SPATIAL ALLOCATION OF PROPERTY RIGHTS – THE CASE OF INTERNATIONAL FISHERY

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Abstract

Since Samuelson’s (1954) seminal work on the theory of public goods, there has been much discussion about the decisive characteristics that define public goods. One line of thought, which we follow in this paper, argues that the criterion of non-exclusiveness is the main characteristic of public goods, which can be of a twofold nature. In some cases (such as moonlight), it is the technical nature that does not allow to exclude anybody from the consumption of the public good. In other cases, non-exclusiveness is due to the socially constructed environment and may be a consequence of legally unestablished and/or not enforced property rights. International fishery represents a particularly interesting example as both sources of non-exclusiveness are simultaneously present. On the one hand, the pattern of migration of fish stocks determines the degree of technical non-exclusiveness. On the other hand, the design of international law (e.g. the UN Convention on the Law of the Sea (UN 1982)) determines the spatial allocation of property rights and hence the degree of socially constructed non-exclusiveness. In this paper, we investigate how the technical and social nature of non-exclusiveness influence the strategic behavior of countries exploiting fish resources and the possibility of establishing regional fishery management organizations (RFMOs) as self-enforcing cooperative arrangements to protect fish stocks.

Our model depicts the high seas, the common property, as well as Exclusive Economic Zones (EEZs), the private properties of coastal states. All zones are interconnected through the migration of fish where migration is driven by differences in stock densities. The evolution of stocks in different zones is described by a biological model. Countries’ behavior is derived from an economic model that assumes that fishing nations aim at maximizing their economic rents from fishing in the various zones. We compare the outcomes (in terms of fishing efforts, equilibrium stocks and resulting payoffs) from non-cooperative Nash behavior and full cooperation (social optimum). Furthermore, we investigate whether and under which conditions full or partial cooperative arrangements in the form of RFMOs as proposed by the UN will be stable in the sense of internal and external stability. The impact of a variation of the two sources of non-exclusiveness on the outcome of various forms of cooperation is studied by varying the intensity of fish migration and the share of the resource that belongs to the public domain.

The results show that for no or only partial cooperation fishing efforts increase whereas fish stocks and total payoffs decrease as migration intensifies. The grand coalition, which would be socially optimal, is never stable, except for the trivial case where it coincides with uncooperative Nash behavior. Furthermore, the incentive to deviate from full and partial cooperation increases with increasing migration and the efficiency of harvesting. We show that whenever cooperation would be needed most from a global point of view, it is most unlikely to be achieved. However, with the share of the common property not too high, production efficiency not too high, and fish migration sufficiently small, partial cooperation proves to be stable.

JEL References: Q22, C72, H41, F53

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1. Introduction

Already Musgrave (1959: 13) stressed: “Certain public wants may fall on the border line between private and social wants, where the exclusion principle can be applied to part of the benefits gained but not to all.” Such impure public goods raised much attention in economics. For instance, Andreoni (1989, 1998) applies the basic approach developed by Cornes and Sandler (1984) to the field of philanthropy and shows that neutrality of income redistribution (the neutrality theorem by Warr (1982, 1983)) does not hold in the case of impure public goods. Cornes and Sandler (1994) demonstrate that divergent degrees of substitutability/complementarity of the private and public good lead to quite different comparative static results.

Recently, the inefficiently low provision of impure public goods at an international level receives much attention in the literature. Comparative static analyses based on the model by Cornes and Sandler (1994) are conducted by Rübbelke (2003) who investigates climate policy as well as by Kotchen (2005) who considers environmentally friendly consumption where the public good characteristic is tropical biodiversity. Rübbelke (2003) includes an alternative technology producing the impure public good’s private characteristic independently of the public one, while Kotchen (2005) allows for both, an independent production of the private as well as of the public characteristic.

Even in the context of climate change which is typically regarded as the prototype of a pure public good it has been argued that combating global warming generates not only global public benefits by slowing climate change (primary benefits), but also ancillary benefits, i.e. in the form of reduced local air pollution, which are enjoyed privately by the individual climate protecting nations (IPCC 1996: 217).[1] Ancillary benefits will call for higher globally optimal abatement levels but this will also be the case in the non-cooperative equilibrium.

[1] Ancillary benefits are benefits generated by climate policy that are not derived from the slowing of climate change. Other terms which convey this idea are secondary benefits, co-benefits and spillover benefits (see IPCC 2001 and Markandya and Rübbelke 2004: 489).

Because of the gap between optimal and non-cooperative climate protection levels, international coordination is still needed.

Although the analysis of the impact of private characteristics on the non-cooperative and optimal policy levels is important, the analysis of the strategic implications for the prospects of cooperation is still in its infancy. Such implications may affect the willingness of countries to participate in agreements that coordinate internationally the provision of impure public goods. It is this strategic dimension of private characteristics that we are interested in, but which has been neglected so far in the literature on impure public goods.

In this paper, we will deal with international fishing as an impure public good. While some parts of oceanic fish resources belong to the public domain, called the high seas, and are therefore in general subject to exploitation by several countries, coastal fisheries in so-called exclusive economic zones, are part of the private domain of the respective country (see the description of the legal framework below). Preservation of the fish stocks in the high seas does not only generate public benefits, but also affects the domestic fishery through the migration of fish shoals. By the same token, low harvest rates in the exclusive economic zones generate not only private benefits but also public benefits through the migration of fish shoals. Optimal management of renewable resources that lie entirely within the jurisdiction of a single country has been studied extensively and can be found in various textbooks, such as the one by Clark (2005). Shared resources, however, face the pivotal restriction that supranational institutions, which could enforce efficient global cooperation, do not exist. Due to the lack of global coercive authority, countries have to voluntarily negotiate and agree upon such coordination, i.e. they have to form self-enforcing agreements. While coalitional games have been used extensively to study international environmental agreements in general (for an overview see Finus 2003, for an introduction e.g. Finus 2001), the application to fishery issues is still emerging.

Kaitala and Lindroos (1998) introduced coalition games to the economic analysis of straddling fish stocks and fisheries economics in general by using a three-player model. They find that there is a partial cooperative equilibrium stock level that is higher than the non-cooperative stock level (Clark 1980), though lower than the fully cooperative stock level

(Clark and Munro 1975). Lindroos (2004a) extended the Kaitala-Lindroos model (1998) by allowing for restricted coalition formation in a four-player game. This is analyzed in the context of straddling fish stock negotiations where distant water fishing states (DWFSs) negotiated with coastal states. They show that, by joining together, DWFSs gain compared to unrestricted negotiations. Arnason et al. (2000) studies the case of Atlanto-Scandian herring and finds that Norway is a crucial country for any coalition to be stable. This result is related to Lindroos (2004a) who considers the possibility of veto countries. The effect of uncertainty and selectivity is studied by Lindroos (2004b). Pintassilgo (2003) models straddling stock fisheries as a partition function game and derives general results regarding the stability of coalition structures. Pham Do and Folmer (2003) study the feasibility of partial cooperation and its impacts on fishing effort through a game in partition function form.

The significance of international fishery issues arises both from their economic importance and the threats that heavy overfishing imposes on them. The Food and Agriculture Organization of the United Nations (FAO) estimates that harvests from shared fish stocks, which are defined as being exploited by two or more states (FAO 2007), account for as much as one third of global marine capture fishery harvests (Munro et al. 2004). At the same time these stocks are estimated to be particularly vulnerable and are reported to be heavily overexploited or even depleted. In a sense, the history of the international Law of the Sea represents a paradigm of globalization driven by technological change. Overfishing had already been an issue for more than a century, but for a long time concern was mainly with domestic fisheries and their optimal management. As, in many cases, regulation failed and stocks were depleted anyway, some governments assigned the blame to foreign vessels and unilaterally declared Exclusive Economic Zones (EEZs), thus evicting all foreign fleets from what they claimed to be their private property. The 1982 UN Convention on the Law of the Sea (UN, 1982) harmonized the various unilateral declarations in assigning the right to coastal states to establish Exclusive Economic Zones (EEZs), comprising the first 200 nautical miles, in which the respective country has the exclusive right to exploit the natural resources. However, beyond the borders of the EEZs, in the high seas, fish stocks are still subject to exploitation by coastal states and by so-called distant water fishing states. Initially, the significance of high seas fisheries was underestimated and therefore the issue was hardly addressed in the 1982 UN Convention. Further technological change, such as the introduction of fish carriers and vessels with on board fish processing equipment, has made the high seas resources more accessible. Subsequent overfishing and an increasing awareness of the problem led to the 1995 UN Fish Stocks Agreement (UN 1995). This agreement provides for the cooperative management of fish stocks in the high seas by Regional Fisheries Management Organizations (RFMOs). Following the FAO classification (FAO 2007), shared stocks can be divided up into the following categories:

Transboundary stocks inhabit (or cross) the EEZs of two or more coastal states.

Highly migratory stocks are to be found both within the EEZs and the adjacent high seas and are highly migratory in nature.

Straddling stocks also cover both EEZs and the high seas but are more stationary.

Discrete high seas fish stocks inhabit exclusively the high seas.

This classification is based on two distinguishing features, namely the location of the stocks and their degree of mobility. These key factors determine the degree of technical non-exclusiveness of the common resource and the degree of private benefits generated by the preservation of fish stocks. The spatial allocation of property rights, i.e. the assignment of EEZs determines the degree of socially constructed non-exclusiveness. We investigate how these two determinants of publicness/non-exclusiveness influence the strategic behavior of the countries exploiting the fish resources in the high seas and the EEZs.

We extend the analysis of Pintassilgo et al. (2008), whose stability analysis of RFMOs is confined to the high seas, by including also EEZs. All zones are assumed to be connected through the migration of fish stocks, driven by differences in stock densities. This description of dispersal originates from population biology (Levin 1976, Hastings 1982) and has found its way to bioeconomic fishery models through the contributions of Mullen (1989) and Sanchirico and Wilen (1999). The evolution of stocks in the different zones is described by an elementary biological model developed by Gordon (1954) and Schaefer (1954). In a first step, we compare the outcomes (in terms of fishing efforts, equilibrium stocks and resulting payoffs) from non-cooperative behavior (Nash equilibrium) and full cooperative behavior (social optimum). Furthermore, we investigate whether and under which conditions partial cooperative arrangements will be stable in the sense of internal and external stability (I&ES), a concept introduced by d'Aspremont et al. (1983).

This paper is structured as follows. In section 2 we first introduce the bioeconomic model with its components growth, harvest and dispersal, and the coalition formation model. In section 3, according to the sequence of backward induction, we present and discuss the results of the second stage of coalition formation, i.e. equilibrium fishing efforts, stocks and payoffs for given coalition structures. Section 4 discusses the results for the first stage of coalition formation, that is, we investigate the conditions under which stable coalitions may arise. Finally, section 5 sums up our main findings, discusses their policy implications and points to future research issues.

2. The Model

2.1 Preliminaries

Our model aims at capturing the impact of different degrees of socially constructed and technical non-exclusiveness on the exploitation but also on the prospective of cooperation of a common property resource. This is done in a systematic, though in a stylized way, due to analytical tractability. We assume that a given number of players N exploit a shared natural resource of size k. In the context of biological populations, such as fish stocks, k is called the carrying capacity of the biological system, which we interpret as the geographical size of the system (Pezzey et al. 2000). In our context, the resource is the fish stock and the system is the ocean. However, as mentioned in the introduction, parts of the system have been privatized through the establishment of exclusive economic zones. Hence, there are two types of geographical zones, the high seas, the common property where all nations can fish, abbreviated HS, and the exclusive economic zones, the private properties where only the coastal state i owning this zone is allowed to fish, abbreviated EEZ_i. Thus, if we denote the entire size of the system by k_{tot} for clarity, we assume that only a share α of the resource is subject to open access and define:

$$k_{HS} = \alpha k_{tot} \tag{1}$$

$$k_{EEZ} = \frac{1-\alpha}{N} k_{tot} \tag{2}$$

Hence, in our international context, players are sovereign countries engaged in fishing, i.e. coastal states, each owning an EEZ with exclusive fishing rights, though they can also fish in the high seas. Through this simplification, we abstract that EEZs could be of different size and that so-called distant water fishing nations without EEZ engage in fishing.

The underlying biological dynamics are captured by our biological model which is sequentially developed in section 2.2. Subsection 2.2.1 introduces the classical Gordon-Schaefer model, subsection 2.2.2 extends this model to account for the spatial allocation of property rights and subsection 2.2.3 extends this model to capture migration of fish between different zones.

The economic model is laid out in section 2.3 which captures the strategic behavior of the fishing nations under various assumptions of the degree of cooperation and the definition of stable cooperative arrangements. Cooperation refers to the formation of Regional Fishery Management Organizations (RFMOs) and stability captures the notion of self-enforcing agreements.

Since the biological and economic model are linked, we call it the bioeconomic model. How this model is solved is described in section 2.4.

2.2 The Biological Model

2.2.1 The Classical Gordon-Schaefer Model

The biological model is based on the classical Gordon-Schaefer model (Gordon 1954, Schaefer 1954) which has been frequently used to analyze the steady-state of an exploited (fish) resource (for an introduction, cf. Clark 2005). The following three equations describe the relation between total harvest H due to individual extraction efforts E_i, growth G and stock X of the fish resource:

$$\frac{dX}{dt} = G(X) - H(X) \tag{3}$$

$$G(X) = rX\left(1 - \frac{X}{k}\right) \tag{4}$$

$$H(X) = q\sum_{i=1}^{N} E_i X \tag{5}$$

where t denotes time, r the intrinsic growth rate and q the so-called catchability coefficient. The first equation simply states that the evolution of stock in time is driven by the difference between growth (i.e. regeneration) and total harvest. The second equation describes growth as a logistic process. When the stock is small compared to the carrying capacity k of the system ($X << k$), growth is essentially proportional to the stock itself, resulting in an exponential increase of the fish stock. However, as the stock approaches k, growth slows down, taking into account the limitations of the biological system like food and space. The harvest function $H(X)$ indicates that the total harvest increases with the catchability coefficient and the stock level (both facilitating harvesting) as well as the total fishing effort. The fishing effort can be seen as a physical measure of the inputs devoted to harvesting, such as days spend at sea. The catchability coefficient q reflects the efficacy of the current fishing technology, whereas the growth rate r is a measure for the reproductivity of the resource.

In the following, we will focus on the steady-state given by $dX / dt = 0$, leaving aside transition phenomena. Substituting equations (4) and (5) into (3), the steady-state stock is given by:

$$X^* = \frac{k}{r}\left(r - q\sum_{i=1}^{N} E_i\right) \tag{6}$$

As expected, the steady-state stock X^* is negatively related to the total fishing effort by all countries.

2.2.2 Spatial Allocation of Property Rights: Socially Constructed Exclusiveness

In this section, we extend the classical Gordon-Schaefer model and take into account the spatial allocation of property rights. This is derived from the socially constructed partitioning of the ocean: the high seas, which is subject to open access and therefore simultaneous exploitation by all parties, and the remainder which is made up of privately owned exclusive economic zones. As a consequence, we now have to distinguish between the stocks X_i, $i = 1,...,N$, in the EEZs and the stock X_{HS} in the high seas. Using the definitions (1) and (2), the extension of equations (3)-(5) is straightforward:

$$\frac{dX_{HS}}{dt} = G_{HS}\left(X_{HS}\right) - H_{HS}\left(X_{HS}\right) \tag{3a}$$

$$\frac{dX_i}{dt} = G_i\left(X_i\right) - H_{EEZ,i}\left(X_i\right) \quad , i = 1,...,N \tag{3b}$$

$$G_{HS}\left(X_{HS}\right) = rX_{HS}\left(1 - \frac{X_{HS}}{k_{HS}}\right) \tag{4a}$$

$$G_i\left(X_i\right) = rX_i\left(1 - \frac{X_i}{k_{EEZ}}\right) \quad , i = 1,...,N \tag{4b}$$

$$H_{HS}\left(X_{HS}\right) = q\sum_{i=1}^{N} E_{HS,i} X_{HS} \tag{5a}$$

$$H_{EEZ,i}\left(X_i\right) = qE_{EEZ,i} X_i \quad , i = 1,...,N \tag{5b}$$

Equations (3a) and (3b) indicate the steady-state condition for the high seas and the EEZs, respectively. Growth in the respective zones is described by equations (4a) and (4b), whereas equations (5a) and (5b) restate the harvest function. Note that equation (5b) accounts for the fact that in each EEZ_i only country i is allowed to fish. Using vector notation, $\boldsymbol{X} = \left(X_1,...,X_N,X_{HS}\right)$, $\boldsymbol{G} = (G_1,...,G_N,G_{HS})$ and $\boldsymbol{H} = (H_{EEZ,1},...,H_{EEZ,N},H_{HS})$, the steady-state condition for all stocks can be described by a single equation:

$$\frac{d\boldsymbol{X}}{dt} = \boldsymbol{G} - \boldsymbol{H} = 0 \tag{7}$$

This represents a system of $N+1$ equations which are not linked, i.e. stocks in different zones do not depend on each other and the steady-state stocks can be determined separately for every zone. With the extension in the following section, this will not hold any longer.

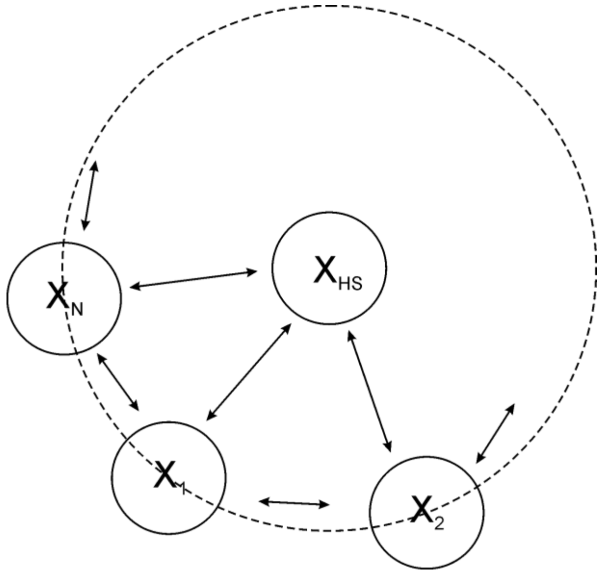
2.2.3 Migration Pattern: Technical Exclusiveness

In this subsection, we take into account that zones might not be isolated because of spillovers or technical externalities. In the case of fishery, this is also called fish migration, dispersal or diffusion (Sanchirico and Wilen 1999) and depends (linearly, in a first order approximation) on the differences in stock densities between zones. That is, fish may migrate from one to another zone if the competition for food and space there is less fierce. In order to account for dispersal, the steady state condition (7) has to be modified:

$$\frac{d\boldsymbol{X}}{dt} = \boldsymbol{G} - \boldsymbol{H} + D\boldsymbol{X} = 0 \ . \tag{8}$$

The dispersal matrix $D = \left(d_{ij}\right)$ contains all the information needed to describe the dispersal process: important is not only whether zone i and zone j are connected via dispersal at all ($d_{ij} \neq 0$ and/or $d_{ji} \neq 0$) but also the strength of interaction, i.e. the absolute value of d_{ij} and d_{ji}. In our case, there are N EEZs, which have the same property of being exploited by only one country, and the high seas which is different in the sense that it is exploited by all players. To be able to analyze the dispersal pattern in a most symmetrical and tractable way, we choose an intuitive and symmetric arrangement of these $N+1$ zones: the EEZs are arranged in a circle with the high seas at its center, as depicted in Figure 1. This avoids boundary effects that would emerge with a linear arrangement and approximates well the geographical settings of many examples (as, for example, the Donut Hole (see below)).

Figure 1: Migration Pattern and Spatial Allocation of Property Rights*



* Arrows indicate potential dispersal.

Other possible arrangements are described by Sanchirico and Wilen (1999) and include the fully integrated system in which all zones are directly connected to each other, and sink-source models, which model dispersal as a unidirectional flow from a source to a sink.[3]

To demonstrate the relevance of dispersal and to show that the stylized circular arrangement approximates quite well some real situations, let us briefly mention the so-called 'Donut Hole' as an example. This area in the Bering Sea has the status of the high seas, but is enclosed by the EEZs of Russia and the United States. Over-fishing in the high seas also threatened the fish resources in the EEZs as the fish migrated from the EEZs to the high seas. This phenomenon forced (among others) the United States to agree on a multilateral convention to protect the Bering Sea from over-exploitation of fish (Dunlap 1994). Thus, the

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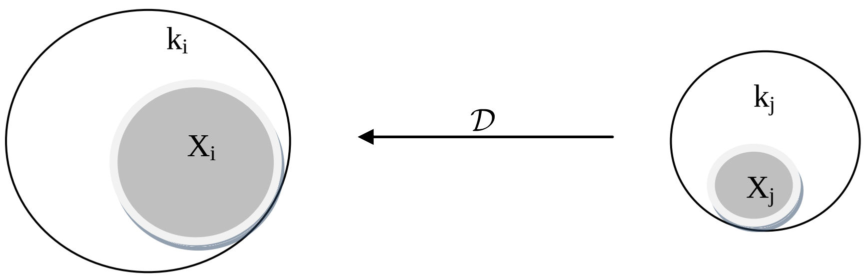
3 The fully integrated system might seem to be very general and symmetric. However, it is unrealistic for the case $N > 3$, since it is impossible to arrange five or more zones in such a way that every two of them share a border. This follows directly from the *four-color theorem* (Gonthier 2008). For all cases $N \leq 3$, our circular arrangement is identical to the fully integrated system.

interconnection of EEZs and high seas cannot be neglected as this determines crucially the strategic interplay between players.

With respect to the strength of interaction, let us consider the case of only two zones of different sizes k_i and k_j as depicted in Figure 2. Diffusion from zone j to zone i, i.e. the time rate of change of X_i due to diffusion, is given by $\mathcal{D} := d_{ii} X_i + d_{ij} X_j$.

Figure 2: Diffusion between Two Zones*



* Carrying capacities k_i, k_j and stock sizes X_i, X_j of two zones i and j.

It seems reasonable to expect that $\mathcal{D}$ depends on the stocks and the carrying capacities, $\mathcal{D} = \mathcal{D}(X_i, X_j, k_i, k_j)$ and should satisfy the following properties:

- $\frac{\partial \mathcal{D}}{\partial X_i} < 0$: The higher the stock in zone i, the lower the incoming diffusion will be.

- $\frac{\partial \mathcal{D}}{\partial X_j} > 0$: The higher the stock in zone j, the higher incoming diffusion (to zone i) will be.

- $\frac{\partial \mathcal{D}}{\partial k_i} > 0$: The higher the carrying capacity of zone i, the higher the incoming diffusion will be.

- $\frac{\partial \mathcal{D}}{\partial k_j} < 0$: The higher the carrying capacity of zone j, the lower the incoming diffusion (to zone i) will be.

- $\mathcal{D}(X_j, X_i, k_j, k_i) = -\mathcal{D}(X_i, X_j, k_i, k_j)$: Diffusion from zone j to zone i should be the opposite of diffusion from zone i to zone j.

Apart from these general properties, it seems reasonable to expect that dispersal is driven by differences in stock densities (see, e.g. Sanchirico and Wilen 2005, Kvamsdal and Groves 2008). That is, areas with a high density, i.e. with a high stock-carrying capacity ratio X_i / k_i will be characterized by outgoing diffusion if the adjacent zones have a lower density. The following formal description of diffusion between two zones as a density-dependent process captures this idea and satisfies all the five properties listed above:

$$\mathcal{D} = \gamma(k_i, k_j)\left[\frac{X_j}{k_j} - \frac{X_i}{k_i}\right] \qquad (9)$$

Following Kvamsdal and Groves (2008), we model the migration rate as being dependent on carrying capacities, setting $\gamma(k_i, k_j) = d\, k_i k_j$.[4] The parameter d, which we assume for simplicity to be identical for all diffusion processes, is an indicator for the intensity of diffusion. Dispersal takes place between each EEZ_i, $i \in \{1...N\}$, and its neighbors EEZ_{i+1}, EEZ_{i-1} and the high seas[5]. Altogether, we obtain for the temporal evolution due to diffusion, i.e. the components of the vector $D\boldsymbol{X}$:

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4 The meaning of the parameter γ can be understood from equation (9). If the stock densities in the two zones differ by a certain value δ, and if this difference is maintained by some means, then the amount of fish that flows from one zone to the other in one period of time equals $\gamma\delta$. Note that the steady-state condition does not require diffusion to vanish but to be balanced by growth and harvest in every zone.

5 Note that, due to the circular arrangement, the neighbors of EEZ_1 are EEZ_N and EEZ_2, and the neighbors of EEZ_N are EEZ_{N-1} and EEZ_1.

$$\left(D\boldsymbol{X}\right)_i = d\left[k_{EEZ}^2\left(\frac{X_{i+1}}{k_{EEZ}}-\frac{X_i}{k_{EEZ}}\right)+k_{EEZ}^2\left(\frac{X_{i-1}}{k_{EEZ}}-\frac{X_i}{k_{EEZ}}\right)+k_{EEZ}k_{HS}\left(\frac{X_{HS}}{k_{HS}}-\frac{X_i}{k_{EEZ}}\right)\right] \qquad (10)$$

$$\left(D\boldsymbol{X}\right)_{HS} = dk_{EEZ}k_{HS}\sum_{i=1}^{N}\left(\frac{X_i}{k_{EEZ}}-\frac{X_{HS}}{k_{HS}}\right) \qquad (11)$$

In equations (10) and (11) each summand accounts for one dispersal process between two adjacent zones. The direction and intensity of diffusion is determined by differences in densities which correspond to the expressions in brackets. In order to include the size dependency of the process, each difference is multiplied by the carrying capacities of the two involved zones. While each EEZ has three neighboring zones, namely two EEZs and the high seas, the high seas are connected to N EEZs as expressed by the sum in eq. (11).

2.3 Economic Model

Each player receives an economic rent or as we call it a payoff Π_i that is obtained from the harvest extracted from the player's private and public share of the resource:

$$\Pi_i = pq\left(E_{EEZ,i}X_i + E_{HS,i}X_{HS}\right) - c\left(E_{EEZ,i}+E_{HS,i}\right) \qquad (12)$$

where *p* is the (exogenously) given fish price and *c* is the (constant) marginal cost of fishing effort, which is assumed to be identical for all players for simplicity.[7] Each player i has two strategic variables, namely the fishing effort in the own EEZ, $E_{EEZ,i}$, and the fishing effort in the high seas, $E_{HS,i}$. It is a common assumption in the literature on fishery management (Gordon 1954, Sanchirico and Wilen 1999, Pezzey et al. 2000) that costs depend linearly on extraction efforts, though they are strictly convex if expressed in terms of harvests $H_{EEZ,i}$ and $H_{HS,i}$.

[7] The assumption of symmetric players is widespread in the literature on coalition formation, not only on international environmental treaties but also in the context of other economic problems (see e.g. Bloch 2003, and Yi 2003 for an overview).

Cooperation among a group of players corresponds to the establishment of a regional fishery management organization (RFMO) with the purpose of managing and conserving the fish stocks jointly. Participation in an RFMO is open to all nations as reflected by Article 8(3) of the UN Fish Stocks Agreement (UN 1995). Moreover, states which decide against membership in an RFMO cannot be prevented from harvesting.

In order to capture these institutional features, we chose from the set of coalition formation games the single coalition open membership game due to d'Aspremont et al. (1983) which has been frequently applied in the literature on international environmental agreements (e.g. Carraro 2000 and Finus 2003, 2008 for overviews). This coalition game is a two-stage game.

In the first stage, players decide upon their membership. 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. The decisions in the first stage lead to a coalition structure $K = \left\{C, \mathbf{1}_{(\text{N-n})}\right\}$ where C is the set of n coalition members, $n \in \{1,...,N\}$, and $\mathbf{1}_{(\text{N-n})}$ is the vector of $N-n$ singletons. Given the simple structure of the first stage, a coalition structure is fully characterized by coalition C. In the second stage, players choose 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 by backward induction.

In the second stage, given some coalition C has formed in the first stage, non-members act as singletons and maximize their individual payoff, Π_i, while members maximize the aggregate payoff of the coalition, $\Pi_C = \sum_{i \in C} \Pi_i$:

$$\left(E^*_{EEZ,j}, E^*_{HS,j}\right) = \underset{\left(E_{EEZ,j}, E_{HS,j}\right)}{\arg\max}\; \Pi_j\left(\boldsymbol{E}\right) \quad \forall\, j \notin C \tag{13}$$

$$\left(\boldsymbol{E}^*_{EEZ,C}, \boldsymbol{E}^*_{HS,C}\right) = \underset{\left(\boldsymbol{E}_{EEZ,C}, \boldsymbol{E}_{HS,C}\right)}{\arg\max}\; \Pi_C\left(\boldsymbol{E}\right) \tag{14}$$

Here, $\boldsymbol{E} = \left(E_{EEZ,1},...,E_{EEZ,N},E_{HS,1},...,E_{HS,N}\right)$ denotes the vector of all fishing efforts whereas $\boldsymbol{E}_{EEZ,C} = \left(E_{EEZ,i}\right)_{i\in C}$ and $\boldsymbol{E}_{HS,C} = \left(E_{HS,i}\right)_{i\in C}$ denote the vectors of fishing efforts of the coalition members in the EEZs and in the high seas, respectively (equilibrium values are labeled with an asterisk).

The assumption that members choose their fishing efforts cooperatively both in the high seas and in their EEZs is in line with the FAO (2007: 123) which states: "*Each RFMO is,* inter alia*, called upon to ensure that the management measures for the high seas segments of the resources and those measures for the intra-EEZ segments of the resources are compatible with each other*".

Technically, this assumption implies that the coalition and the single players play a Nash equilibrium with the coalition de facto acting as a metaplayer (Haeringer 2004). We call this a coalitional Nash equilibrium[8] in order to distinguish it from a Nash equilibrium. However, note that the coalitional Nash equilibrium is identical to the Nash equilibrium fishing vector if coalition C comprises only a single player, $C = \{ i \}$, or is empty $C = \emptyset$. Moreover, note that if coalition C comprises all players, $C = N$, the coalitional Nash equilibrium corresponds to the socially optimal fishing vector. Hence, in terms of equilibrium fishing efforts, the second stage of coalition formation conceptually captures the entire range from no cooperation, partial cooperation to full cooperation where no cooperation coincides with the Nash equilibrium and full cooperation with the social optimum.

It is also worthwhile to mention that the solution to (13) and (14) will be identical for every coalition $C \in N$, i.e., the degree of cooperation does not matter if and only if $\alpha = 0$ and all $d_{ij} = 0$. That is, there is no externality among players. Even if all $d_{ij} = 0$, i.e. there is no diffusion between any zone, as long as $\alpha > 0$, there is an area of common property resource that can be exploited by all countries. Even if $\alpha = 0$, i.e. all property is privately owned, as long as there is diffusion among at least two zones, i.e. there exists at least one $d_{ij} > 0$, the

8 It has also been called a partial agreement Nash equilibrium between the coalition and outsiders (e.g. Chander and Tulkens 1997).

action of one player has an impact on other players and hence no, partial and full cooperation imply different vectors of equilibrium fishing efforts.

Equilibrium efforts $\boldsymbol{E}^*(C)$, as determined by equations (13) and (14), have to be inserted into the payoff function (12) to determine individual payoffs $\Pi_i^*(C)$ and the resulting coalitional payoff. Since we deal with identical players, we assume an equal sharing rule, i.e. the coalitional payoff is split equally among the members, i.e., $\Pi_i^*(C) = \Pi_C / n$. Having determined equilibrium individual payoffs for every possible coalition structure in the second stage, we can now proceed to the first stage and check for stability of a given coalition structure.

In the first stage, a coalition C is considered to be stable if it fulfills the following two conditions:

Internal Stability:

No member $i \in C$ finds it profitable to deviate, i.e. the gain G_i from leaving the coalition is non-positive: $G_i := \Pi_i^*(C \setminus \{i\}) - \Pi_i^*(C) \leq 0, \forall i \in C$.

External Stability:

No non-member $j \notin C$ finds it profitable to join the coalition, i.e. the gain Q_j from joining the coalition is non-positive: $Q_j := \Pi_j^*(C \cup \{j\}) - \Pi_j^*(C) \leq 0, \forall j \notin C$.

Note that the grand coalition is externally stable by definition as there is no outsider left that could join the coalition. Even more important, the coalition structure of only singletons is stable by definition, which ensures existence of a stable coalition structure. This follows from the fact that, if all players announce not to be a member of the coalition, i.e. $C = \emptyset$, a single deviation by one player will make no difference. This would be different for $C = \{i\}$, which also implies the singleton coalition structure and which would also be internally stable, but not necessarily externally stable if a second player wants to join.

When dealing with identical players, a coalition C is fully characterized by the number of members n. In this case, it follows that the two conditions of internal and external stability are closely related: C is internally stable if and only if $C \setminus \{ i \}$ is not externally stable for any $i \in C$. Moreover, C is externally stable if and only if $C \cup \{ j \}$ is not internally stable for any $j \notin C$.

2.4 Solving Procedure

As mentioned above, the model is solved by backward induction. The most difficult part relates to the second stage. In the second stage of the game, optimal fishing efforts have to be determined for a given coalition structure. For this, the system of equations (8) has to be solved in order to obtain steady-state stocks as functions of fishing efforts. Subsequently, these functions have to be inserted into the payoff functions (12) yielding payoffs as functions of efforts. The equilibrium in the second stage is then derived from the optimization procedure described in (13) and (14).

However, already the first step of this procedure cannot be solved analytically, i.e. it is not possible to derive analytical solutions for the steady-state stocks depending on efforts. Therefore we rely on numerical simulations which are described in the appendix.

It is evident that computing time and memory requirements increase exponentially with the number of players. For this reason, we have to confine ourselves to the case of $N = 3$ players. This is certainly the minimum number of players that makes the analysis of coalition formation interesting, but as it turns out, it is sufficient to derive interesting qualitative results. For $N = 3$, we have to consider three possible coalition structures, namely the grand coalition, the two-player coalition and the all-singletons coalition structure. Furthermore, we will restrict the analysis to symmetric parameter values for all players. This implies symmetric equilibria in the Nash equilibrium and the social optimum. Moreover, all possible two-player coalitions are equivalent with symmetric payoffs for coalition members, though they differ from the payoff of the non-member.

As described in the appendix, simulations require the assumption of numerical values for the parameters of the model. As it turns out that results only depend on what is commonly referred to as the 'inverse efficiency parameter' $\frac{c}{pqk_{tot}}$, we normalize p and q to 1. The parameter k_{tot} is normalized to 4 as there are four zones.[9] The spatial allocation of property rights is then captured by the parameter α according to equations (1) and (2). We set the base value to $\alpha = 0.25$, which means that all zones have the same size, and subsequently vary α in the interval $\alpha \in [0,1]$. Hence, with reference to the inverse efficiency parameter, a variation of the cost parameter c is, ceteris paribus, de facto a variation of the relation c/pq. We set base case value to $c = 0.5$ but also conduct a sensitivity analysis for other values (see Table 1). Finally, results also depend on the growth rate r where we set base value to $r = 0.5$ but consider also other values in a sensitivity analysis (see Table 1).

Table 1: Simulation Runs*

Simulation Run	c	r	d	α	Result
A	0.5	0.5	**0 – 1.28**	0.25	1-5, 7
B	**0.25 - 0.75**	0.5	**0 – 1.28**	0.25	6
C	0.5	**0.25 - 0.75**	**0 – 1.28**	0.25	6
D	0.5	0.5	**0 – 0.32**	**0 - 1.0**	8, 9

* Column "Result" lists corresponding results in section 3 and 4. Parameter variations in a simulation run are indicated bold; $p = 1$, $q = 1$ and $k_{tot} = 4$ are assumed throughout.

The primary interest in simulation runs A, B and C is to investigate the dependency of efforts, stocks and payoffs on the diffusion parameter *d*, measuring the technical exclusiveness of the

9 This is in line with the common normalization $k = 1$ applied in articles dealing with a single zone (e.g. Pezzey et al. 2000). In our model, assuming no diffusion between zones, $k_{tot} = 4$, and setting $\alpha = 0.25$ results in four isolated zones with carrying capacities $k = 1$. See equations (1) and (2).

common property. In all these simulation runs $\alpha = 0.25$ and hence EEZs and high seas have the same carrying capacity $k_{HS} = k_{EEZ} = 1$, resulting in a totally symmetric arrangement of the four fishing zones. The only difference between the EEZs and the high seas is that the latter are subject to exploitation by three parties. In simulation run A, also the values of the cost and growth parameter are set to their base values, i.e. $c = 0.5$ and $r = 0.5$. In order to check whether the results are robust to parameter variations, a sensitivity analysis is conducted in simulation runs B and C, varying c while keeping r constant and vice versa. Apart from proving the robustness of the results obtained from simulation run A, simulation runs B and C deliver comparative static results with respect to c and r. In simulation run D, we depart from the assumption of equally sized zones ($\alpha = 0.25$) and allow for variations of α.

In the following, we analyze the impact of a variation of parameters on equilibrium fishing efforts (and associated fish stocks and payoffs) of the second stage of coalition formation in section 3. Subsequently, we analyze stability of cooperative arrangements in the first stage of coalition formation in section 4.

3. Results: Second Stage of Coalition Formation

In the following, we describe first how equilibrium fishing efforts, stocks and payoffs in the social optimum, i.e. full cooperation (Result 1), in the Nash equilibrium, i.e. no cooperation (Result 2) and in the coalitional Nash equilibrium, i.e. partial cooperation (Result 3) depend on the diffusion parameter d. The coalitional Nash equilibrium assumes that the coalition comprises two countries. For notational convenience, we skip in the following the term "equilibrium". Unless otherwise stated, we always refer to efforts, stocks and payoffs in the respective equilibrium (Nash equilibrium, social optimum and coalitional Nash equilibrium).

Result 1: Social Optimum (Full Cooperation)

The total fishing effort and the fishing efforts in each zone are independent of the diffusion parameter d*. Hence, stocks in all zones and aggregate payoffs are unaffected by* d*. The total fishing effort in the entire EEZ is three times the fishing effort in the high seas.*

(Simulation Runs A, B and C.)

In the social optimum, the distinction between high seas and EEZs does not matter for equilibrium strategies as we assume all zones to be of equal size. Hence, the optimal fishing efforts (and the equilibrium stocks) in all zones are the same. Since in the social optimum externalities across all players are internalized, i.e. the social planner maximizes aggregate payoffs over all zones, diffusion does not matter. This is different in the Nash equilibrium.

Result 2: Nash Equilibrium (No Cooperation)

Total fishing efforts in the high seas increase with the diffusion parameter d *and may increase or decrease in the EEZs (depending on the value of* c*), though total fishing efforts in all zones increase in* d*. The stocks in the EEZs decrease with* d*, whereas the stock in the high seas may decrease or increase, though the total stock in the entire fishing area decreases in* d*. The individual payoff of players and the total payoff decrease in* d*.*

(Simulation Runs A, B and C.)

A general conclusion, different from the social optimum, is that diffusion does matter if players behave non-cooperatively. At the aggregate level, the higher the diffusion between zones, i.e., the lower the degree of technical exclusiveness, the more will be the fish stock exploited (high fishing efforts), resulting in low stocks. This translates into low individual payoffs and a low aggregate payoff.

The interpretation of the results regarding the fishing efforts and stocks in the different zones is more difficult. Since the equilibrium fish stock in the high seas is always lower than in the EEZs (due to more players fishing there), diffusion will always flow from the EEZs to the high seas. This encourages high fishing efforts in the high seas which increase in the value of *d*. The mirror image is found in the EEZs which suffer from outgoing diffusion. The optimal reaction to this is unclear: lower fishing efforts to preserve the own fish stock or higher fishing efforts to slow down diffusion to the common property high seas. These countervailing tendencies lead to the ambiguity for equilibrium fishing efforts in the EEZ as a function of d.

Regarding stock levels, the EEZs suffer from increasing outgoing diffusion with increasing d, leading to decreasing stocks. The high seas benefit from increasing incoming diffusion but suffer from increasing efforts, which does not allow to establish a clear-cut relationship between the stock and *d*.

Viewed together, the results illustrate that there is an interesting and subtle incentive structure if players behave non-cooperatively if zones are linked through diffusion. This complicated incentive structure is preserved if some players behave cooperatively, but not all, as assumed in the coalitional Nash equilibrium considered below.

Result 3: Coalitional Nash Equilibrium

Consider a coalition with n *players such that* $n > 1$ *but* $n < N$ *. Coalitional fishing efforts in the EEZs and in the high seas may increase or decrease in diffusion parameter* d *, but fishing efforts of outsiders in their own EEZ and in the high seas increase in* d *. Total efforts in all EEZs may increase or decrease in* d *, but total efforts in the high seas and in all zones increase in* d *. The stock in each EEZ decreases in* d *whereas the stock in the high seas may increase or decrease in* d *, though the total stock in the entire fishing area decreases in* d *. The individual payoff of signatories decreases in* d *and those of outsiders increase in* d *, though total payoffs decrease in* d *.*

(Simulation Runs A, B and C.)

A general conclusion from Result 3 is that partial cooperation (coalitional Nash equilibrium) shares many features with no cooperation (Nash equilibrium), quite different from those under full cooperation (social optimum). As long as not all externalities are internalized across all players, the strategic interaction between members and non-members implies that a low degree of exclusiveness, i.e. a high value of d , has a detrimental effect on the total stock and the total payoff. Like in the Nash equilibrium, at the level of individual zones, relations are less clear-cut for the same reasons mentioned above.

For instance, regarding efforts, it is unclear whether the coalition can benefit from increasing diffusion by increasing their efforts since two of the three EEZs belong to the coalition. Increasing efforts would therefore also harm the stocks of the coalition. However, the outsider is in the position of a free-rider. He benefits from increased diffusion from the coalition members' EEZs which encourages him to increase his fishing efforts in the high seas and his own EEZ.

The following results compare individual equilibrium fishing efforts (Results 4), total equilibrium fishing efforts, stocks and payoffs (Result 5) for the three scenarios, namely the Nash equilibrium, social optimum and the two-player coalition.

Result 4: Individual Fishing Efforts

Let the individual fishing efforts in the social optimum, Nash equilibrium and the coalitional Nash equilibrium with coalition C having $1<n<N$ members be denoted by $E^S_{EEZ,i}$, $E^S_{HS,i}$, $E^N_{EEZ,i}$, $E^N_{HS,i}$, $E^C_{EEZ,i\in C}$, $E^C_{EEZ,i\notin C}$, $E^C_{HS,i\in C}$ and $E^C_{HS,i\notin C}$, respectively, then

a) $E^N_{EEZ,i} \geq E^C_{EEZ,i\in C}$ *with strict inequalities for* $d>0$. *The efforts of signatories can be even lower than in the social optimum (depending on d).*

b) $E^C_{EEZ,i\notin C} \geq E^N_{EEZ,i} \geq E^S_{EEZ,i}$ *with strict inequalities for* $d>0$.

c) $E^C_{EEZ,i\notin C} \geq E^C_{EEZ,i\in C}$ *with strict inequality for* $d>0$.

d) $E^N_{HS,i} > E^C_{HS,i\in C}$. *The efforts of signatories can be even lower than in the social optimum (depending on d).*

e) $E^C_{HS,i\notin C} > E^N_{HS,i} > E^S_{HS,i}$.

f) $E^C_{HS,i\notin C} > E^C_{HS,i\in C}$.

(Simulation Runs A, B and C.)

Compared to no cooperation, under partial cooperation the two-player coalition reduces its fishing efforts, not only in the high seas but also in their own EEZs, being aware of the mutual externalities in the high seas, between coalition members' EEZs and between all these zones. However, the coalitional efforts to preserve the fish stock under their control are thwarted by the free-rider whose effort levels increase in his own EEZ and in the high seas. This leakage effect is due to the downward sloping reaction function of the coalition and of the outsider as observed in the context of public and impure public goods in many models. As we will analyze in Section 4, this feature is the driving force why self-enforcing cooperation proves difficult and will be only possible in a few cases.

The next result compares fishing efforts at an aggregate level as well as fish stocks and payoffs.

Result 5: Total Fishing Efforts, Stocks and Payoffs

1) Let the total fishing effort in all EEZs, the high seas and in the entire fishing area in the social optimum, Nash equilibrium and the coalitional Nash equilibrium with coalition C having $1 < n < N$ members be denoted by E_{EEZ}^{S}, E_{EEZ}^{N}, E_{EEZ}^{C}, E_{HS}^{S}, E_{HS}^{N}, E_{HS}^{C}, E^{S}, E^{N}, and E^{C}, respectively, then

$E_{EEZ}^{N} \geq E_{EEZ}^{C} \geq E_{EEZ}^{S}$ *with strict inequalities for* $d > 0$,

$E_{HS}^{N} > E_{HS}^{C} > E_{HS}^{S}$ *and hence*

$E^{N} > E^{C} > E^{S}$.

The differences $E^{N} - E^{C}$, $E^{C} - E^{S}$ *and* $E^{N} - E^{S}$ *are positive and increase in d.*

2) Let the total equilibrium fish stock in the EEZs, high seas and in the entire fishing area in the social optimum, Nash equilibrium and the coalitional Nash equilibrium with coalition C having $1 < n < N$ members be denoted by X_{EEZ}^{S}, X_{EEZ}^{N}, X_{EEZ}^{C}, X_{HS}^{S}, X_{HS}^{N}, X_{HS}^{C}, X^{S}, X^{N}, and X^{C}, respectively, then

$X_{EEZ}^{S} \geq X_{EEZ}^{C} \geq X_{EEZ}^{N}$ *with strict inequalities for* $d > 0$

$X_{HS}^{S} > X_{HS}^{C} > X_{HS}^{N}$ *and hence*

$X^{S} > X^{C} > X^{N}$.

The differences $X^S - X^C$, $X^C - X^N$ and $X^S - X^N$ are positive and increase in d.

3) Let total payoffs in the social optimum, Nash equilibrium and the coalitional Nash equilibrium with coalition C having $1 < n < N$ members be denoted by Π^S, Π^N and Π^C, then

$$\Pi^S > \Pi^C > \Pi^N$$

where $\Pi^S - \Pi^C$, $\Pi^C - \Pi^N$ and $\Pi^S - \Pi^N$ increase in d.

(Simulation Runs A, B and C.)

By definition, total payoffs are highest in the social optimum. Result 5 stresses that already partial can improve upon no cooperation. This highlights the importance of cooperation in the presence of externalities. The importance increases the lower the degree of technical exclusiveness, i.e. the higher the diffusion parameter d is. Moreover, it underlines the rationale to analyze whether and under which conditions full or partial cooperation is self-enforcing as we do in section 4.

Comparing Result 5, 1 with Result 4 illustrates that despite leakage effects, total fishing efforts decrease under partial compared to no cooperation. Technically, this implies that the slopes of the reaction functions are smaller than one in absolute terms. The relations between total fishing efforts in Result 5, 1, are directly reflected in terms of stocks in Result 5, 2 and payoffs in Result 5, 3.

The next result looks at the effect of a variation of the cost parameter c, reflecting the unit production cost of fishing, and the growth parameter r, reflecting by how much the stock recovers from fishing.

Result 6: The Role of the Cost Parameter *c* and the Growth Parameter *r*

a) Individual and total fishing efforts and individual and total payoffs decrease and total stocks in all zones increase with the cost parameter c, irrespective of the diffusion parameter d.

b) Individual and total fishing efforts and individual and total payoffs increase in r whereas stocks in all zones remain unaffected, irrespective of the diffusion parameter d.

This holds for the social optimum, the Nash equilibrium and the coalitional Nash equilibrium, i.e. for all possible coalition structures.

(Simulation Runs A, B and C.)

The intuition of Part a of Result 6 is straightforward. With increasing unit production costs, equilibrium fishing efforts are reduced, resulting in lower payoffs, though higher fish stocks. Thus from an ecological point of view, higher production costs help to preserve fish stocks but from an economic point of view it reduces the economic rent of fishing nations. It may be worthwhile to recall that not the absolute value of c matters for results but the ratio c/pq. Thus, a higher c has the same effect as a lower price p or a lower catchability coefficient q, measuring the technological effectiveness of harvesting fish. Hence a higher price and technological effectiveness are detrimental to the ecological system but conducive to economic rents.

Also part b of Result 6 conforms to intuition. A high growth rate encourages fishing and is associated with an economic advantage. For this model, the stock remains unaffected as a higher growth rate is balanced by higher fishing efforts.

Part a and b of Result 6 are in line with Pintassilgo et al. (2008) where these results are proved analytically, though in a simpler model that covers only the high seas. It will be interesting to see how both parameters affect the prospectives for full or partial cooperation, analyzed in section 4.

4. Results: First Stage of Coalition Formation

In the previous section, we have analyzed equilibrium fishing efforts, stocks and payoffs in the Nash equilibrium, social optimum and coalitional Nash equilibrium with $1 < n < N$ coalition members. As pointed out, in terms of coalition formation, this corresponds to three possible coalition structures. A coalition structure with only singletons (Nash equilibrium), also called no cooperation, a coalition structure with one coalition comprising all players, the grand coalition, also called full cooperation, and in our context of $N=3$, a coalition structure with a two-player coalition and one singleton, also called partial cooperation. As noted before, the all-singletons coalition structure is stable by definition. Hence, we are interested whether full or partial cooperation could be a second equilibrium.

We will first assume equal zone sizes ($\alpha = 0.25$) as done up to now (Result 7). Then we investigate the effect of a variation of α on the stability of coalitions (Results 8 and 9).

Result 7: Stability of Full and Partial Cooperation: Zones of Equal Size

Consider a coalition C with n players, $1 < n \leq N$. Suppose one player leaves the coalition such that $n' = n-1$ and $C \setminus \{ i \}$ forms.

a) The gain from leaving is always strictly positive and increases with the diffusion parameter d. That is, for all C and all $i \in C$: $G_i := \Pi_i^*(C \setminus \{ i \}) - \Pi_i^*(C) > 0$ and $\frac{\partial G_i}{\partial d} > 0$.

b) The loss to the remaining coalition members is always positive and increases with d. That is, for all C and all $j \in C$: $L_j := \Pi_{j \neq i}^*(C) - \Pi_{j \neq i}^*(C \setminus \{ i \}) > 0$ and $\frac{\partial L_j}{\partial d} > 0$.

c) G_i and L_j decrease with the cost parameter c and increase with the growth parameter r.

(Simulation Runs A, B and C.)

Result 7, a) is quite depressing: irrespective of the value of the diffusion, cost and growth parameter neither the grand coalition nor the two-player coalition are internally stable (and hence stable), i.e. the gain from deviating is always positive. Moreover, whenever cooperation would be most desirable from a global point of view, i.e. the difference between the total payoff from either full or partial cooperation and no cooperation is particularly pronounced (compare with Result 5, in particular part c), because diffusion rates are high, also the incentive to deviate is high. This implies that the lower the degree of technical exclusiveness, the more pronounced will be the incentive to free-ride. The mirror image of these conclusions shows up on the side of the members that remain in the coalition after another member has left (Result 7b). The loss due to free-riding increases with diffusion d. This is the reversed statement that the gains from cooperation increase with the degree of technical spillovers.

Result 7 c) indicates that decreasing production costs, e.g. due to technological change, would worsen the situation even more. Moreover, the free-rider incentives are more pronounced for high growth rates as this encourages overfishing.

In the following, we will depart from the assumption that all zones are of equal size and allow for different values of α (parameter set D). This means we vary the degree of socially constructed exclusiveness, i.e. the spatial allocation of property rights. We anticipate that for a lower share of the common property (lower α), some form of cooperation might be stable.

Result 8: Stability of Full Cooperation: Zones of Unequal Size

The incentive to deviate from the grand coalition is always positive if $d > 0$ and/or $\alpha > 0$, i.e. the grand coalition is never stable, except for $d = 0$ and $\alpha = 0$. In this case, however, there is no gain from cooperation.

(Simulation Run D.)

It is evident that $d = 0$ and $\alpha = 0$ is a special case: there is no common property, and there is no diffusion between EEZs. Accordingly, due to the lack of interdependency, there is no externality and hence social optimum, Nash equilibrium and coalitional Nash equilibrium fishing efforts coincide. Consequently, the incentive to deviate is zero. Since the grand coalition is never stable when departing from this special case, we investigate in the next step whether partial cooperation can be stable.

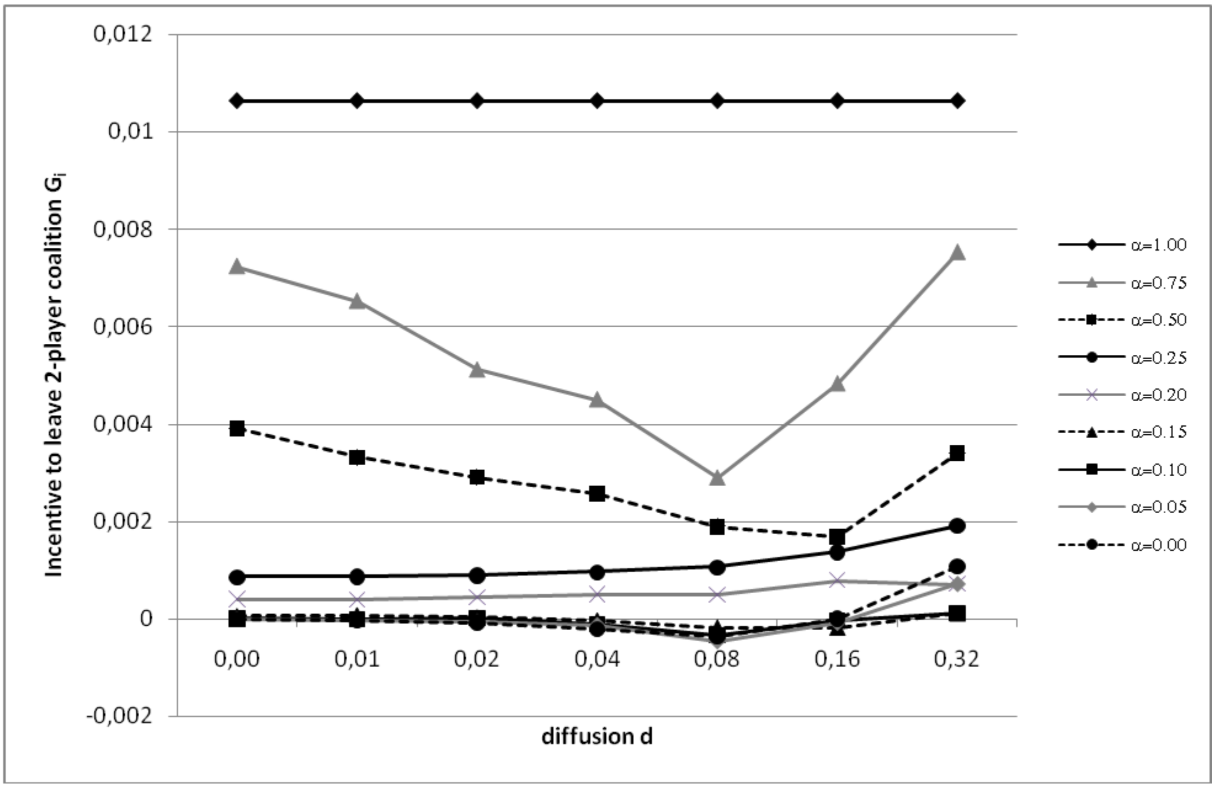
Result 9: Stability of Partial Cooperation: Zones of Unequal Size

The incentive to leave the two-player coalition is not always positive, i.e. there is a range of values of d and α for which partial cooperation is stable. Whenever $d \geq 0.32$ or $\alpha \geq 0.2$ holds, internal stability fails for the two-player coalition.

(Simulation Run D.)

In order to understand better the underlying driving forces of Result 9, Figure 3 has a closer look at the stability of a two-player coalition for various values of the parameters d and α. The fact that the grand coalition is never internally stable according to Result 8, allows us to conclude that a two-player coalition is always externally stable. Hence, Figure 3 focuses on internal stability, i.e. the incentive to leave a two-player coalition. Internal stability holds for all parameter combinations for which this incentive is non-positive.

Figure 3: Incentive to Leave a Two-player Coalition

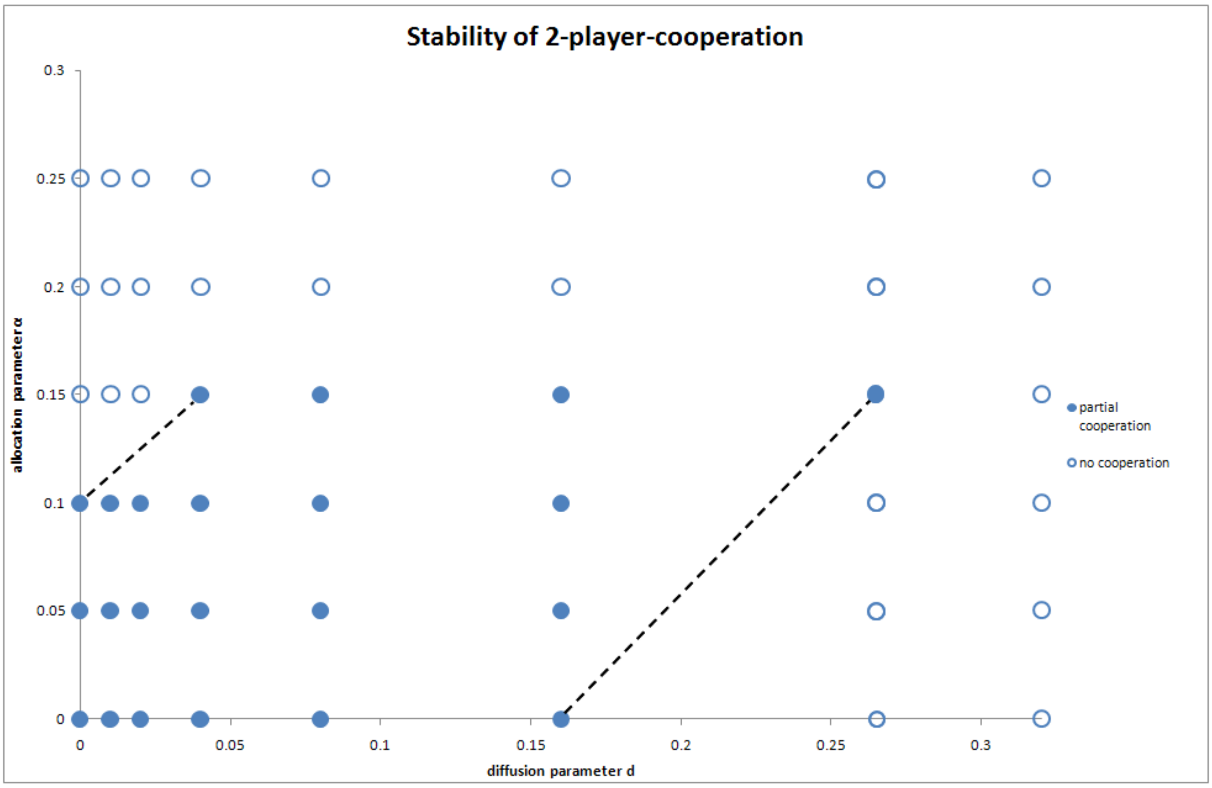


There are two countervailing effects. The first effect is related to the spatial allocation of property rights, the socially constructed exclusiveness, captured by the parameter α. On the one hand, the larger α, the larger the portion of the common property resource, the larger is the degree of externality and hence the larger are the gains from cooperation. On the other hand, with increasing α, also the incentive to deviate sharply increases. Overall, a two-player coalition will only be internally stable, if α is sufficiently small.

The second effect is related to the diffusion parameter d, the degree of technical exclusiveness. On the one hand, the larger d, the larger is the degree of externality and hence the gains from cooperation. On the other hand, the larger d, the larger are the incentives to free-ride. Taken together, a two-player coalition will only be internally stable, if d is sufficiently small.

Both effects are also illustrated in Figure 4 which summarizes the information from Figure 3 in a reduced form.

Fig. 4: Stability of a Two-player Coalition.



It is evident that partial cooperation is only stable if a sufficiently large share of the resource is privately owned (small values of α). Moreover, depending on the value of α, some modest diffusion can be conducive to stability. The lower and upper boundaries of d increase with α which leads to a corridor of stability indicated by the dashed lines in Figure 4.. However, above $\alpha = 0.15$, this corridor is empty.

5. Conclusion

This paper presented an integrated model for international fishery, in which a certain share of the natural resource, namely the high seas, belongs to the public domain and is therefore subject to exploitation by all countries, whereas the remaining domain, the EEZs, is privately owned. We extended the classical Gordon-Schaefer bioeconomic model and introduced dispersal between the various zones. Strategic behavior of the parties engaged in fishing is described by a two-stage coalition formation game. In the first stage, countries decide whether to join an RFMO or to stay outside. In the second stage, countries choose their fishing efforts. Having identified dispersal and the allocation of property rights as the driving forces, we investigated how any change in these parameters affects the outcome. A sensitivity analysis with respect to the cost and growth parameters proved the robustness of the results.

Our analysis showed that, except for full cooperation, the strength of dispersal between the various fishing grounds does indeed matter, both with respect to equilibrium fishing efforts, stocks and payoffs and regarding the prospect of stable coalitions. Hence, the spatial dimension in international fisheries should not be neglected but requires an integrated model that accounts for fishing activities in exclusive economic zones and high seas simultaneously.

In detail, for a given coalition structure other than the grand coalition, diffusion proves to have a detrimental influence in the sense that total fishing efforts increase whereas total fish stocks and total payoffs decrease as migration intensifies. In short, the technical non-exclusiveness generated by diffusion creates a negative externality coming along with fishing activities. However, when it comes to coalition stability, our results indicate that a modest degree of diffusion can be conducive to cooperation, given that the degree of socially constructed non-exclusiveness is not too high. In other words, a certain share of the resource has to be private property so that the private benefits (in the EEZs) from fishing reductions (in the high seas) are sufficient to have an impact on the strategic behavior of countries.

With regard to the grand coalition, which would achieve the social optimum, we obtain the common and depressing result that whenever full cooperation would be needed most from a global point of view, it is most unlikely to be achieved due to strong free-rider incentives.

Moreover, the grand coalition is never stable except for the trivial case in which it is equivalent to non-cooperative Nash behavior because of missing interdependency.

As could be expected, in the case of low fishing costs or, correspondingly, a high efficiency of the industry exploiting the resource, the situation is worsening in the sense that total fishing efforts are higher and equilibrium stocks are lower. This would call for cooperation, but it turns out that the incentives to deviate from a coalition are even more pronounced in the case of low costs. As a more counterintuitive result, we obtain that a higher growth or regeneration rate reduces the chances of cooperation, although total payoffs are higher.

There remain several issues for further research. First, Pintassilgo et al. (2008) have shown that asymmetry (with respect to the cost parameter) can be conducive to cooperation. Therefore it seems promising to relax the restriction of identical countries. Furthermore, the scope of cooperation represents an interesting issue, since the legal framework only calls for compatibility of domestic and high seas measures in some cases, but not in all. We expect that restricted cooperation, which does not affect the national jurisdiction of a country, would be easier to achieve. Finally, we expect that assigning an existence value to the fish stocks themselves would change the results significantly, creating an additional incentive to cooperate.

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APPENDIX: SOLVING PROCEDURE

According to the sequence of backward induction, an analytical solution would require that, in the first place, equilibrium fishing efforts in the second stage are determined for every possible coalition structure. This, in turn, implies that the system of equations (8) has to be solved in order to obtain steady-state stocks as functions of fishing efforts. Subsequently, these functions have to be inserted into the payoff functions (12) yielding payoffs as functions of efforts. The equilibrium in the second stage is then derived from the optimization procedure described in (13) and (14) which gives rise to the following first order conditions:

$$\frac{\partial \Pi_j}{\partial E_{EEZ,j}} = 0 \quad \forall j \notin C \tag{15}$$

$$\frac{\partial \Pi_j}{\partial E_{HS,j}} = 0 \quad \forall j \notin C \tag{16}$$

$$\frac{\partial \Pi_C}{\partial E_{EEZ,i}} = 0 \quad \forall i \in C \tag{17}$$

$$\frac{\partial \Pi_C}{\partial E_{HS,i}} = 0 \quad \forall i \in C \tag{18}$$

This system of $2N$ presumably nonlinear equations then has to be solved to determine the equilibrium fishing efforts. However, already the first step of this procedure cannot be solved analytically, i.e. it is not possible to derive analytical solutions for the steady-state stocks, let alone equations (15)-(18). Therefore, we have to rely on numerical simulations using an iterative approximation procedure which works as follows.

First, a set of parameter values is chosen. Then, the game is discretized, i.e. for certain values of the efforts the resulting stocks are computed solving the system of equations (8) numerically. The stocks are then inserted into the payoff functions in order to obtain the payoffs corresponding to the chosen effort combination. This procedure is repeated for a great number of different effort combinations, creating a $2N$-dimensional payoff matrix or, more precisely, a payoff tensor (N players, each one having 2 strategic variables).

Let z denote the number of discrete values that every strategic variable can take. Then the payoff matrix contains z^{2N} entries, each one representing the payoff vector for a given effort combination. This payoff matrix is then searched through for the social optimum, the Nash equilibrium and the coalitional Nash equilibrium, just like in a simple 2x2 normal-form game. The corresponding effort values will only be approximations since, in general, the exact values will not lie on the intersections of the discrete strategy space grid. Therefore, the procedure is repeated iteratively, i.e. the grid is refined in the respective region of interest until the step size or resolution of the grid is smaller than 1 % of the absolute values of equilibrium fishing efforts.