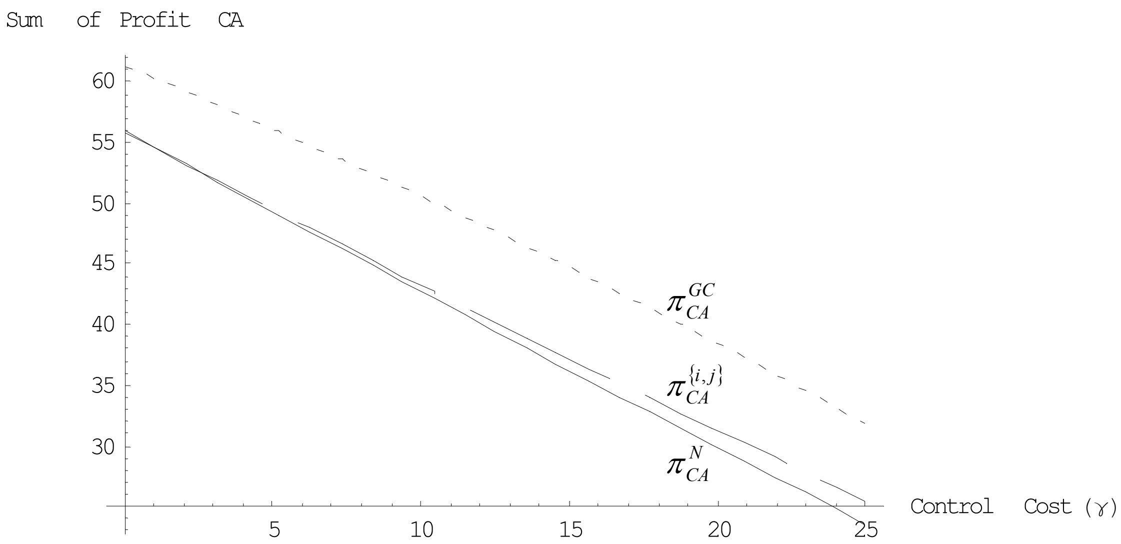
Projecting our simulation model to the Baltic Sea cod fishery, where enforcement is set at the national level, the probability of being caught is not very high, at least not in countries belonging to the EU (Holden 1994). This supports the conclusion that enforcement set at a decentralised level implies a low level of control. The simulation model then indicates that fishermen should join together and form coalitions. This happens to some extent since the fishermen in some countries join together in POs, but it is not as common as our model suggests, and there is no grand coalition. There might be several explanations for this. One is that the fishermen might not be aware of the benefits, another might be, that our model is only a stylised model, where the resource is exploited by three fishermen, in reality more fishermen are represented in the fishery, and even though they apply the same technology, they might not join together as a group, perhaps because of cultural and language barriers. If the number of fishermen increases, it most likely becomes more difficult, if not impossible, to achieve a grand coalition solution. Olson (1965) discusses this as a general problem to collective goods, and Hannesson (1997) discusses it as a problem in fishery models, where he defines the critical number of fishermen for a full co-operative solution. However, there is some cooperation among POs (at least in Denmark) and they plan to assist the Eastern European fishermen to organize POs when the EU is enlarged towards the east. This can be regarded as a step towards a coalition.

Another point of interest is to determine which solution the authorities prefer. We are not able to solve this problem analytically, however we are able to give an indication of the preferred solution by applying our numerical example. We cannot determine the case of a partly centralised authority, but we determine the sum of the benefits for the authorities and we compare these to determine which of the scenarios yields the highest sum of benefits.[17] The benefits from the three scenarios where the authorities are completely centralised are plotted in figure 5.

17 It should be noted, that this simulation only yields an indication of which solution is preferred by the authorities. We are not determining the stability of the solutions and we are not determining the benefits from the two-player coalition among authorities.

π_{CA}^{GC}

Figure 5. Total benefits for authorities in the three scenarios where the authorities are centralised



Using our numerical parameter values, figure 5 shows that when the authorities are centralised, they prefer a solution where the fishermen form a grand coalition. The figure is plotted assuming the authorities choose the corner solution with zero control effort when fishermen form a grand coalition. If there are control effort costs these, however, remain. The sum of benefits when the authorities are decentralised yields the same picture, namely that the overall solution is preferred when fishermen form a grand coalition. Comparing the two scenarios where fishermen form a grand coalition and the authorities have the choice between being centralised or decentralised, the centralised scenario yields a higher payoff since the centralised authority only has to pay the fixed cost of control once.[18] We can conclude that the authorities receive the highest sum of payoffs when they are centralised, setting a zero-level of control effort and then taking advantage of the self-enforcing mechanism where the fishermen form a grand coalition.

18 The sums of benefits for the authorities are, however, the same if the costs of control are zero.

In the Baltic Sea the authorities do not cooperate on enforcement, which, according to our simulation model is not the solution with the highest benefits. We have, however, not determined the stability of having centralised authorities and are therefore not able to comment on the actual behaviour of authorities in the Baltic Sea.

7. Discussion, limitations and Conclusion

This paper contributes to the literature by setting up a model to discuss coalition formation both on the intergovernmental level and on the fishermen level. The paper shows that the control policy set by regional, national or multinational authorities influences the cooperative behaviour of the fishermen. We show that centralised authorities tend to set a level of enforcement that is higher than the level set by the decentralised authorities, and the gap between the effort levels increases as the unit costs of control increase. The main reason for this conclusion is that the control effort becomes an externality when authorities play a Nash game against each other, and the more expensive the control becomes, the less control effort the single authority is going to apply. Therefore, if society wants a high level of control effort, this is easier to reach if the control effort is decided on a multinational level. The conclusion underlines the fact that the probability of an offence being detected in the EU, where enforcement is decentralised, is very low (Holden 1994). The paper also shows that the grand coalition among fishermen is stable and socially optimal if and only if the authorities set a zero control effort; this is true no matter whether the authorities are centralised or decentralised. The intuition is, that without any control effort, the grand coalition among fishermen faces the same objective function as the society, and the solution becomes socially optimal.

The paper sets up a simulation model applying parameter values inspired by the Baltic Sea cod fishery. The simulation model shows that for low values of control effort the fishermen will organise adequate control themselves by joining together. For high values of control effort fishermen will act as singletons. The intuition is that the gain from cooperation is much larger if there is no control.

There is, however, a great uncertainty about the level of the carrying capacity. Therefore the paper includes a sensitivity analysis, to analyse the effects of changes in the carrying capacity. This analysis shows that the overall results do not change significantly. It is worth noting that the simulation model shows that without any control effort, the fishermen are not powerless, but may well organize a control of their own via formation of a grand coalition or a two-player coalition. For high values of control effort the fishermen let the government do the controlling and they play a non-cooperative Nash game against each other. What does change when the carrying capacity increases is that it becomes more attractive to form coalitions, also for mid-high values of the level of control effort. For example a 500% increase in the carrying capacity implies that for mid-high values of the level of control effort the grand coalition is stable for the fishermen. It is, however, not a socially optimal solution since we showed that only zero control effort would be socially optimal if fishermen form a grand coalition. The reason that it becomes more optimal for fishermen to join together when the carrying capacity increases is that externalities in the fishery become more significant, which implies that the benefits from coalitions increase.

The model could not determine the stability of the coalitions among authorities or take into what happens if the countries are no longer symmetric. However, it is not possible to analyse these scenarios with the set up we have chosen for the model.

The model suggests a socially optimal solution, where authorities may or may not form coalitions, but where no control effort should be applied and fishermen should form coalitions. We suggest an alternative way of thinking, namely, how to reach a cooperative solution among fishermen. One (perhaps naïve) way to reach such a solution might be for government to drop the existing system with TACs, quotas and enforcement and instead encourage cooperation among fishermen. The cooperation can be encouraged for instance by subsidising or informing about ownership across boarders or by encouraging existing POs to help organize POs in the eastern European countries when the EU is enlarged towards the east. A cooperative solution, where fishermen are somehow self-enforcing, is seen in real-world fisheries in England and Netherlands where TACs are distributed only to POs.

The model could further be developed to take into account what happens if the numbers of fishermen or authorities are increased. This is an important issue since, if the group becomes too large, it often implies that it becomes more difficult, if not impossible, to achieve a cooperative solution. Cooperation in the form of PO's can, however, help to keep the number of fishermen down. The number of fishermen can be increased either because fishermen are not homogeneous enough to form a PO or by potential entrants. In our model we have implicitly assumed that there are no potential entrants, perhaps due to some kind of entry deterrence. The Baltic Sea is a reasonably remote and closed area with no international waters, which could explain the entry deterrence on the authority level. In years with an exceptionally large biomass, the number of fishermen is increased, but these fishermen come from countries already represented in the sea and we therefore assume they are members of POs already represented in the area. The effect on the stability of coalitions with potential entrants is ambiguous (Lindroos 2002).

Other assumptions include; the growth of the resource stock follows a logistic growth function and the harvest function is a Gordon-Schaefer type. These functions are simple functions, but their main contribution to the model is to describe a relationship between the fish stock and the harvest. Changing these functions might change the quantitative results, but it is our belief that the qualitative results are intuitively clear and reasonably general. The model assumes that the stock is in steady state. This is not true in most real world setting, but we might be on a path to steady state, where over- and undershooting of capacity occurs, but since our model is a one shot game, we have assumed that the steady state approximately reflects the real world situation. That our game is a one shot game is an area for further research. Coalitions on the national and fishermen level modelled in a dynamic game setting would be interesting since other studies show that memory and/or threat strategies can strengthen the stability of a grand coalition (see e.g. Hannesson 1997).

Assuming identical authorities might not really relate to the Baltic Sea cod fishery, where one player (the EU) is dominant in its size and therefore may act as a Stackelberg leader, also towards other authorities. This situation is not illustrated in our model and might also be an area for further research. We do, however, argue that the symmetry among authorities in the sense of fishermen belonging to the countries is not critical to our model. Finally, it should be mentioned that assuming constant marginal costs is also a limitation of our model. This assumption implies that some technologies are not represented when fishermen form coalitions, and one might argue that redistribution among players joining the coalition would be more appropriate. This requires a redefinition of costs of harvesting, which will complicate the analysis.

The simulation model shows that with the low level of enforcement control in the Baltic Sea, the fishermen should organize adequate control themselves, by joining together. This happens to some extent, in the form of POs and cooperation between these. The real-world situation therefore already includes some cooperation. Our model suggests that further cooperation would be beneficial and should be encouraged. The reason that our model does not precisely depict the real world setting might be sought in the fact that the fishermen are too heterogeneous to form only 3 groups of fishermen.

We are aware that our model describes the possible effects of cooperation on both the intergovernmental level and the fishermen level in a simplistic fashion. The assumptions and the limitations of the model should be kept in mind when projecting the model to real world settings.

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9. Appendix

Table A.I. The optimal fishing effort when the authorities are centralised

Coalition among fishermen	**Optimal fishing effort**
3 singletons	$e_i^N = \dfrac{\left(1 - \dfrac{3b}{q_i} + \dfrac{b}{q_j} + \dfrac{b}{q_k}\right) r}{4q_i}$, $\forall i, i \neq j \neq k$
Two-player coalition	$e_i^{\{i,k\}} = \dfrac{r\left(1 - \dfrac{2b}{q_i} + \dfrac{b}{q_j}\right)}{3q_i}$ for i,j, $e_k^{\{i,k\}} = 0$, $i \neq j \neq k$
Grand coalition	$e_i^{GC} = \dfrac{r\left(1 - \dfrac{b}{q_i}\right)}{2q_i}$

where $b = \dfrac{c}{(1-\Psi)pK}$.

Table A.II. The optimal control effort when the authorities are centralised

Coalition among fishermen	Optimal control effort
3 singletons	$Z_{CA}^N = 1 - \dfrac{rc^2}{8rc^2 q^2\left(\dfrac{1}{q_i^2} + \dfrac{1}{q_j^2} + \dfrac{1}{q_k^2}\right) + 2rc^2 + Kpqrc - 8Kpq^2\gamma}$
Two-player coalition	$Z_{CA}^{\{i,k\}} = 1 - \dfrac{2rc^2(q_i + q_j)}{6rc^2(q_i^2 - q_i q_j + q_j^2) + Kprc(q_i^2 q_j + q_i q_j^2) - 9Kpq_i^2 q_j^2\gamma}$
Grand coalition	$Z_{CA}^{GC} = 1 - \dfrac{rc^2}{rc^2 - 2Kpq_i^2\gamma}$

where $\dfrac{1}{q} = \dfrac{1}{q_i} + \dfrac{1}{q_j} + \dfrac{1}{q_k}$. Only a corner solution, where $Z_{CA}^{GC} = 0$, satisfies $0 \leq Z < 1$. This is seen from the fact that the second term on the RHS either becomes greater than or equal to one or is negative. This depends on the denominator. If

$rc^2 > 2KPq_i^2\gamma$, the optimal level of control effort becomes negative, or if $rc^2 < 2KPq_i^2\gamma$, the control effort asymptotically approaches 1 from above.

Table A.III. The optimal fishing effort when the authorities are decentralised

Coalition among fishermen	Optimal fishing effort
3 singletons	$e_i^N = \dfrac{r\left(1-\dfrac{3b_{DA}}{q_i}+\dfrac{b_{DA}}{q_j}+\dfrac{b_{DA}}{q_k}\right)}{4q_i} \quad \forall i,\ i \neq j \neq k$
Two-player coalition	$e_i^{\{i,k\}} = \dfrac{r\left(1-\dfrac{2b_{DA}}{q_i}+\dfrac{b_{DA}}{q_j}\right)}{3q_i}$ for i,j, $e_k^{\{i,k\}} = 0$, $i \neq j \neq k$
Grand coalition	$e_i^{GC} = \dfrac{r\left(1-\dfrac{b_{DA}}{q_i}\right)}{2q_i}$

where $b_{DA} = \dfrac{3c}{(3-\Psi_1-\Psi_2-\Psi_3)pK}$

Table A.IV. The optimal control effort when the authorities are decentralised

Coalition among fishermen	Optimal control effort
3 singletons	$Z_{DA}^N = 1-\dfrac{rc^2}{8rc^2q^2\left(\dfrac{1}{q_i^2}+\dfrac{1}{q_j^2}+\dfrac{1}{q_k^2}\right)+2rc^2+Kpqcr-24Kpq^2\gamma}$
Two-player coalition	$Z_{DA}^{\{i,k\}} = 1-\dfrac{2rc^2(q_i+q_j)^2}{6rc^2(q_i^2-q_iq_j+q_j^2)+crKpq_iq_j(q_i+q_j)-27Kpq_i^2q_j^2\gamma}$
Grand coalition	$Z_{DA}^{GC} = 1-\dfrac{rc^2}{rc^2-6Kpq_i^2\gamma}$

where $\dfrac{1}{q} = \dfrac{1}{q_i}+\dfrac{1}{q_j}+\dfrac{1}{q_k}$. Only $Z_{DA}^{GC} = 0$, satisfies $0 \leq Z < 1$.

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