STABILITY AND SUCCESS OF REGIONAL FISHERIES MANAGEMENT ORGANIZATIONS

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Abstract

According to international law, straddling fish stocks should preferably be managed cooperatively through regional fisheries management organizations (RFMOs). A major problem faced by these organizations is the unregulated fishing undertaken in the high seas by non-members. This paper analyzes the problem of unregulated fishing as a game in partition function form based on the classical Gordon-Schaefer bioeconomic model. It analyzes the prospects of mitigating the overfishing problem through RFMOs in which all or some fishing states participate. The success of RFMOs is related to the economic and biological parameters of the bioeconomic model. Particular emphasis is placed on the level and asymmetry of harvesting costs.

JEL References: C72; Q22.

Keywords: straddling fish stock, regional fishery management organizations, unregulated fishing, bioeconomic model, coalition formation model, free-riding.

1. Introduction

The 1982 UN Convention on the Law of the Sea (UN, 1982) brought forth the regime of 200 nautical miles coastal state Exclusive Economic Zones (EEZs), which revolutionized the management of world capture fisheries. However, an important aspect was not addressed: the management of fisheries resources at the boarder of EEZ and the adjacent high seas where the resources are subject to exploitation by so called distant water fishing states. These fishery resources are commonly referred to as straddling fish stocks.

Straddling fish stocks, which account for about 20 per cent of the worlds capture fishery harvests (Munro, Van Houtte and Willmann, 2004), were subject to heavy overexploitation in the decade following the advent of the 1982 UN Convention. This led to further action by the UN in the first half of the 1990s, resulting in a supplement to the 1982 UN Convention in the form of an international agreement, popularly known as the 1995 UN Fish Stocks Agreement (UN, 1995). Under this agreement, straddling fish stocks are to be managed on a region by region basis by Regional Fisheries Management Organizations (RFMOs), having as members all coastal states and distant water fishing states claiming to have a “real interest” in the relevant fish stocks (UN, 1995, Article 8). Examples of such RFMOs, with the strong support of the Food and Agriculture Organization of the UN (FAO), are for instance the Northwest Atlantic Fisheries Organization (NAFO), and the Northeast Fisheries Commission (NEAFC). Whereas vigorous actions can be taken against RFMO members if they do not abide by the rules, no such actions can be taken against non-RFMO members. Since membership in RFMOs is voluntary, straddling fish stocks constitute an open access resource. It is therefore important to analyze participation in and stability of RFMOs and their prospects to mitigate overfishing.

The stability of international fisheries agreements on straddling and highly migratory fish stocks has been analyzed using game theory. For instance, Kaitala and Munro (1997), based on the classical dynamic fisheries bioeconomic model (Clark and Munro, 1975), study the threat to cooperative agreements posed by prospective new members by comparing the charter members' payoffs under a cooperative solution and under complete non-cooperation. Hannesson (1997) studies the impact of the number of agents on the prospects of achieving full cooperation through threat of punishments within a repeated game. Empirical studies on the prospects of cooperative agreements have been conducted for instance by (e.g. Kennedy, 2003, and Lindroos, 2004). However, only recently, Pintassilgo (2003) introduced the partition function approach to the study of coalition formation in fisheries which is better suited to study the formation and stability of subcoalitions. This approach has been further pursued in Pintassilgo and Lindroos (forthcoming), characterizing coalition formation in fisheries based on classical Gordon-Schaefer bioeconomic model, though they assume symmetric players.

In this paper, we extend the analysis of Pintassilgo and Lindroos (forthcoming). Different from this paper but also those which study coalition formation in the context of other economic problems based on the partition function approach (see, e.g. Bloch 2003 and Yi 2003 for an overview), we relax the assumption of symmetric players. Our main contribution is twofold. Firstly, we provides a comprehensive analysis of the economic and biological fundamentals that influence the success of coalition formation in straddling stock fisheries, e.g. the price for fish, the level and asymmetry of production costs, the number of players, the intrinsic growth rate of the fisheries and the carrying capacity of the ecosystem. Secondly, we generalize and qualify results obtained for symmetric players. By adopting a probabilistic approach over a larger parameter range, our approach is more general than previous studies which for instance assumed only two types of players (Hannesson, 1997, and Lindroos, forthcoming) or considered in a particular parameter set in a deterministic empirical setting (Kennedy, 2003, and Pintassilgo, 2003).

The paper proceeds as follows. The model, comprising the bioeconomic model and the coalition formation model, is presented in section 2. Then the two-stage fishery coalition game is analyzed according to the sequence of backward induction. In section 3, assuming some coalition has formed in stage 1, we analyze how economic and biological fundamentals influence the fish stock and the payoffs of fishing states and hence their incentive to participate in RFMOs. Then in section 4, we analyze the stability of coalitions in the first stage and determine the overall success of coalition formation. Finally, section 5 summarizes our main results, discusses its policy implications and points to future research issues.

2. The Model

2.1 The Bioeconomic Model

The bioeconomic model uses the classical Gordon-Schaefer model (Gordon, 1954). Due to its simplicity, this model has been frequently used for game-theoretic analyses of internationally shared fish resources (e.g. Ruseski, 1998, and Lindroos, forthcoming). It captures the relation between the fish stock, X, the harvest of an individual player *i*, H_i, with the set of players $N=\{1,...,n\}$ representing *n* different fishing states, and the fishing effort exerted by player *i*, E_i, by the following three equations:

$$\frac{dX}{dt}=G(X)-\sum_{i=1}^{n}H_i \qquad (1)$$

$$G(X)=rX\left(1-\frac{X}{k}\right) \qquad (2)$$

$$H_i=qE_iX \qquad (3)$$

where t denotes time, r the intrinsic growth rate of fish, k the carrying capacity of the ecosystem; and q the catchability coefficient which constitute the parameters of the model.

According to (1), the variation of the stock in time is the difference between the stock growth and total harvest. Stock growth is described by the logistic function (2). This inverted U-shaped function implies that stock growth increases up to a maximum value, often referred to as the maximum sustainable yield, which occurs at the stock level $k/2$. Beyond this level, growth decreases until the stock reaches the carrying capacity of the ecosystem k.

This captures the phenomenon that for low levels of fish stock growth is high, but once the fish population starts to compete for food growth decreases until a level is reached at which the population stabilizes at the carrying capacity of the ecosystem. The harvest function (3) indicates that the harvest of each player increases with the catachability coefficient and stock level (both facilitating harvesting) as well as the fishing effort. The fishing effort can been seen as a physical measure of the inputs devoted to harvesting, such as days spend at sea.

The steady stock level is given by $dX/dt = 0$ in (1). Upon substitution of (2) and (3), the steady state or equilibrium stock level can be expressed as function of the total fishing effort that is constant through time:

$$X^* = \frac{k}{r}\left(r - q\sum_{i=1}^{n} E_i \right) . \tag{4}$$

This indicates the negative relation between the equilibrium stock and players' total fishing effort, $\sum_{i=1}^{n} E_i$. It also illustrates the common pool problem of fisheries: the stock decreases with the individual fishing effort of each state, E_i. This externality problem is also evident by considering the economic rent or payoff of fishing state *i*, Π_i, which is defined as:

$$\Pi_i = pH_i - c_i E_i \tag{5}$$

where p is the price for fish; and c_i the individual cost per unit of effort of player i.

By allowing for different cost per unit of fishing effort, we relax the assumption of symmetric players. The subsequent analysis will stress that this extension leads to fundamental different results.

Substituting (3) into (5), $\Pi_i = pqE_iX^* - c_iE_i$, illustrates that the revenue of player *i*, $R_i = pqE_iX^*$, is a function of the stock, which, as already pointed out, is a negative function of the fishing effort of all states according to (4) and hence $\partial\Pi_i / \partial\sum_{j\neq i} E_j < 0$. Like revenues, total cost of player *i*, $TC_i = c_iE_i$, is expressed in monetary terms, which eases subsequent derivations. However, it should be noted that by expressing (5) in terms of H_i instead of E_i, $\Pi_i = pH_i - c_iH_i / qX^*$, it can be shown that total cost is a strictly convex function of harvest H_i. In this case, the externality problem shows up in the cost function where the cost of player *i* is an increasing function of the harvest of the other players as this reduces the stock X^* and hence $\partial\Pi_i / \partial\sum_{j\neq i} H_j < 0$.

2.2 The Coalition Formation Model

We assume that a RFMO is established with the purpose of managing and conserving a given straddling fish stock. Participation in a RFMO is voluntary and open to all nations. This reflects the legal framework set by the UN Fish Stocks Agreement. According to Article 8(3), any state with a real interest in the fisheries should not be precluded from becoming a member of a RFMO (UN 1995). Those states which decide against membership in a RFMO are allowed to harvest the stock in their EEZs or in the high seas by international law.

In order to capture these features in a simple way, we chose from the set of coalition formation games the cartel formation game due to d'Aspremont et al. (1983), also known in the literature as open membership single coalition game (Finus and Rundshagen 2003 and Yi 2003) which has been frequently applied in the literature to analyze international environmental agreements (e.g. Finus 2003 for an overview). In the first stage, players decide on their participation. Those players that join the RFMO form the coalition and are called members, those that do not join are called non-members and act as singletons. Note that the decisions in the first stage lead to a coalition structure $K=\left\{S,1_{(n-m)}\right\}$ where S is the non-empty set of m coalition members, $m\in\left\{1,...,n\right\}$, and $1_{(n-m)}$ is the vector of $n-m$ singletons. Given the simple structure of the first stage, a coalition structure is fully characterized by coalition S. In the second stage, players chose their economic strategies which are fishing efforts in our bioeconomic model. In each stage, strategies (participation and fishing effort) form a Nash equilibrium. The game is solved backward for the subgame-perfect equilibrium.

In the following, we analyze the fishing game according to the sequence of backward induction. We start by analyzing the second stage, assuming that some coalition has formed. Subsequently, we move to the first stage and analyze the stability of the RFMO.

3. The Second Stage of Coalition Formation

3.1 Preliminaries

In the second stage, given a coalition structure $K=\left\{S,1_{(n-m)}\right\}$ formed in the first stage, the vector of equilibrium fishing efforts, E^*, must satisfy the following inequality system:[1]

$$\begin{aligned}
&\sum\nolimits_{i\in S}\Pi_i(E^{S*}(S),E^{-S*}(S))\geq\sum\nolimits_{i\in S}\Pi_i(E^{S}(S),E^{-S*}(S)) && \forall E^S, i\in S \quad and\\
&\Pi_j(E^{S*}(S),E_j^*(S),E^{-j*}(S))\geq\Pi_j(E^{S*}(S),E_j(S),E^{-j*}(S)) && \forall E_j, j\notin S
\end{aligned}\tag{6}$$

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[1] We use superscripts for vectors and subscripts for individual strategies.

where E^S is the fishing effort vector of coalition S, E^{-S} the effort vector of all states not belonging to S, E_j the fishing effort of non-member $j \notin S$, and E^{-j} the fishing vector of all other non-members of *S*. Asterisks denote equilibrium strategies. From (6) it is evident that equilibrium fishing efforts depend on coalition S (and on the parameters of the model which have been omitted for convenience). Since for every coalition S there is a unique fishing vector $E^*(S)$ as we show below, we can simplify notation by denoting the payoff or worth of coalition S by $\Pi_S(S) = \sum_{i \in S} \Pi_i(S)$ and the payoff or worth of a non-member by $\Pi_{j \notin S}(S)$. Thus, we define a partition function Π such that it assigns a single real number $\Pi_S(S)$ to coalition S and real numbers $\Pi_j(S)$ to every singleton $j \notin S$: $\Pi : S \mapsto \Pi(S) = (\Pi_S(S), \Pi_j(S))$.

Note that (6) implies that $E^*(S)$ is derived as a Nash equilibrium between coalition *S* (which de facto acts as a meta player; Haeringer 2004) and the *n-m* singletons to which we refer as coalitional Nash equilibrium. This is to distinguish it from the Nash equilibrium which is identical to the coalitional Nash equilibrium fishing vector if coalition *S* comprises only a single player, $S = \{i\}$. If coalition S comprises all players, $S = N$, the coalitional Nash equilibrium fishing vector corresponds to the global optimum. In the following, however, we will refer to coalitional Nash equilibrium fishing efforts, stock and payoffs simply as equilibrium fishing efforts, stock and payoffs, respectively, when no misunderstanding is possible.

In order to determine the coalitional Nash equilibrium for payoff function (5), we solve the following maximization problems:

$$\underset{E^S}{Max}\, \Pi_S(S) = \sum_{i \in S} \Pi_i(S) = \sum_{i \in S} \left(pH_i - c_i E_i \right) \quad \forall\, i \in S \tag{7}$$

$$\underset{E_j}{Max}\, \Pi_{j \notin S}\left(S\right) = pH_j - c_j E_j \quad \forall\ j \notin S\ . \tag{8}$$

Due to the linearity of costs in fishing efforts, only the coalition member with the lowest unit cost in coalition *S*, which we denote by c_S^{min}, will harvest. Consequently, using (3) and (4), denoting the fishing effort of the player by c_S^{min} in coalition *S* by E_S, we can write:

$$\underset{E_S}{Max}\, \Pi_S(S) = \sum\nolimits_{i \in S} \Pi_i(S) = pqE_S \frac{k}{r}\left(r - q\left(E_S + \sum\nolimits_{j \notin S} E_j\right)\right) - c_S^{min} E_S \tag{7'}$$

$$\underset{E_j}{Max}\, \Pi_{j \notin S}\left(S\right) = pqE_j \frac{k}{r}\left(r - q\left(E_j + E_S + \sum\nolimits_{k \neq j \notin S} E_k\right)\right) - c_j E_j\ . \tag{8'}$$

The solution of this problem leads to following reaction or best reply functions:

$$E_S = \begin{cases} \dfrac{r}{2q}\left(1 - b_S^{min}\right) - \dfrac{1}{2}\sum\limits_{j \notin S} E_j & if \quad \sum\limits_{j \notin S} E_j < \dfrac{r}{q}\left(1 - b_S^{min}\right) \\ 0 \quad if \quad \sum\limits_{j \notin S} E_j \geq \dfrac{r}{q}\left(1 - b_S^{min}\right) & \end{cases} \tag{9}$$

$$E_j = \begin{cases} \dfrac{r}{2q}\left(1 - b_j\right) - \dfrac{1}{2}\left(E_s + \sum\limits_{k \neq j \notin S} E_k\right) & if \quad E_s + \sum\limits_{k \neq j \notin S} E_k < \dfrac{r}{q}\left(1 - b_j\right) \\ 0 \quad if \quad E_s + \sum\limits_{k \neq j \notin S} E_k \geq \dfrac{r}{q}\left(1 - b_j\right) & \end{cases} \tag{10}$$

where $b_S^{min} = \dfrac{c_S^{min}}{pqk}$ and $b_j = \dfrac{c_j}{pqk}$. These parameters are usually referred to as “inverse efficiency parameters” (Mesterton-Gibbons, 1993) because they increase with the cost per unit of effort c_i and decrease with the price *p* and the catchability coefficient *q*. They always lie in the range $\left[0;1\right]$.[2]

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[2] This can easily be shown by noting that the equilibrium stock levels in the open access regime are given by $X_S^{OA} = c_S^{min} / pq$ and $X_j^{OA} = c_j / pq$. These values are obtained by substituting (3) into (5) and setting profits to zero, as the open access regime is characterized by the dissipation of the

From (9) and (10) it is evident that best reply functions are downward sloping with a slope less than 1 in absolute terms. Hence, fishing efforts are strategic substitutes in this fishing game. Considering only interior solutions and solving (9) and (10) simultaneously, the unique equilibrium fishing efforts (because best reply functions are contractions are given by:

$$E_S^*(S) = \frac{(n-m+1)r}{(n-m+2)q}\left(1-b_S^{min}\right) - \frac{r}{(n-m+2)q}\sum_{j\notin S}\left(1-b_j\right) \tag{11}$$

$$E_j^*(S) = \frac{(n-m+1)r}{(n-m+2)q}\left(1-b_j\right) - \frac{r}{(n-m+2)q}\left[\left(1-b_S^{min}\right) + \sum_{k\neq j\notin S}\left(1-b_k\right)\right] \tag{12}$$

where *n* is the total number of players and *m* the number of RFMO members. In order to ensure strictly positive fishing efforts according to (11) and (12) all b_i´s must be strictly smaller than 1. Moreover, since $E_S^*(S)$ and $E_{j\notin S}^*(S)$ increase with the number of coalition members m, and for $m=1$ $E_S^*(\{k\}) = E_j^*(\{k\})$ and $E_j^*(\{k\}) > E_l^*(\{k\})$ if $b_j < b_l$ (see Appendix), a sufficient condition for strictly positive fishing efforts for all possible coalition structures is derived from (12) by setting $m=1$.

$$b_l + \sum_{k\neq l}\left(b_l - b_k\right) < 1,\ b_l = max\left\{b_1,...,b_n\right\} \tag{13}$$

This ensures that even the most inefficient player choses a strictly positive fishing effort when all players act as singletons. Considering that the b_i´s only differ because of different cost parameters, this essentially means that cost parameters cannot be too dispersed in an interior solution. That is, in our model the *n* players are active fishing states; other states simply do no fish as their costs are to high.

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economic rent. Thus, the inverse efficiency parameters can be written as $b_S^{min} = X_S^{OA}/k$ and $b_j = X_j^{OA}/k$. These ratios always lie in the range $\left[0;1\right]$ as the equilibrium stock levels in open access lie between the minimum of zero (depletion of the stock) and a maximum of the carrying capacity of the ecosystem (no harvest), k.

Using (11) and (12), the total fishing effort (14) is given by

$$E^*(S)=E_S^*(S)+\sum_{j\notin S}E_j^*(S)=\frac{r}{(n-m+2)q}\left[\left(1-b_S^{min}\right)+\sum_{j\notin S}\left(1-b_j\right)\right] \tag{14}$$

Upon substitution of (14) into (4) the steady-state fishing stock level is obtained.

$$X^*(S)=k\left[1-\frac{1}{n-m+2}\left(\left(1-b_S^{min}\right)+\sum_{j\notin S}\left(1-b_j\right)\right)\right] \tag{15}$$

Finally, equilibrium payoffs of coalition S and singleton j are given by:

$$\Pi_S^*(S)=\frac{rpk}{(n-m+2)^2}\left(1-(n-m+1)b_S^{min}+\sum_{j\notin S}b_j\right)^2 \tag{16}$$

$$\Pi_{j\notin S}^*(S)=\frac{rpk}{(n-m+2)^2}\left(1-(n-m+1)b_j+b_S^{min}+\sum_{k\neq j\notin S}b_k\right)^2 . \tag{17}$$

We now turn to analyze some economic fundamentals of our model.

3.2 Economic Fundamentals and Impacts of Different Coalition Structures

In this section, we first look at some economic fundamentals in order to deepen the understanding of the bioeconomic model. Then we look at the effects on different players due to a change in the coalition structure. This will help to explain some of the results in section 4 related to the incentives to form coalitions and their stability. The analysis presumes that some coalition has formed out of the 2^n possible coalitions in the first stage.

We first analyze how exogenous changes of the parameters of the bioeconomic model affect the equilibrium fishing stock and the equilibrium payoffs of players. This leads to the following proposition, which – as all subsequent propositions - is proved in the Appendix.

Proposition 1: Comparative Statics of a Variation of Parameters

A change of the parameters of the bioeconomic model (c_S^{min} *=unit cost of the RFMO,* c_j *=unit cost of a non-member of the RFMO,* p *=price of fish,* q *=catchability coefficient,* k *=carrying capacity and* r *=intrinsic growth rate of the fish stock) has the implications summarized in Table 1.*

Table 1: Economic Fundamentals*

Parameter	*Stock* $X^*(S)$	*Profit of S* $\Pi_S^*(S)$		*Profit of* $j \notin S$ $\Pi_j^*(S)$		*Total Profits* $\Pi_S^*(S)+\sum_{j \notin S}\Pi_j^*(S)$	
		gen.	sym.	gen.	sym.	gen.	sym.
c_S^{min}	+	–	–	+	+	und.	–
c_j	+	+	+	$k \neq j = +$, $j = -$	$k \neq j = +$, $j = -$	und.	und.
all c_i	+	–	–	–	–	–	–
p	–	und.	+	und.	+	und.	+
q	–	und.	+	und.	+	und.	+
k	+	und.	+	und.	+	und.	+
r	0	+	+	+	+	+	+

Legend: Parameters as described in section 2.1. $X^*(S)$ as defined in (15); $\Pi_S^*(S)$ and $\Pi_j^*(S)$ as defined in (16) and (17), respectively. “gen.” stands for general in the context of heterogeneous players, “sym.” stands for symmetric players, + (–) means an increase in this parameter (first column) has a positive (negative) effect on equilibrium levels in subsequent columns, and “und.” stands for undetermined effect. In the case of a change of c_S^{min} and c_j, symmetry means symmetry before the change. “all c_i” means a uniform change by $\Delta h > 0$.

The first five parameters in the first column of Table 1 may be viewed as those that determine the economic environment in which fishing states operate, and the last two as those that determine the ecological environment. There are at least three main results which we think should receive particular attention.

1) The ecological implications – measured as a change of the equilibrium stock – are clear-cut and are well in line with economic intuition. An increase in the unit cost of

either the RFMO or a non-RFMO member leads to a downward adjustment of fishing efforts of the affected party. This primary effect dominates the secondary effect of an expansion of fishing efforts by non-affected parties and hence the aggregate fishing effort decreases and the fish stock increases. A uniform increase of all unit costs c_i, a decrease of price p, and a decrease of the catchability coefficient q makes fishing more attractive and hence will decrease the equilibrium fish stock. An increase in the carrying capacity, k, and the intrinsic growth rate, r, imply on the one hand a higher "restoration capacity" of the ecological system and, on the other hand, higher incentives to expand equilibrium fishing efforts. In our setting, the first effect dominates the second effect in the case of k whereas both effects cancel out for r.

2) If the RFMO becomes more efficient via a lower unit cost, c_S^{min}, this has a positive effect on own payoffs but a negative effect on all non-RFMO members. Similarly, a decrease in the cost parameter of a non-RFMO member c_j has a positive effect on own payoffs but a negative effect on all other players, i.e. all other non-RFMO members and the RFMO. This is because fishing efforts are strategic substitutes and all players compete for the fish stock. The net effect at the aggregate cannot be generally predicted, except in the specific case that c_S^{min} changes and all players are symmetric. Predictions are also possible if all unit cost increase equally as this affects all players negatively.

3) It is striking, though not surprising, given the multiple channels through which exogenous changes of parameters affect equilibrium payoffs that no clear-cut predictions are possible for the other parameters (i.e. the effect may be positive or negative; see Appendix) if we do not impose any restriction on the type of asymmetry of players, except for the case of a change of the intrinsic growth rate r. This clearly

> stresses that conclusions derived from the assumption of symmetric players do not always carry over to the more general context of heterogeneous players. In the case of symmetric players, all effects are in line with intuition: a higher price, catchability coefficient, carrying capacity and intrinsic growth rate make fishing more attractive and hence have a positive effect on the payoffs of all players.

The next proposition looks the phenomenon known in the literature on fisheries as the "new entrant problem" (Kaitala and Munro, 1997, Pintassilgo and Costa Duarte, 2001, and McKelvy et al., 2003).

Proposition 2: New Entrant Problem

Suppose a new player i enters the fishing game such that the number of active players increases from n *to* $n' = n+1$.

a) If the new player acts as a singleton, the equilibrium stock $X^*(S)$, *the equilibrium payoff of all current non-members* $\Pi_j^*(S)$, *as well as the equilibrium coalitional payoff* $\Pi_S^*(S)$ *decreases.*

b) If the new player joins coalition S, *forming* $S' = S \cup \{i\}$, *then the equilibrium stock level will decrease,* $X_S^*(S) > X_{S'}^*(S')$, *the equilibrium coalitional payoff will increase,* $\Pi_S^*(S) < \Pi_{S'}^*(S')$, *and the equilibrium payoff of all non-members* $j \notin S, S'$ *will decrease,* $\Pi_j^*(S) > \Pi_j^*(S')$, *if the new member´s is more efficient than the most efficient player of coalition* S, $b_i < b_S^{min}$, *and leave them unaffected otherwise (*$b_i \geq b_S^{min}$*).*

The new entrant maybe seen as a previously inactive fishing state which decides now to enter the "game". This maybe be because the relative costs of fishing (i.e. opportunity costs) or absolute costs of this nation have decreased, making fishing now attractive. This potential entrant increases the competition for the fish stock.

If the new entrant does not join the RFMO and therefore behaves as a singleton, this has a negative impact on all current fishing nations, regardless whether they have joined the RFMO or not (Proposition 2a). However, if the new entrant decides to join the RFMO, effects depend on its production technology (Proposition 2b). If the new entrant is less efficient than the most efficient RFMO member, nothing changes. Of course, the fact that $\Pi_S^*(S)$ does not change simply means that current RFMO members have to share their rent with one more member which is not in their interest. However, the alternative that the new entrant remained outside their RFMO would decrease their total rent. Which of the two options is preferred by the current RFMO members is not clear, though not an issue at stake in the context of open membership.

If the new entrant is more efficient than the most efficient current RFMO member, competition for non-RFMO members increases which decreases their rents. Again the net effect for current RFMO members is not clear (but also not relevant in the context of open membership) as they have to share a higher economic rent with one more player.

We now study the impacts of an enlargement of the coalition for a given number of players n, i.e. if a non-RFMO member joins the RFMO.

Proposition 3: A Non-member joins the RFMO

Let there be n *players. Suppose a non-member* $j \notin S$ *joins the RFMO such that* $S' = S \cup \{j\}$.

a)

i) The equilibrium fishing effort of the RFMO will increase, $E_S^*(S) < E_{S'}^*(S')$*, as well as those of all non-RFMO members,* $E_{j \notin S}^*(S) < E_{j \notin S'}^*(S')$*. The total fishing effort will decrease,* $E^*(S) > E^*(S')$ *and hence the equilibrium stock will increase,* $X^*(S) < X^*(S')$.

ii) The coalitional payoff will increase, $\Pi^*_S(S) < \Pi^*_{S'}(S')$*. The payoff of all non-members* $k \notin S, S'$*,* $k \neq j$*, will also increase,* $\Pi^*_k(S) < \Pi^*_k(S')$ *(Positive Externality Property – PEP).*

b) The aggregate payoff of those players involved in the merger will increase or decrease, $\Pi^*_S(S) + \Pi^*_j(S) <> \Pi^*_{S'}(S')$ *(Superadditivity – SAD).*

c) The aggregate payoff of all players is strictly higher in the grand coalition, $S = N$*, than in any other coalition.*

The intuition of part a) i) is that if player *j* joins the RFMO, then there is one less free-rider or less competition for the fish stock. Due to negatively sloped best reply functions, the coalition as well as the non-members will adjust their fishing efforts upwards. At the aggregate level, this secondary effect is dominated by the primary effect that the new number will no longer exert non-cooperative fishing efforts. Consequently, starting from the singleton coalition structure (corresponding to the Nash equilibrium fishing efforts) and considering a sequence of mergers, the total equilibrium (being precise: the total coalitional Nash equilibrium) fishing effort will decrease and the equilibrium stock level will increase with the degree of cooperation. Hence, if the grand coalition is formed (corresponding to the global optimum), equilibrium total fishing effort is at its minimum level and the equilibrium stock at its maximum level. Thus, cooperation helps to internalize externalities.

Building on this intuition, part a) ii) suggests that a higher degree of cooperation has a positive effect on the coalitional payoff but also on non-members. The latter effect is known in the literature on coalition formation as the Positive Externality Property (PEP) (Bloch 2003 and Yi 2003). This effect is the most important driving force why the formation of large stable coalitions proves difficult in the context of a common pool resource as long as nobody can be excluded. This problem is virulent despite mergers increase the coalitional payoff, but

– even more important – despite the players involved in the mergers may gain at the aggregate, a condition which has been called superadditivity (SAD), and referred to in part b).

On the one hand, even if SAD held, as long as the PEP-effect is stronger, which tends to occur for large coalitions, free-riding may still be attractive. In other words, even if all current and new members are better off from an expansion of cooperation, it may even be more attractive to take a free-ride. This means that stability may be violated for large coalitions due to strong free-rider incentives.

On the other hand, the free-rider problem is aggravated when SAD fails. This failure is not uncommon in coalition formation games and applies to many economic problems (see e.g. Eyckmans and Finus 2004 for an overview). Due to negatively sloped reaction functions the good intentions of the coalition members are obstructed by non-members.

Finally, not surprisingly, part c) states that the aggregate economic rent in the grand coalition, corresponding to the global optimum, is strictly higher than in any other coalition. This simply follows from the fact that by assumption the total rent over all players is maximized in the grand coalition (which proves the term “higher”) and the equilibrium effort vector $E^*(N)$ differs in at least one element from any other coalition $S \neq N$ (which proves the term “strictly”) as can be seen from equations (11) and (12).

4. First Stage of Coalition Formation: Stability and Overall Success

4.1 Preliminaries

Section 3 clarified how the partition function assigns to every coalition S a vector of payoffs or worth, $\Pi : S \mapsto \Pi(S) = (\Pi_S(S), \Pi_j(S))$ in the second stage of the coalition formation process and how these values depend on the model parameters, on a new entrant or a non-

RFMO member joining the RFMO. Now we move on to the first stage, analyzing which coalitions are stable.

In the first stage, participation strategies also form a Nash equilibrium. This is characterized by the absence of incentives to change the participation decision, both by RFMO members and non-members. In order to focus on the driving forces of the stability of RFMOs, we use the concept of internal and external stability as suggested by d'Aspremont et al. (1983):

Internal Stability: $V_i(S) \geq V_i(S \setminus \{i\}) \quad \forall\, i \in S$ (18)

External Stability: $V_j(S) \geq V_j(S \cup \{j\}) \quad \forall\, j \notin S$ (19)

where we assume that there is some valuation function (which has also been called per-membership partition function; e.g. Bloch 2003) which maps the aggregate payoff or worth into valuations such that $\Pi_S(S) + \sum_{i \notin S} \Pi_{i \notin S}(S) = \sum_{i \in N} V_i(S)$. This means that valuations add up to the total worth of the game and there are no resources outside the game.

The analysis based on individual payoffs, implied by the valuation function, requires some assumption about the sharing rule. Strictly speaking, though often neglected, this would even be true if we assumed symmetric players and a symmetric distribution among coalition members, though this may seem an "obvious assumption". In the following, we show that for the present game the analysis can be based on very general assumptions.

Firstly, let us concentrate on internal stability as this seems to be the most prompting free-rider problem. Assume that the coalitional payoff is only shared among its members, i.e. $\Pi_S(S) = \sum_{i \in S} V_i(S)$, and $\Pi_{i \notin S}(S) = V_{i \notin S}(S)$. Using condition (18) and summing over all members of coalition S we obtain:

$$\Pi_S(S) \geq \sum_{i \in S} \Pi_i(S \setminus \{i\}) \ . \tag{20}$$

Condition (20) has been termed potentially internally stability (PIS) by Eyckmans and Finus (2004). As already Pintassilgo (2003) noted if PIS holds, then there exists some sharing rule which makes coalition S internally stable. This suggests that internal stability can be analyzed without prior assumptions about the sharing scheme. Implicitly, however, it means that we trust the members of the coalition that whenever their coalition is PIS they ensure that their coalition is internally stable. This is surely the most favorable assumption in terms of internal stability but certainly a sensible benchmark. This is particularly true as it allows us to conclude that whenever PIS fails, internal stability fails regardless of the transfer scheme.

Secondly, consider external stability in (19). Clearly, in an open membership it does to make sense to look for a similar condition which could be called potential external stability. However, suppose to ensure internal stability whenever a coalition is PIS, we invoke the almost ideal sharing scheme proposed by Eyckmans and Finus (2004) which gives every player in coalition S its free-rider payoff plus a share $\lambda_i(S)$ of the surplus of the coalitional payoff over the sum of free-rider payoffs $\Delta(S)$:

$$V_i(S) = \Pi_i\left(S\setminus\{i\}\right) + \lambda_i(S)\Delta(S);\ \Delta(S) = \Pi\left(S\right) - \sum_{i\in S}\Pi_i\left(S\setminus\{i\}\right),$$

$$\sum\nolimits_{i\in S}\lambda_i(S) = 1,\ \lambda_i(S) > 0, \forall\, i \in S\ . \tag{21}$$

It is easy to see that whenever condition (20) holds, i.e. coalition S is PIS, then this transfer scheme makes S internally stable, irrespective of weights λ_i. If, on the contrary, coalition S is not PIS (hence $\Delta(S) < 0$), there are no weights that make S internally stable. This allows to establish a direct link between internal and external stability: if coalition S is not PIS, then all coalitions $S\setminus\{i\}$ for all $i \in S$ are externally stable, irrespective of weights. Consequently, both the sets of internally and externally stable coalitions (and hence the set of stable coalitions) are independent of weights. Moreover, it means that we can infer external stability from PIS.

Thirdly, as Carraro et al. (2006) prove, given transfer scheme (21), every stable coalition cannot be enlarged by coalition members paying transfers to non-members for joining. The intuition is simple. If coalition S is stable, every coalition $S \cup \{ j \}$, for all $j \notin S$, is not PIS which is a necessary condition for this strategy to be successful.

Summarizing, by assuming the general transfer scheme in (21) we determine the largest stable coalitions. We can neglect transfers between the RFMO and outsiders earmarked to enlarge a coalition. Checking PIS allows to infer internal and external stability and hence stability. PIS always holds for the trivial coalition structure in which all players behave as singletons $(m=1)$ as no player can deviate further. For all other cases $(m \geq 2)$, PIS-condition (20) has to be analyzed. Using equilibrium payoffs (16) and (17), this condition can be written as:

$$\left(\frac{n-m+3}{n-m+2}\right)^2 \left(1-(n-m+1)b_S^{\min} + \sum_{j \notin S} b_j\right)^2 \geq \sum_{i \in S} \left(1-(n-m+2)b_i + b_{S'}^{\min} + \sum_{k \neq i \notin S'} b_k\right)^2 \qquad (22)$$

where $S' = S \setminus \{i\}$ and $b_{S'}^{\min}$ is the lowest b in coalition S'. The interesting aspect of this condition is that, for a given number of players n, and coalition size m, potential internal stability only depends on the vector $b = (b_1, ..., b_n)$ where we may recall that $b_i = {c_i}/{pqk}$, $0 \leq b_i \leq 1$.

In the case of symmetric players, Pintassilgo and Lindroos (forthcoming) have shown that (22) can only be satisfied if and only if $n = m = 2$. Thus for any larger number of players only the singleton coalition structure is stable. Hence, it is important to test whether this also holds in the context of asymmetric players. As we do no want to impose any restriction on the asymmetry of players (except that parameter restriction (13) must hold for an interior solution), we have to resort to simulations which are described in the next section.

4.2 Simulation Method

4.2.1 Introduction

The use of simulation methods in the stability analysis of fisheries and international environmental agreements was recently introduced in the literature. Kronbak and Lindroos (2006) use a simulation method to determine the conditions under which the grand coalition among fishermen is stable and whether governments are able to affect fishermen's coalition formation by choosing the enforcement level. Dellink et al. forthcoming analyze stability of agreements reducing greenhouse gases in the context of uncertainty, using Monte Carlo simulations to estimate the probability of a given coalition being stable, which they call stability likelihood.

This paper also estimates the stability likelihood of different coalition structures. Moreover, we compute indexes that measure the success of coalition formation. For this it is assumed that the inverse efficiency parameters are uniformly distributed in the range $\left[0;1\right]$, i.e. $b_i \sim U\left(0{,}1\right)$, $\forall\, i \in \left\{1,...,n\right\}$. We opt for this distribution because of its simplicity and the fact that it is completely defined by the parameter range. An algorithm for Monte Carlo simulations is programmed using the software package Matlab, incorporating the restriction of strictly positive fishing effort (13). The simulation of the vector b was repeated whenever the restriction was violated.

4.2.2 Stability Likelihood

Let us start by describing the estimation procedure for internal stability. According to (22), internal stability of a m-size coalition, for a given number of players *n*, is completely determined by the vector b. Simulating a large number of vectors b allows to estimate the probability of a random m-size coalition being internally stable, i.e. its internal stability likelihood (ISL), hereafter denoted by θ. This parameter as well as the other following probabilities are estimated as a "sampling proportion". In the case of ISL, this implies that $\hat{\theta} = {}^{Y}\!/_{nsim}$ where $nsim$ denotes the number of simulations and Y the number of times a random m-size coalition is internally stable in those simulations. This is an unbiased estimator and also the maximum likelihood estimator for θ.

A total of *50,000* simulations are undertaken. As the standard deviation of the estimator is given by $\sigma\left(\hat{\theta}\right) = \sqrt{\frac{\theta(1-\theta)}{nsim}}$, the maximum value is only $\sigma\left(\hat{\theta}\right) = 0.002$, which occurs for $\theta = 0.5$. Furthermore, the central limit theorem applies to $\hat{\theta}$.[3] According to this theorem, $\hat{\theta}$ follows approximately a normal distribution. Therefore, the maximum margin of error for confidence intervals can be computed. For instance for a 95% confidence interval the maximum margin of error is approximately only 0.004. Hence, the high number of simulations guarantees a very low margin of error for the estimated probabilities.

The probability of a random m-size coalition being externally stable, or its external stability likelihood (ESL), was also estimated. As pointed out in section 4.1, external stability is linked to internal stability through sharing scheme (21). Hence, coalition S is externally stable if all coalitions $S \cup \{ j \}$ are not PIS, i.e., the surplus $\Delta(S \cup \{ j \})$ is non-positive. Since PIS and hence the surplus only depends on the vector b, it is possible to determine directly external stability for each vector. Following the same procedure to estimate ISL, ESL of a random m-size coalition was estimated as the proportion of externally stable coalitions over all samples.

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[3] Using the rule of thumb that $(nsim)\theta > 5$ and $(nsim)(1-\theta) > 5$ (Lind et al. 2005), it applies for all θ in the range $[0.0001; 0.9999]$.

Finally the probability of a random m-size coalition being stable, i.e. its stability likelihood (SL), is estimated as the proportion of coalitions that are simultaneously internally and externally stable in the simulations.

4.2.3 Overall Success Indexes

The algorithm is also used to compute two relative welfare measures which only depend on the vector b. The first is called the Social Gain Index (SGI) and is a measure of the relative gain from cooperation that could be obtained if the grand coalition formed and is defined as follows:

$$SGI(b,n) = \frac{\Pi(N) - \sum_{i=1}^{n} \Pi_i\left(1_{(n)}\right)}{\Pi(N)}$$

where $\Pi(N)$ represents the aggregate payoff of the grand coalition and $\sum_{i=1}^{n} \Pi_i\left(1_{(n)}\right)$ the aggregate payoff when all players are singletons.

As the vector b is simulated over a uniform distribution, the expected value of this index, $E\left(SGI(n)\right)$, was estimated as the average over all samples:

$$\overline{SGI}(n) = \frac{\sum_{k=1}^{nsim} SGI\left(b(k),n\right)}{nsim}$$

where $nsim$ represents the number of simulations.

The second index is called the Closing the Gap Index (CGI) and is a measure of the relative gain from cooperation obtained by stable coalitions. It is a measure by how much stable equilibria succeed in closing the gap between full cooperation and no cooperation. For a given stable coalition $\left(S_j\right)$ this index is defined as:

$$CGI\left(S_j\left(b\right),n\right)=\frac{\left(\Pi_{S_j}\left(S_j\right)+\sum_{i\notin S_j}\Pi_i\left(S_j\right)\right)-\sum_{i=1}^{n}\Pi_i\left(1_{(n)}\right)}{\Pi\left(N\right)-\sum_{i=1}^{n}\Pi_i\left(1_{(n)}\right)}\ .$$

Assuming that all stable equilibria are equally likely, for a given vector b, the average CGI index can be computed as the average of the values obtained for each equilibrium:

$$CGI\left(b,n\right)=\frac{\sum_{j=1}^{nsc(b)}CGI\left(S_j\left(b\right),n\right)}{nsc(b)}$$

where $nsc\left(b\right)$ represents the number of stable coalitions for a given vector b.

Finally, the expected value of CGI, $E\left(CGI(n)\right)$, is estimated for the average b value over all generated samples:

$$\overline{CGI}\left(n\right)=\frac{\sum_{k=1}^{nsim}CGI\left(b\left(k\right),n\right)}{nsim}\ .$$

Both $\overline{SGI}\left(n\right)$ and $\overline{CGI}\left(n\right)$ are the natural estimators of the expected values of both indexes as they are unbiased and are the maximum likelihood estimators. Furthermore, the high number of simulations used (*nsim=50,000*) guarantees a low standard deviation of these estimators.

4.3 Simulation Results: Base Case

In this section, we analyze simulation results of what we call the base case. That is, each element of the vector b is uniformly distributed in the range [0;1]. Hence, all admissible values of the inverse efficiency parameters are considered. Table 2 displays the estimates of internal stability likelihood for 2 to 10 players. Recall that the singleton coalition is stable by definition. Hence, all diagonal elements in Table 2 show probability 1.

Table 2: Internal Stability Likelihood Estimates

		Number of Players *(n)*								
		2	3	4	5	6	7	8	9	10
Number of Coalition Members (*m*)	n	1	0.777	0.345	0.103	0.022	0.004	0.001	0	0
	n-1	1	0.826	0.417	0.147	0.037	0.007	0.001	0	0
	n-2	–	1	0.646	0.273	0.080	0.019	0.004	0.001	0
	n-3	–	–	1	0.538	0.195	0.054	0.011	0.002	0.001
	n-4	–	–	–	1	0.466	0.150	0.037	0.007	0.002
	n-5	–	–	–	–	1	0.409	0.120	0.026	0.005
	n-6	–	–	–	–	–	1	0.367	0.098	0.021
	n-7	–	–	–	–	–	–	1	0.333	0.081
	n-8	–	–	–	–	–	–	–	1	0.308
	n-9	–	–	–	–	–	–	–	–	1

From Table 2 two main results emerge.

Result 1

For a given number of players, n*, internal stability likelihood decreases with the number of coalition members, m.*

Result 1 compares probabilities within columns. This shows that free-rider incentives increase with the coalition size. According to Proposition 3 in section 3.3, an increase of the coalition size produces two opposite effects on the coalitional surplus which is the difference between the coalitional payoff and the sum of the free-rider payoffs. On the one hand, the coalitional payoff increases with the number of RFMO members, though the aggregate payoff of those players involved in the enlargement may not necessarily increase, i.e. superadditivity may fail to hold. On the other hand, it also increases the sum of free-rider payoffs, both because of a higher number of potential free-riders in the enlarged coalition, and an increase of the free-rider payoffs of the original members due to the positive externality effect. The results show that this second effect is stronger. Note that the case of $n = 2$ is an exception. In this particular case saying that the grand coalition is potential internal stability is equivalent to saying that the grand coalition generates a strictly higher aggregate payoff than in any other coalition (Proposition 3c).

Result 2

Internal stability likelihood of a coalition with $m = n - k$ *members,* $k = \{0,...,n-1\}$*, decreases with the number fishing states n.*

Result 2 compares probabilities within rows. From Table 2 it is evident that the probability of the grand coalition being internally stable decreases with the number of players. Already for seven players will the internal stability likelihood be zero in the example. In other words, for a not too small number of fishing nations it is very unlikely that the RFMO comprises all members (as internal stability is a necessary condition for stability). Hence, there will always be some free-riders, causing the equilibrium fish stock to be below globally optimal levels. However, not only for the grand coalition but also for smaller coalitions the likelihood of internal stability decreases with the number of fishing nations. This may be interpreted as follows: the tougher the competition for the fish stock, the more unlikely it is that a RFMO of particular size is internally stable.

Comparing rows for a given number of coalition members $m = n - k$ can be related to the “new member problem” mentioned in Proposition 2b. Accordingly, when a new entrant joins coalition S, this increases or leaves $\Pi_S(S)$ unaffected and decreases or leaves $\Pi_{j \notin S}(S)$ unaffected and hence also $\Pi_{j \notin S}(S \setminus \{i\})$. Nevertheless, theoretical predictions about a change of the coalitional surplus $\Delta(S)$ are anything else than straightforward for at least two reasons. Firstly, even if $\Pi_S(S)$ increases this coalitional payoff has to be shared with one more member. Secondly, even if $\Pi_{j \notin S}(S \setminus \{i\})$ decreases, there is now one more potential free-rider and hence the sum of free-rider payoffs may increase. According to the simulations, the sum of free-rider incentives increases more than the coalitional payoff causing internal stability likelihood of a coalition with $m = n - k$ members to decreases with n.

Turning now to external stability (see Table 3) we notice that this is basically the mirror image of internal stability. This is due the link between internal and external stability introduced by the general transfer scheme (21).

Result 3

For external stability Results 1 and 2 are reversed.

For a given number of players, external stability likelihood increases with the number of players (comparison within a column). That is, it becomes less attractive for non-RFMO members to join the RFMO. Furthermore, for a given number of singletons, k, external stability likelihood increases with the number of players, *n* (comparison within rows).

Table 3: External Stability Likelihood Estimates

		Number of Players *(n)*								
		2	3	4	5	6	7	8	9	10
Number of Coalition Members (*m*)	n	1	1	1	1	1	1	1	1	1
	n-1	0	0.223	0.655	0.897	0.978	0.996	0.999	1	1
	n-2	–	0.028	0.412	0.773	0.938	0.988	0.998	1	1
	n-3	–	–	0.036	0.499	0.832	0.959	0.992	0.999	1
	n-4	–	–	–	0.035	0.560	0.867	0.969	0.995	0.999
	n-5	–	–	–	–	0.030	0.610	0.891	0.977	0.996
	n-6	–	–	–	–	–	0.026	0.648	0.908	0.982
	n-7	–	–	–	–	–	–	0.025	0.677	0.922
	n-8	–	–	–	–	–	–	–	0.020	0.702
	n-9	–	–	–	–	–	–	–	–	0.017

Finally, simulation results on stability, which comprises both internal and external stability, are displayed in Table 4.

Table 4: Stability Likelihood and Success Indexes Estimates

		Number of Players *(n)*								
		2	3	4	5	6	7	8	9	10
Number of Coalition Members *(m)*	n	1	0.777	0.345	0.103	0.022	0.004	0.001	0	0
	n-1	0	0.127	0.149	0.074	0.023	0.004	0.001	0	0
	n-2	–	0.028	0.148	0.101	0.036	0.010	0.002	0	0
	n-3	–	–	0.036	0.126	0.071	0.023	0.005	0.001	0
	n-4	–	–	–	0.035	0.112	0.053	0.015	0.003	0.001
	n-5	–	–	–	–	0.030	0.101	0.040	0.011	0.002
	n-6	–	–	–	–	–	0.026	0.090	0.031	0.007
	n-7	–	–	–	–	–	–	0.025	0.082	0.025
	n-8	–	–	–	–	–	–	–	0.020	0.076
	n-9	–	–	–	–	–	–	–	–	0.017
$\overline{\mathrm{SGI}}(\mathrm{n})$		14.8	25.5	33.6	39.9	45.1	49.4	53.0	56.1	58.8
$\overline{\mathrm{CGI}}(\mathrm{n})$		100	87.2	55.4	30.4	16.3	9.3	5.9	4.0	2.8

As internal stability decreases within a column from the top to the bottom entry and decreases within a row from the very left to the very right entry (see Table 2), and just the opposite holds for external stability (see Table 3), it is not surprising that the regular patterns observed above in Tables 2 and 3 are not found in Table 4. Nevertheless, the results in Table 4 can be summarized as follows.

Result 4

For a sufficiently large number of fishing nations (e.g. $n \geq 5$*) the stability likelihood of a RFMO with a significant number of fishing states (e.g.* $m \geq n-3$*) is small and tends sharply to zero as* n *increases.*

This result confirms an observation already made for internal stability: in the presence of a sufficiently fierce competition for the fish stock, the formation of a RFMO of a size that can make a noticeable difference to the overfishing of the stock is very unlikely. Only in fisheries characterized by few harvesting states, i.e. two or three, is the formation of a stable RFMO involving all states a likely outcome. This is compactly summarized by our two indexes (see section 4.2 for a definition). On the one hand, the estimates of $E\left(SGI(n)\right)$, $\overline{SGI}\left(n\right)$, measuring the relative difference between the global optimum (i.e. full cooperation) and the Nash equilibrium (i.e. no cooperation) increase with the number of fishing states. In other words, the more states engaged in fishing, the more prompting would be the need for cooperation. On the other hand, with an increasing number of fishing states the success of cooperation declines as measured by the estimates of $E\left(CGI(n)\right)$, $\overline{CGI}\left(n\right)$. In the next section we will test the robustness of this conclusion.

4.4 Simulation Results: The Asymmetry and Efficiency Effect

In this section, we analyze two effects: the asymmetry and the efficiency effect. In order to isolate the effect of asymmetry, we run simulations for different ranges of each element of the uniformerly distributed vector b (implying different standard deviations) but with the same expected value: $E\left(b_i\right)$. Given the definition of $b_i = c_i \big/ pqk$, the larger the standard deviation, the more states differ in terms of unit production costs c_i. A representative example includes the estimates of $E\left(SGI(n)\right)$ and $E\left(CGI(n)\right)$, for $b_i = 0.2$ (no asymmetry), $b_i \in \left[0.1; 0.3\right]$ and $b_i \in \left[0; 0.4\right]$ for all $i \in N$ in Table 5. The result can be summarized as follows.

Result 5

For given number of players $n > 2$ *and* $E\left(b_i\right)$, $E\left(CGI(n)\right)$ *increases with the range of the parameters* b_i*, i.e. the degree of asymmetry.*

This result suggest that the success of coalition formation is positively correlated with the degree of cost asymmetry among fishing states. The significance of this result gains even more momentum by recalling from section 4.1 that in the case of symmetric players no RFMO would be stable for $n > 2$. Hence, as long as $n > 2$, CGI would always be zero for symmetric players irrespective of the value of the parameters b_i. In other words, asymmetry is not an obstacle but conducive to the stability and success of establishing a RFMO.

Table 5: Success Indexes Estimates: Asymmetry and Efficiency Effect

Range of b_i´s		Number of Players								
		2	3	4	5	6	7	8	9	10
		Asymmetry Effect								
0.2	$\overline{SGI}(n)$	11.1	25.0	36.0	44.4	51.0	56.3	60.5	64.0	66.9
	$\overline{CGI}(n)$	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[0.1;0.3]	$\overline{SGI}(n)$	16.1	29.9	39.2	45.6	50.1	53.5	56.2	58.7	60.8
	$\overline{CGI}(n)$	100.0	43.8	17.3	9.9	6.6	4.7	3.5	2.7	2.1
[0;0.4]	$\overline{SGI}(n)$	17.3	28.2	35.5	41.2	45.9	49.9	53.3	56.3	59.0
	$\overline{CGI}(n)$	100.0	76.7	42.7	23.3	13.5	8.4	5.5	3.9	2.8
		Efficiency Effect								
[0;0.2]	$\overline{SGI}(n)$	15.8	29.7	39.4	46.2	50.9	54.4	57.2	59.5	61.6
	$\overline{CGI}(n)$	100	38.9	15.2	8.5	5.7	4.1	3.1	2.4	1.9
[0.2;0.4]	$\overline{SGI}(n)$	16.4	29.9	38.8	44.8	49.0	52.4	55.3	57.9	60.2
	$\overline{CGI}(n)$	100.0	50.2	19.8	11.4	7.6	5.4	4.0	3.0	2.3
[0.4;0.6]	$\overline{SGI}(n)$	17.2	29.3	36.9	42.3	46.8	50.6	53.8	56.7	59.2
	$\overline{CGI}(n)$	100	67.8	31.6	17.6	11.1	7.3	5.0	3.6	2.6

Unfortunately, this striking result has also a strikingly difficult intuition. The simplest explanation would just be to point out that the success rate of coalition formation can almost not be worse with heterogeneous players than in the benchmark case of symmetric players (see section 4.1). However, also a deeper and very involved analysis[4] can only show that asymmetry, in fact the degree of asymmetry, increases the coalitional payoff as well as the payoff of all outsiders for a given coalition S and hence also free-rider payoffs. Since both effects work in the same directions, analytical predictions with respect to potential internal stability based on (22), letting alone stability and the success of coalition formation measured by $E(CGI(n))$, seem impossible.

In order to isolate the effect of efficiency, we run simulations for different $E(b_i)$ but with the same range (and hence same standard deviation). The higher $E(b_i)$, the lower the overall efficiency. Table 5 shows estimates of $E(SGI(n))$ and $E(CGI(n))$ for a representative example: $b_i \in [0;0.2]$, $b_i \in [0.2;0.4]$ and $b_i \in [0.4;0.6]$, implying that $E(b_i)$ increases from 0.1 to 0.3, reaching finally 0.5. The results can be summarized as follows.

Result 6

For a given number of players n*, and given range of the parameters* b_i*,* $E(CGI(n))$ *increases with* $E(b_i)$*, i.e. the level of inefficiency.*

According to this result the lower the efficiency level, or equivalently the higher the $E(b_i)$, the higher $E(CGI(n))$. Given that $b_i = c_i / pqk$, a uniform increase of this parameter for all players can be due to a uniform increase in the unit cost c_i, a decrease in the price *p*, the catchability coefficient *q* or the carrying capacity of the ecosystem *k*. According to Proposition 1, including the proofs in the Appendix, a change of these parameters in this

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[4] A proof is available upon request.

direction reduces the total fishing effort as fishing becomes less attractive. Hence, competition for the fish stock is lower, making it easier to form larger stable coalitions.

Finally, looking at Tables 4 and 5 together shows a robust result.

Result 7

For a given range of the parameters b_i, $E\left(SGI(n)\right)$ *increases and* $E\left(CGI(n)\right)$ *decreases with the number of players,* $E\left(SGI(n)\right) < E\left(SGI(n')\right)$ *and* $E\left(CGI(n)\right) > E\left(CGI(n')\right)$, $n < n'$.

That is, the larger the relative gap between social optimum and Nash equilibrium, $E\left(SGI(n)\right)$, which increases with the number of players engaging in fishing, the lower is the relative average success of forming stable RFMOs, $E\left(CGI(n)\right)$, which also decreases with n. Hence, the paradox of the global commons, which has first been described for global emissions by Barrett (1994), also applies to international fisheries: whenever cooperation would be most needed, it achieves only little.

5. Summary and Conclusions

This paper analyzed that formation, stability and success of regional fisheries management organizations (RFMOs) to regulate straddling and highly migratory fish stocks. For this the classical Gordon-Schaefer bioeconomic model was linked to the coalition formation model of d´Aspremont et al (1983). In the first stage, fishing states decide whether to join the RFMO or to remain outside. In the second stage, RFMO members coordinate their fishing efforts whereas non-members behave non-cooperatively. The game is solved backward, requiring that strategies form a Nash equilibrium in each stage. A central and new feature of our model is the differences in unit costs of harvesting across fishing states.

The effects of an exogenous change of the parameters of the model, as well as the number of players and the coalition size, on the fish stock and the payoffs of players - affecting their incentives to participate in a RFMO - could be derived analytically. In contrast, the analysis of the implications for stability and the overall success of RFMOs had to rely on Monte Carlo simulations which showed a clear-cut and robust pattern. Among the many results, we would like to highlight three.

1) The larger the number of fishing states that compete for the fish stock, the higher would be the relative gains from full cooperation, but the lower is the likelihood that large RFMOs are stable and their relative success of closing the gap between full and no cooperation. The number of fishing states includes those currently actively engaging in fishing which may change if a previously non-active state decides either to join the RFMO or to behave non-cooperatively. This paradox is due to the fact that RFMO members cannot exclude non-members from harvesting the fish stock. The larger the RFMO, the more non-members benefit from the cooperative management efforts of the RFMO, which reduces their incentive to join the RFMO. Moreover, these efforts are contradicted by non-members, as fishing efforts are strategic substitutes.

2) The higher the overall efficiency of all fishing states in harvesting the fish, the lower the relative success of coalition formation. In our model, a high efficiency was related to either low unit production costs, a high market price for fish, a high catchability coefficient or a high carrying capacity of the ecological system. All this makes fishing attractive; increasing the competition for the fish stock, but is detrimental to the formation of stable RFMOs that successfully manage to preserve the fish stock at high levels.

3) The higher the cost asymmetry among fishing states, the higher the relative success of RFMOs. This result only assumed a very general sharing scheme of the gains from

cooperation; it is striking as it runs counter to intuition and - to the best of our knowledge - has not been shown before.

This paper opens at least two avenues for further research. First, the model can be used to specifically address the threats to cooperative agreements posed by unregulated fishing of new entrants. It would be interesting to analyze the options available to current RFMO members to counterbalance these threats. Second, the model could be generalized to a truly dynamic bioeconomic model which explicitly models the migration of the fish stock and extends asymmetry to other model parameters.

References

d’Aspremont, C., A. Jacquemin, J.J. Gabszewicz and J.A. Weymark (1983). On the Stability of Collusive Price Leadership. *Canadian Journal of Economics,* vol. 16(1), 17-25.

Barrett, S. (1994). Self-enforcing International Environmental Agreements. *Oxford Economic Papers*, vol. 46, 878-894.

Bloch, F. (2003). Non-cooperative Models of Coalition Formation in Games with Spillovers. In: Carraro, C. (ed.). *The Endogenous Formation of Economic Coalitions*. Edward Elgar, Cheltenham, UK et al., ch. 2, 35-79.

Carraro, C., J. Eyckmans and M. Finus (2006). Optimal Transfers and Participation Decisions in International Environmental Agreements. *Review of International Organizations*, vol. 1 (4), 379-396.

Clark, C. and G. Munro (1975). The Economics of Fishing and Modern Capital Theory: A Simplified Approach. *Journal of Environmental Economics and Management,* vol. 2, 92-106.

Eyckmans, J. and M. Finus (2004). An Almost Ideal Sharing Scheme for Coalition Games with Externalities. Working Paper No. 155.2004, Fondazione Eni Enrico Mattei, Italy. Current version as presented at the 7th Meeting on Game Theory and Practice Dedicated to Energy, Environment and Natural Resources, May 2007, Montreal, Canada.

Finus, M. (2001). *Game Theory and International Environmental Cooperation*, Edward Elgar, Cheltenham UK.

Finus, M. (2003). Stability and Design of International Environmental Agreements: The Case of Global and Transboundary Pollution. In: Folmer, H. and T. Tietenberg (eds.), *International Yearbook of Environmental and Resource Economics 2003/4*. Edward Elgar, Cheltenham, UK et al., ch. 3, 82-158.

Finus, M. and B. Rundshagen (2003). Endogenous Coalition Formation in Global Pollution Control: A Partition Function Approach. In: Carraro, C. (ed.), *The Endogenous Formation of Economic Coalitions*. Edward Elgar, Cheltenham, UK et al., ch. 6, 199-243.

Gordon, H. (1954). The Economic Theory of a Common Property Resource: the Fishery, *Journal of Political Economy,* vol. 62, 124-142.

Haeringer, G. (2004). Equilibrium Binding Agreements: A Comment. *Journal of Economic Theory*, vol. 117, 140-143.

Hannesson, R. (1997). Fishing as a Supergame. *Journal of Environmental Economics and Management*, vol. 32, 309-322.

Kaitala, V. and G. Munro (1997). The Management of High Seas Fisheries. *Marine Resource Economics*, vol. 8, 313-329.

Kennedy, J. (2003). Scope for Efficient Multinational Exploitation of North-East Atlantic mackerel. *Marine Resource Economics,* vol. 18, 55-80.

Kronbak, L. and M. Lindroos (2006). An Enforcement-Coalition Model: Fishermen and Authorities Forming Coalitions. *Environmental & Resource Economics*, vol. 35, 169-194.

Lind, D. A., W.G. Marchal and S. A. Wathen (2005). Statistical *Techniques in Business & Economics*, McGraw-Hill (twelfth edition).

Lindroos, M. (2004). Sharing the Benefits of Cooperation in the Norwegian Spring-spawning Herring, *International Game Theory Review*, vol. 6 (1), 35-53.

Lindroos, M. (forthcoming). Coalitions in International Fisheries Management, *Natural Resource Modeling*.

McKelvey, R., L. Sandal and S. Steinshamn (2003). Regional Fisheries Management on the High Seas: the Hit-and-run Interloper Model. *International Game Theory Review*, vol. 5 (4), 327-345.

Mesterton-Gibbons, M. (1993). Game-theoretic Resource Modeling. *Natural Resource Modeling* 7 (2), 93-147.

Munro, G., A. Van Houtte and R. Willmann, R. (2004): *The Conservation and Management of Shared Fish Stocks: Legal and Economic Aspects*, FAO Fisheries Technical Paper No. 465, Rome.

Pintassilgo, P. (2003). A Coalition Approach to the Management of High Seas Fisheries in the Presence of Externalities. *Natural Resource Modeling*, vol. 16 (2), 175-197.

Pintassilgo, P. and C. Costa Duarte (2001). The New-Member Problem in the Cooperative Management of High Seas Fisheries. Marine Resource Economics, vol. 15, 361-378.

Pintassilgo, P. and M. Lindroos (forthcoming). Coalition Formation in Straddling Stock Fisheries: a Partition Function Approach, *International Game Theory Review*.

Ruseski, G. (1998). International Fish Wars: the Strategic Roles for Fleet Licensing and Effort Subsidies. *Journal of Environmental Economics and Management*, vol. 36, 70-88.

United Nations (1982). *United Nations Convention on the Law of the Sea*. UN Doc. A/Conf.62/122.

_____ (1995). *United Nations Conference on Straddling Fish Stocks and Highly Migratory Fish Stocks. Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 Relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks*, UN Doc. A/Conf./164/37.

Yi, S.-S. (2003). Endogeneous Formation of Economic Coalitions: a Survey of the Partition Function Approach, in Carraro, Carlo (eds.), *The Endogeneous Formation of Economic Coalitions*. The Fondazione Eni Enrico Mattei (FEEM) Series on Economics and the Environment, Edward Elgar, Cheltenham, UK et al., ch. 3, 80-127.

Appendix I: Deriving equations (11), (12) and (13) in the text

From (9) and (10), strictly positive fishing efforts imply

$$E_S = \frac{r}{2q}\left(1-b_S^{\min}\right)-\frac{1}{2}\sum_{j\notin S}E_j \tag{A1}$$

$$E_j = \frac{r}{2q}\left(1-b_j\right)-\frac{1}{2}\left(E_s+\sum_{k\neq j\notin S}E_k\right) \ . \tag{A2}$$

Summing (A2) over all $j\notin S$ gives

$$\sum_{j\notin S}E_j = \frac{r}{q(n-m+1)}\sum_{j\notin S}(1-b_j)-\frac{n-m}{n-m+1}E_S \ . \tag{A3}$$

Substitution of (A3) into (A1) and solving for E_S gives (11) in the text. Applying a similar procedure leads to (12) in the text. A sufficient condition for $E_S^*(S)>0$ in (11) and $E_{j\notin S}^*(S)>0$ in (12) is

$$A := 1-(n-m+1)b_S^{min}+\sum_{j\notin S}b_j>0$$

$$B := 1-(n-m+1)b_j+b_S^{min}+\sum_{k\neq j\notin S}b_k>0$$

respectively. Both conditions are assumed to hold throughout the paper and will be used frequently in the subsequent proofs. As we show below in Appendix II, $E_S^*(S)$ and $E_{j\notin S}^*(S)$ increase with the number of coalition members m, and for $m=1$ $E_S^*(\{k\})=E_j^*(\{k\})$ and $E_j^*(\{k\})>E_l^*(\{k\})$ if $b_j<b_l$. Thus, a sufficient condition for strictly positive fishing efforts of all players and for all possible coalition structures is derived by substituting $m=1$ in B and replacing b_j by b_l: $B=1-nb_l-\sum_{k\neq l}b_k>0$ with $b_l=max\{b_1,...,b_n\}$, which is equivalent to (13) in the text. Hence, condition (13) is a sufficient condition for conditions A and B to hold.

Appendix II: Results of Proposition 3

Consider n players and a given coalition S with m members. Suppose a singleton player i joins coalition S such that $S' = S \cup \{ i \}$ and hence $m' = m+1$. Denote $b_{S'}^{min}$ the smallest b_k in coalition S'. Let $\Delta E^* = E^*(S) - E^*(S')$. Then using (14) in the text:

$$\Delta E^* = \frac{r}{(n-m+2)q}\left[\left(1-b_S^{min}\right)+\sum_{j\notin S}\left(1-b_j\right)\right]-\frac{r}{(n-m+1)q}\left[\left(1-b_{S'}^{min}\right)+\sum_{j\notin S'}\left(1-b_j\right)\right] .$$

After some basic manipulations, we derive:

$$sign\left(\Delta E^*\right) = sign\left[-\left(1-b_S^{min}\right)-\sum_{j\notin S}\left(1-b_j\right)-\left(n-m+2\right)\left(-1+b_i+b_S^{min}-b_{S'}^{min}\right)\right] .$$

If $b_i < b_S^{min}$, then $b_i = b_{S'}^{min}$. Replacing $b_{S'}^{min}$ by b_i in the expression above, we have:

$$sign(\Delta E^*) = sign\left[A\right] .$$

If $b_i \geq b_S^{min}$, then $b_S^{min} = b_{S'}^{min}$. Replacing $b_{S'}^{min}$ by b_S^{min} in the expression above, we have:

$$sign(\Delta E^*) = sign\left[B\right] .$$

Since $A > 0$ and $B > 0$ by assumption in Appendix I, $\Delta E^* > 0$.

Subtracting $\frac{1}{2}E_S$ on both sides of equality (A1) above, using the equilibrium values of variables and rearranging terms, we find:

$$E_S^*(S) = \frac{r}{q}\left(1-b_S^{\min}\right)-E^*(S) .$$

From above we know that $E^*(S) > E^*(S')$, $b_S^{min} \geq b_{S'}^{min}$, $S' = S \cup \{i\}$ and hence $E_S^*(S) < E_{S'}^*(S')$. Applying a similar procedure shows that $E_{j\notin S}^*(S) < E_{j\notin S'}^*(S')$. Finally, since the stock decreases with the total fishing effort, as this is evident from equation (4) in the text, $X^*(S) < X^*(S')$. Taken together, this proves Proposition 3a, i.

Consider now payoffs. Let $\Delta\Pi^*_{S,S'} = \Pi^*_S(S) - \Pi^*_{S'}(S')$. Then using (16) in the text, we find after some manipulation (proceeding along the same lines to sign ΔE^*):

$$sign(\Delta\Pi^*_{S,S'}) = sign\left[1-(n-m+2)(n-m)b^{min}_{S'} + (n-m+1)^2 b^{min}_S + \sum_{j\notin S} b_j - (n-m+2)b_i\right].$$

If $b_i < b^{min}_S$, then $b_i = b^{min}_{S'}$. Replacing $b^{min}_{S'}$ by b_i in the expression above, we have:

$$sign\left(\Delta\Pi^*_{S,S'}\right) = sign\left[\left(1-(n-m+1)b_i + b^{min}_S + \sum_{j\neq i\notin S} b_j\right) + \left((n-m+1)^2 - 1\right)\left(b^{min}_S - b_i\right)\right].$$

The first term in brackets is condition $B > 0$. The second term is strictly positive because $n > m$ (due to the assumption $S' = S \cup \{i\}$) and the last term is positive by assuming $b_i < b^{min}_S$.

If however $b_i \geq b^{min}_S$, then $b^{min}_S = b^{min}_{S'}$. Replacing $b^{min}_{S'}$ by b^{min}_S in the expression above, we have:

$$sign\left(\Delta\Pi^*_{S,S'}\right) = sign\left[1-(n-m+1)b_i + b^{min}_S + \sum_{j\neq i\notin S} b_j\right]$$

where the term in brackets is condition $B > 0$. Thus, $\Delta\Pi^*_{S,S'} > 0$.

A similar procedure along the lines of signing $\Delta\Pi^*_{S,S'}$ (using conditions A and B), letting $\Delta\Pi^*_{j\notin S,S'} = \Pi^*_{j\notin S}(S) - \Pi^*_{j\notin S'}(S')$ would show that $\Delta\Pi^*_{j\notin S,S'} > 0$. Taken together, this proves Proposition 3a, ii.

If superadditivity holds, then $\Pi^*_{S'}(S') \geq \left(\Pi^*_S(S) + \Pi^*_i(S)\right)$, $S' = S \cup \{i\}$, $i \notin S$. Using (16) and (17) in the text, this implies:

$$\frac{rpk}{\left(n-m+3\right)^2}\left(1-\left(n-m\right)b^{\min}_{S'}+\sum_{j\notin S'} b_j\right)^2 \geq$$

$$\frac{rpk}{\left(n-m+2\right)^2}\left(1-\left(n-m+1\right)b^{\min}_S+\sum_{j\notin S} b_j\right)^2 + \frac{rpk}{\left(n-m+2\right)^2}\left(1-\left(n-m+1\right)b_i + b^{\min}_S + \sum_{k\neq i\notin S} b_k\right)^2$$

Dividing through by rpk, assuming symmetric players, this requires:

$$\left(1-b\right)^2\left[\left(\frac{n-m+2}{n-m+1}\right)^2 - 2\right] \geq 0$$

or since $1-b>0$

$$\frac{n-m+2}{n-m+1} \geq \sqrt{2} \Leftrightarrow n-m \leq \frac{2-\sqrt{2}}{\sqrt{2}-1} \simeq 1.41 \ .$$

Hence if and only if $m = n-1$ does superadditivity hold. This proves Proposition 3,b.

Appendix III: Results of Proposition 1

Noting $b_i = {c_i}/{pqk}$, the equilibrium stock as given in (15) in the text can be written as follows:

$$X^*(S) = k - \frac{1}{\left(n-m+2\right)pq}\left[(n-m+1)pqk - c^{\min}_S - \sum_{j\notin S} c_j\right] \ .$$

Hence, we derive:

$$\frac{\partial X^*(S)}{\partial c^{\min}_S} = \frac{\partial X^*(S)}{\partial c_j} = \frac{1}{\left(n-m+2\right)pq} > 0\,,\ \frac{\partial X^*(S)}{\partial p} = -\frac{c^{\min}_S + \sum_{j\notin S} c_j}{\left(n-m+2\right)qp^2} < 0\,,$$

$$\frac{\partial X^*(S)}{\partial q} = -\frac{c_S^{min} + \sum_{j \notin S} c_j}{\left(n-m+2\right) q^2 p} < 0\ , \ \frac{\partial X^*(S)}{\partial k} = \frac{1}{\left(n-m+2\right)} > 0\ , \ \frac{\partial X^*(S)}{\partial r} = 0\ .$$

Moreover:

$$dX^*(S) = \frac{\partial X^*(S)}{\partial c_S^{min}} dc_S^{min} + \sum_{j \notin S} \frac{\partial X^*(S)}{\partial c_j} dc_j = \frac{1}{\left(n-m+2\right) pq} dc_S^{min} + \sum_{j \notin S} \frac{1}{\left(n-m+2\right) pq} dc_j\ .$$

Assuming a uniform increase in the unit costs of all players, $dc_S^{\min} = dc_j = h > 0 \ \ \forall j \notin S$:

$$dX^*(S) = \frac{\left(n-m+1\right) h}{\left(n-m+2\right) pq} > 0\ .$$

Noting that $b_i = {c_i}/{pqk}$, the effect of a change of c_i on payoffs can be captured by a change of b_i. Using (16) and (17) in the text, we find:

$$\frac{\partial \Pi_S^*(S)}{\partial c_S^{min}} = \frac{\partial \Pi_S^*(S)}{\partial b_S^{min}} \frac{\partial b_S^{min}}{\partial c_S^{min}} = -\frac{2r(n-m+1)}{q\left(n-m+2\right)^2} A < 0$$

$$\frac{\partial \Pi_{j \notin S}^*(S)}{\partial c_S^{min}} = \frac{\partial \Pi_{j \notin S}^*(S)}{\partial b_S^{min}} \frac{\partial b_S^{min}}{\partial c_S^{min}} = \frac{2r}{q\left(n-m+2\right)^2} B > 0$$

because $A > 0$ and $B > 0$ from above.

$$\frac{\partial \left[\Pi_S^*(S) + \sum_{j \notin S} \Pi_{j \notin S}^*\left(S\right) \right]}{\partial c_S^{min}} = \frac{\partial \left[\Pi_S^*(S) + \sum_{j \notin S} \Pi_{j \notin S}^*\left(S\right) \right]}{\partial b_S^{min}} \frac{\partial b_S^{min}}{\partial c_S^{min}}$$
$$= \frac{2r\left(-1 + \left((n-m+1)^2 + n-m \right) b_S^{min} - \left(n-m+3\right) \sum_{j \notin S} b_j \right)}{q\left(n-m+2\right)^2}$$

In case of symmetric players before the change of b_S^{min} (e.g. $b_S^{min} = b_j = b_k = b$), the term in brackets in the numerator simplifies to $b - 1 < 0$. However, in the general case of asymmetric players, this term may be positive. For instance, assume $n = 4$, $b = \left(b_1, b_2, b_3, b_4\right) = \left(0.6, 0.6, 0.5, 0.5\right)$ and $S = \{1, 2\}$, then $-1 + 11 \cdot 0.6 - 5 \cdot 1 > 0$, though condition (13) in the text holds.

$$\frac{\partial \Pi_S^*(S)}{\partial c_j} = \frac{\partial \Pi_S^*(S)}{\partial b_j}\frac{\partial b_j}{\partial c_j} = \frac{2r}{q\left(n-m+2\right)^2} A > 0$$

$$\frac{\partial \Pi_{j \notin S}^*\left(S\right)}{\partial c_j} = \frac{\partial \Pi_{j \notin S}^*\left(S\right)}{\partial b_j}\frac{\partial b_j}{\partial c_j} = -\frac{2r(n-m+1)}{q\left(n-m+2\right)^2} B < 0$$

$$\frac{\partial \Pi_{i \notin S}^*\left(S\right)}{\partial c_j} = \frac{\partial \Pi_{i \notin S}^*\left(S\right)}{\partial b_j}\frac{\partial b_j}{\partial c_j} = \frac{2r}{q\left(n-m+2\right)^2}\left[1 - (n-m+1)b_i + b_S^{min} + \sum_{k \neq i \notin S} b_k\right] > 0$$

with $A > 0$ and $B > 0$ as defined above and the term in squared brackets is $B > 0$ when replacing b_j by b_i.

$$\frac{\partial\left[\Pi_S^*(S) + \sum_{j \notin S} \Pi_{j \notin S}^*\left(S\right)\right]}{\partial c_j} = \frac{\partial\left[\Pi_S^*(S) + \sum_{j \notin S} \Pi_{j \notin S}^*\left(S\right)\right]}{\partial b_j}\frac{\partial b_j}{\partial c_j}$$

$$= \frac{2r}{q\left(n-m+2\right)^2}\left(-1 + b_S^{min}\left(-n+m-3\right) + b_l\left((n-m+1)^2 + (n-m)\right) - 2\sum_{k \neq l \notin S} b_k\right)$$

In case of symmetric players before the change of b_j, the term in brackets in the numerator can be simplified to $\left(-1 + b(n-m)^2\right)$. Even in this case the sign can be positive or negative. For example, consider $b = 0.2$, then the term is negative for $n = 4$ and $m = 2$ (–0.2) but is positive for $n = 4$ and $m = 1$ (0.8).

A uniform change of all c_i´s can be captured by the following differential:

$$d\Pi_S^*(S) = \frac{\partial \Pi_S^*(S)}{\partial b_S^{min}}\frac{\partial b_S^{min}}{\partial c_S^{min}}dc_S^{min} + \sum_{j\notin S}\frac{\partial \Pi_S^*(S)}{\partial b_j}\frac{\partial b_j}{\partial c_j}dc_j =$$

$$-\frac{2r}{q(n-m+2)^2}\left(1-(n-m+1)b_S^{min}+\sum_{j\notin S}b_j\right)(n-m+1)dc_S^{min}$$

$$+\sum_{j\notin S}\frac{2r}{q(n-m+2)^2}\left(1-(n-m+1)b_S^{min}+\sum_{j\notin S}b_j\right)dc_j$$

Assuming $dc_S^{min} = dc_j = h > 0$:

$$d\Pi_S^*(S) = -\frac{2r}{q(n-m+2)^2}Ah < 0$$

with $A > 0$ as defined above. A similar procedure, assuming $dc_S^{min} = dc_j = dc_k = h > 0$, gives:

$$d\Pi_{j\notin S}^*(S) = \frac{\partial \Pi_{j\notin S}^*(S)}{\partial b_j}\frac{\partial b_j}{dc_j}dc_j + \frac{\partial \Pi_{j\notin S}^*(S)}{\partial b_S^{min}}\frac{\partial b_S^{min}}{\partial c_S^{min}}dc_S^{min} + \sum_{k\neq j\notin S}\frac{\partial \Pi_{j\notin S}^*(S)}{\partial b_k}\frac{\partial b_k}{\partial c_k}dc_k =$$

$$-2\frac{r}{q(n-m+2)^2}Bh < 0$$

with $B > 0$ as defined above. Hence, $d\Pi_S^*(S) + \sum_{j\notin S} d\Pi_{j\notin S}^*(S) < 0$.

Noting $b_i = {}^{c_i}\!\big/_{pqk}$, equilibrium payoffs (16) and (17) in the text can be written as follows:

$$\Pi_S^*(S) = \frac{r}{(n-m+2)^2 q^2 pk}\left(pqk-(n-m+1)c_S^{\min}+\sum_{j\notin S}c_j\right)^2 \tag{A4}$$

$$\Pi_{j\notin S}^*(S) = \frac{r}{(n-m+2)^2 q^2 pk}\left(pqk-(n-m+1)c_j+c_S^{\min}+\sum_{k\neq j\notin S}c_k\right)^2 . \tag{A5}$$

Then, we have:

$$\frac{\partial \Pi_S^*(S)}{\partial p} = \frac{rk}{(n-m+2)^2}A\left[1+(n-m+1)b_S^{min}-\sum_{j\notin S}b_j\right]$$

with $A>0$ as defined above. For symmetric players the term in squared brackets is $1+b>0$. However for asymmetric players, this term can be negative. For instance, suppose $n=5$, $b=(0.02,0.4,0.4,0.4,0.4)$ and $S=\{1,2\}$. In this case, the term in brackets is $1+(n-m+1)b_S^{\min}-\sum_{j\notin S} b_j = 1+4(0.02)-1.2 = 1.08-1.2 = -0.12<0$, though condition (13) in the text holds: $b_l+\sum_{k\neq l}(b_l-b_k) = 0.4+0.38 = 0.78<1$, $b_l = \max\{b_1,...,b_n\}$.

$$\frac{\partial \Pi^*_{j\notin S}(S)}{\partial p} = \frac{rk}{(n-m+2)^2} B\left[1+(n-m+1)b_j - b_S^{\min} - \sum_{k\neq j\notin S} b_k\right]$$

with $B>0$ as defined above. For symmetric players the term in squared brackets is $1+b>0$. However for asymmetric players, this term can be negative. For instance, suppose $n=4$, $b=(0.05,0.45,0.45,0.4)$ and $S=\{1\}$. Then the term in brackets is $1+(n-m+1)b_1-\sum_{k\notin S} b_k =$ $1+4\cdot 0.05-1.3 = -0.1<0$, though condition (13) in the text holds: $b_l+\sum_{k=l}(b_l-b_k) =$ $0.45+0.4+0.05 = 0.9<1$, $b_l = \max\{b_1,...,b_n\}$.

For effect on aggregate payoffs, we can conclude the following from above. In case of symmetric players, an increase in p increases aggregate payoffs as the coalitional payoff as well as of all singletons increases. In the case of asymmetric players, an increase in p may decrease aggregate payoffs by using the example $n=4$, $b=(0.05,0.45,0.45,0.4)$ and $S=\{1\}$ from above.

$$\frac{\partial \Pi^*_S(S)}{\partial q} = \frac{2prk}{(n-m+2)^2 q} A\left[(n-m+1)b_S^{min} - \sum_{j\notin S} b_j\right]$$

with $A>0$ as defined above. In the case of symmetric players the term in squared brackets reduces to $b>0$. However, in the case of asymmetric players this term could be negative. For instance, consider our previous example $n=5$, $b=(0.02,0.4,0.4,0.4,0.4)$ and $S=\{1,2\}$ where we have shown that condition (13) in the text holds. For the term in brackets we find: $(n-m+1)b_S^{\min}-\sum_{j\notin S} b_j = 4\cdot 0.02-1.2 = 0.08-1.2 = -1.12 < 0$.

$$\frac{\partial \Pi^*_{j\notin S}(S)}{\partial q} = \frac{2prk}{(n-m+2)^2 q} B\left[(n-m+1)b_j - b_S^{\min} - \sum_{k\neq j\notin S} b_k\right]$$

with $B>0$ as defined above. In the case of symmetric players the term in squared brackets reduces to $b>0$. However, in the case of asymmetric players this term could be negative. For instance, consider our previous example $n=4$, $b=(0.05,0.45,0.45,0.4)$ and $S=\{1\}$ where we have shown that condition (13) in the text holds. The term in brackets is: $(n-m+1)b_1-\sum_{k\notin S} b_k = 4\cdot 0.05-1.3 = -1.1 < 0$.

Conclusions for the effect on aggregate payoffs proceed exactly along the same lines outlined for a change of price p.

Observing payoffs (A4) and (A5) above, it is evident that a change of k has the same effect as a change of price p. It is also immediately evident that $\frac{\partial \Pi^*_S(S)}{\partial r} > 0$ and $\frac{\partial \Pi^*_{j\notin S}(S)}{\partial r} > 0$ and hence $\frac{\partial\left[\Pi^*_S(S)+\sum_{j\notin S}\Pi^*_{j\notin S}(S)\right]}{\partial r} > 0$.

Appendix IV: Results of Proposition 2

a) Assume a new player enters the game such that $n'=n+1$. Suppose the new player i acts as a singleton, then $m'=m$. Let $\Delta X^*(S) = X^*(S,n) - X^*(S,n+1)$. Then using (15) in the text:

$$\Delta X^{*}(S)=k\left[1-\frac{1}{n-m+2}\left(\left(1-b_S^{min}\right)+\sum_{j\notin S}\left(1-b_j\right)\right)\right]-k\left[1-\frac{1}{n'-m'+2}\left(\left(1-b_S^{min}\right)+\sum_{j\notin S}\left(1-b_j\right)+\left(1-b_i\right)\right)\right]$$

After some manipulation we derive:

$$sign(\Delta X^{*}(S))=sign\left[1-\left(n'-m+1\right)b_i-b_S^{min}+\sum_{k\neq i\notin S'}b_j\right]$$

where the term in brackets is condition $B>0$ for $n'=n+1$ players and hence $\Delta X^{*}(S)>0$.

Let $\Delta\Pi_S^{*}(S)=\Pi_S^{*}(S,n)-\Pi_S^{*}(S,n+1)$. Then using (16) in the text:

$$\Delta\Pi_S^{*}(S)=\frac{rpk}{\left(n-m+2\right)^2}\left(1-\left(n-m+1\right)b_S^{min}+\sum_{j\notin S}b_j\right)^2-\frac{rpk}{\left(n-m+3\right)^2}\left(1-\left(n-m+2\right)b_S^{min}+\sum_{j\notin S}b_j+b_i\right)^2$$

Dividing by rpk, noting that all squared terms are positive (the two terms in the nominator because this is $A>0$ for $n'=n+1$ players from above), we find after some basic manipulation:

$$sign(\Delta\Pi_S^{*}(S))=sign\left[1-\left(n'-m+1\right)b_i+b_S^{min}+\sum_{j\notin S}b_j\right]$$

where the term in brackets is $B>0$ for $n'=n+1$ players from above and hence $\Delta\Pi_S^{*}(S)>0$.

A similar procedure, letting $\Delta\Pi_{j\notin S}^{*}(S)=\Pi_{j\notin S}^{*}(S,n)-\Pi_{j\notin S}^{*}(S,n+1)$, using (17) in the text, gives:

$$sign(\Delta\Pi_{j\notin S}^{*}(S))=sign\left[1-\left(n'-m+1\right)b_i+b_S^{min}+\sum_{k\neq i\notin S}b_k\right]$$

where the term in brackets is $B>0$ for $n'=n+1$ players from above and hence $\Delta\Pi_{j\notin S}^{*}(S)>0$.

b) Again, assume a new player enters the game such that $n' = n+1$. Suppose the new player i joins coalition S such that $S' = S \cup \{ i \}$, then $m' = m+1$. If $b_i < b_S^{min}$, then $b_{S'}^{\min} = b_i$ and if $b_i \geq b_S^{min}$, then $b_{S'}^{\min} = b_S^{\min}$. Since

$$\frac{\partial X^*(S)}{\partial b_S^{\min}} = \frac{k}{\left(n-m+2\right)} > 0$$

and $n-m+2 = n'-m'+2$, $X^*(S)$ decreases if $b_i < b_S^{min}$ and remains constant if $b_i \geq b_S^{min}$. Considering (16) and (17) in the text, it is obvious that the coalitional payoff increases and the payoff of a non-member decrease if $b_i < b_S^{min}$ and both remain constant if $b_i \geq b_S^{min}$.