

Economics Department Discussion Papers Series

ISSN 1473 – 3307

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Michael Finus, Raoul Schneider and Pedro Pintassilgo

Paper number 11/03

**THE INCENTIVE STRUCTURE OF IMPURE PUBLIC GOOD PROVISION –
THE CASE OF INTERNATIONAL FISHERIES**

Michael Finus, University of Exeter Business School, Exeter, UK

Raoul Schneider*, Department of Economics, Ulm University, Ulm, Germany

Pedro Pintassilgo, Faculty of Economics, University of Algarve, Faro, Portugal

*Corresponding author

Department of Economics
Ulm University
Helmholtzstr. 18
89069 Ulm
GERMANY

Phone: +49(0)731-5023546

Fax: +49(0)731-5023737

E-mail: Raoul.Schneider@uni-ulm.de

THE INCENTIVE STRUCTURE OF IMPURE PUBLIC GOOD PROVISION –

THE CASE OF INTERNATIONAL FISHERIES

Abstract

We argue that international fisheries are a prime example to study the impact of multiple characteristics on the incentive structure of impure public good provision. The degree of technical excludability is related to the pattern of fish migration, the degree of socially constructed excludability is captured by the design of international law and the degree of rivalry is reflected by the growth rate of the resource. We construct a bioeconomic model, including the high seas and exclusive economic zones in order to study the incentives to form stable fully or partially cooperative agreements. We show that the spatial allocation of property rights is crucial for the success of cooperation as long as technical excludability is sufficiently high. Moreover, we show how economic and ecological factors influence the success of cooperation.

JEL References: Q34, C72, H87, F53

Keywords: pure and impure public goods, technical and socially constructed non-excludability, property rights, coalition formation, free-riding, bioeconomic model, shared fish stocks, regional fisheries management organizations.

1. Introduction

There are many cases of international and global public goods for which the decision in one country has consequences for other countries and which are not internalized via markets. Reducing global warming and the thinning of the ozone layer are examples in case. As Sandler [47], p. 221, points out: “Technology continues to draw the nations of the world closer together and, in doing so, has created novel forms of public goods and bads that have diminished somewhat the relevancy of economic decisions at the nation-state level.” The stabilization of financial markets, the fighting of contagious diseases and the efforts of non-proliferation of weapons of mass destruction have gained importance through globalization and the advancement of technologies.

A central aspect in the theory of public goods is to understand the incentive structure that typically leads to the underprovision of public goods as well as the possibilities of mitigation. The incentive structure can be broadly related to the *properties of public goods* which are usually associated with two distinguishing features: non-excludability and non-rivalry, which can be traced back to the seminal work of Samuelson [44] and Musgrave [38]. By varying the degree of excludability and rivalry, various mixed forms of impure public goods emerge as illustrated in Table I (e.g. [10],[11],[27]).

In terms of *excludability*, the expectation is that the higher the degree of excludability, the closer is the non-cooperative equilibrium to the optimum, but also the smaller are the gains from cooperation.¹ Kaul and Mendoza [27] emphasize that the perception of what is public and what is private has changed significantly over time. They distinguish between the intrinsic properties of a good, to which for instance the so-called *technical excludability* belongs,

¹ The importance of private benefits has been emphasized for instance by Cornes and Sandler [10], p. 595: “... the jointly produced private output can serve a privatising role, not unlike the establishment of property rights”; or by Sandler and Sargent [50], p. 153: “private benefits act to raise the gains from unilateral cooperation [...] this serves to foster cooperation.”

and the properties assigned by society to them, to which for instance so-called *socially constructed excludability* belongs. Whereas the degree of technical excludability can be regarded as given, at least in the short and mid-term (e.g. through physical exclusion devices, such as barbed wire fences and electronic sensing devices in the fight against international terrorism), socially constructed excludability is determined by the establishment and enforcement of property rights.

In terms of *rivalry*, the expectations appear to be less clear-cut. On the one hand, Sandler and Arce [49] convincingly show the benefit-cost duality of pure public goods and common pool resources. In the public good game, the costs are private and the benefits from provision are public. In the commons game, the benefits are private and the costs from exploitation are public. On the other hand, despite their formal proof of equivalence, the authors conclude informally that there is a difference: in politics it would be easier to establish joint action in public good games than joint inaction (giving up rights) in commons games.

[Table I about here]

To the best of our knowledge, there is no model which: 1) simultaneously captures all the above-mentioned properties with varying degrees (i.e. different degrees of social constructed and technical excludability as well as rivalry), 2) systematically analyzes their effect on the incentives of public good provision, and 3) tests the possibility to establish full or partial cooperation in a non-cooperative model of coalition formation.²

² A more comprehensive and systematic analysis is available on the relation between the aggregation technology (e.g. weakest-link, weaker link, best-shot and better shot technology) and the incentive of public good provision. We do not pursue this interesting aspect here; see for instance (e.g. [1],[2],[47],[50]).

In terms of the first aspect, we view international fisheries as one of the few and particularly interesting examples where all properties are simultaneously present.³ The degree of technical and socially constructed excludability can be parameterized along the entire horizontal spectrum in Table I (parameter d and α in our model, respectively; see section 3 for details). The pattern and intensity of the migration of fish stocks determines the degree of technical non-excludability. The design of international law (e.g. the UN Convention on the Law of the Sea in 1982) through the establishment of so-called Exclusive Economic Zones (EEZs) determines the spatial allocation of property rights and hence the degree of socially constructed excludability. Also the degree of rivalry can be parameterized along the entire vertical spectrum in Table I through the growth rate of the fish stock (parameter r in our model; see section 3 for details). This allows to study the duality of public goods versus commons in a systematic way.

In terms of the second aspect, strategies (i.e. fishing efforts) are continuous in our model and equilibrium strategies depend on the model parameters. Therefore, the level of underprovision of the impure public good (i.e. “preservation of fish stocks”) can be measured as the difference between fully cooperative, partially cooperative and non-cooperative equilibrium, physically in terms of stock levels and monetarily in terms of payoffs or rents.

³ The sharing of water resources has similar features. Socially constructed excludability can be established through property rights and technical excludability may vary through the diversion of rivers and the erection of dams. However, many other examples feature only some properties. For instance, the acid rain game allows capturing various degrees of technical excludability, but since national boundaries are given, the degree of socially constructed excludability is not an issue. The same applies to the classical example of a pure public good game, climate change mitigation, even if we recognize the privatizing effects of ancillary or co-benefits of improved local air quality from climate mitigation as analyzed for instance in [34]. In the case of the exploration of the natural resources in the Antarctic (like, e.g. oil, gas and minerals), after property rights were properly defined and enforced, excludability would be perfect as technical excludability can be regarded as perfect. In terms of rivalry all examples are only located at one extreme of the spectrum: acid rain and climate change exhibit no rivalry at all whereas for non-renewable resources rivalry is perfect.

Differences can be related to the properties of the public good and important economic and biological parameters that determine the production process.

In terms of the third aspect, in the tradition of the literature on international environmental agreements (IEAs)⁴ and the literature on international fishery agreements (IFAs)⁵, we study the formation of self-enforcing agreements as a means to mitigate free-riding with a non-cooperative coalition model.⁶ However, the IEA-literature has almost exclusively restricted attention to a global emission game⁷ (i.e. pure public good) and the IFA-literature⁸ considered a renewable common resource with only one jurisdiction. In contrast, we allow for the possibility that parts of the ocean may be privatized through the establishment of EEZs. Among EEZs and the high seas there may be links through the migration of fish. This is modelled with the classical Gordon-Schaefer model [21] which is extended to account for migration between different fishing grounds as considered for instance in [45] and [46].

The paper proceeds as follows. In section 2, we provide a brief background on the historical development of the management of international fisheries and the establishment of cooperative agreements. In section 3, we introduce the bioeconomic model including the two-stage coalition formation model. According to the sequence of backward induction, we first discuss

⁴ The literature on IEAs goes back to [4] and [8] and has grown immensely in recent years. For surveys see for instance [5] and [18].

⁵ Stability of fishery agreements has been modelled as cooperative (e.g. [28],[31]) or non-cooperative coalition games (e.g. [30],[42],[43]), but also as a dynamic fishery game with enforcement through punishment (e.g. [22],[52]).

⁶ Possible mitigation options discussed in the literature on public goods are for instance correlated equilibria in chicken games (e.g. [2]), evolutionary stable strategies through “leading by example” (e.g. [1]), non-Nash behaviour in conjectural variation equilibria (e.g. [9]). Coalitions have only been considered from a cooperative game theory perspective (e.g. [3],[48]); but there the focus is not on enforcement but on sharing the gains from cooperation in the grand coalition.

⁷ Exceptions are for instance [33] and [19] in the context of a repeated acid rain game, though they only focus on the stability of the grand coalition and do not exploit the relation between transportation coefficients and stability.

⁸ Already Crutchfield [13], p. 216, based his call for international cooperation on the observation that migration of fish poses a natural limit to the privatization of fishery resources: “[...] the fish themselves seem indisposed to accept such [privatizing] solutions.”

results of the second stage (section 4), then of the first stage (section 5) and finally pull results of both stages together in section 6, which sums up our main findings, discusses their policy implications and points to future research issues.

2. Historical Background on International Fishery Management

The Food and Agriculture Organization of the United Nations (FAO) estimates that harvests from shared fish stocks⁹ account for as much as one third of global marine capture fishery harvests ([16],[37]). These stocks are estimated to be particularly vulnerable and are reported to be heavily overexploited or even depleted in [35]. For a long time, concern mainly focused on the preservation of coastal fishing grounds. Some governments started to declare unilaterally 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 harmonized and legalized the various unilateral declarations in assigning the right to coastal states to establish EEZs, comprising 200 nautical miles. After some initial success, it became clear that further action was required as the significance of high seas fisheries had been underestimated. In particular technological progress, such as the introduction of fish carriers and vessels with on board fish processing equipment, had made the high seas resources more accessible. Increasing awareness of overfishing led to the 1995 UN Fish Stocks Agreement. Under this agreement, shared fish stocks are to be managed, on a region by region basis, by Regional Fisheries Management Organizations (RFMOs). There are currently 17 RFMOs in force as for example the Northwest Atlantic Fisheries Organization (NAFO) and the North East Atlantic Fisheries Commission (NEAFC).¹⁰ As participation in RFMOs is voluntary, cooperative efforts have frequently been undermined by fishing activities of non-members. While there is general consensus that

⁹ With shared fish stocks we summarize three categories of the FAO classification: *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 and *straddling stocks* also cover both EEZs and the high seas but are more stationary.

¹⁰ For an overview see for instance [37] and [17].

unregulated fishing is morally reprehensible, it has not, in the past, been entirely clear what members of an RFMO can do to suppress it. However, also monitoring and enforcement among RFMO members has not been a trivial task.¹¹

3. Model

3.1 Preliminaries

Our model aims at capturing the impact of different degrees of socially constructed and technical excludability as well as the degree of rivalry on the exploitation of a common property resource. This is done in a systematic, though stylized way for 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 k is called the carrying capacity of the biological system, which we interpret as the geographical size of the system as in [41]. In our context, the resource is the fish stock and the system is the ocean. Parts of the system may have been privatized through the establishment of exclusive economic zones. Hence, there are two types of geographical zones: the high seas, abbreviated HS , the common property where all nations can fish, and the exclusive economic zones, abbreviated EEZ_i , the private properties with exclusive fishing rights of coastal state i . Denoting the entire size of the system by k_{tot} , the share of the resource that is subject to open access by α , we can define:

$$k_{HS} = \alpha k_{tot} \text{ and } k_{EEZ} = \frac{1-\alpha}{N} k_{tot} . \quad (1)$$

¹¹ Reports that seriously and consistently measure the effectiveness of RFMOs are scarce. Some evidence is gathered for instance in [23] and [32]. As Willock and Lack [53], p. 32, write: “There appears to be some reluctance to, or at least nervousness about, establishing a standard set of performance indicators against which RFMOs might be held accountable and their performance compared.” From completed self-assessment reports (e.g. [39],[24],[25]) a rather pessimistic picture emerges.

Henceforth, we call α the allocation parameter for short, which measures the degree of socially constructed excludability in our model (see Table I). In our context, players are sovereign countries engaging in fishing, i.e. coastal states, with access to their own EEZ and the high seas. We abstract from the fact that EEZs could be of different size and that so-called distant water fishing nations without EEZ engage in fishing.

The dynamics of the fish stock are captured by our biological model which is sequentially developed in section 3.2. Subsection 3.2.1 introduces the classical Gordon-Schaefer model, subsection 3.2.2 extends this model to account for the spatial allocation of property rights and in subsection 3.2.3 we develop the model further to capture migration of fish between different zones. The economic model is laid out in section 3.3. It captures the strategic behavior of nations under various assumptions about the degree of cooperation; it also includes the definition of stable cooperative arrangements. Since the biological and economic model are linked, we call it bioeconomic model. How this model is solved is described in section 3.4.

3.2 Biological Model

3.2.1 Classical Gordon-Schaefer Model

The biological model is based on the classical Gordon-Schaefer model ([21] and [51]) which has been frequently used to analyze the steady-state of an exploited (fish) resource. The following three equations describe the relation between the fish stock X , growth G and total harvest H due to individual fishing efforts E_i :

$$\frac{dX}{dt} = G(X) - H(X) \quad (2)$$

$$G(X) = rX \left(1 - \frac{X}{k} \right) \quad (3)$$

$$H(X) = q \sum_{i=1}^N E_i \frac{X}{k} \quad (4)$$

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 ($X \ll k$), 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. A central parameter in the growth function is the growth rate r , which is a measure for the (re-)productivity of the resource, and thus measures the degree of rivalry in our model (see Table I). The harvest function $H(X)$ indicates that the total harvest increases with the catchability coefficient and the stock density X/k (both facilitating harvesting) as well as the total fishing effort $\sum_{i=1}^N E_i$. The fishing effort can be seen as a physical measure of the inputs devoted to harvesting, such as days spent at sea. The catchability coefficient q reflects the efficacy of the current fishing technology.

In the following, we will focus on the steady-state given by $dX/dt = 0$, leaving aside transition phenomena. Substituting equations (3) and (4) into (2), the steady-state stock is given by:

$$X^* = k - \frac{q}{r} \sum_{i=1}^N E_i \quad (5)$$

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

3.2.2 Spatial Allocation of Property Rights: Socially Constructed Excludability

In this subsection, 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 remaining area, which comprises privately owned EEZs. As a consequence, we now have to distinguish between the stocks X_i , $i = 1, \dots, N$, in the EEZs and the stock X_{HS} in the high seas. Using the definitions in (1), the extension of equations (2)-(4) is straightforward:

$$\frac{dX_{HS}}{dt} = G_{HS}(X_{HS}) - H_{HS}(X_{HS}) \quad (2a)$$

$$\frac{dX_i}{dt} = G_i(X_i) - H_{EEZ,i}(X_i), \quad i = 1, \dots, N \quad (2b)$$

$$G_{HS}(X_{HS}) = rX_{HS} \left(1 - \frac{X_{HS}}{k_{HS}} \right) \quad (3a)$$

$$G_i(X_i) = rX_i \left(1 - \frac{X_i}{k_{EEZ}} \right), \quad i = 1, \dots, N \quad (3b)$$

$$H_{HS}(X_{HS}) = q \sum_{i=1}^N E_{HS,i} \frac{X_{HS}}{k_{HS}} \quad (4a)$$

$$H_{EEZ,i}(X_i) = qE_{EEZ,i} \frac{X_i}{k_{EEZ}}, \quad i = 1, \dots, N \quad (4b)$$

Stock developments over time are given by equations (2a) and (2b) for the high seas and the EEZs, respectively. Growth in the respective zones is described by equations (3a) and (3b) whereas equations (4a) and (4b) restate the harvest function. Note that equation (4b) accounts

for the fact that in each EEZ_i only country i is allowed to fish. Using vector notation, $\mathbf{X} = (X_1, \dots, X_N, X_{HS})$, $\mathbf{G} = (G_1, \dots, G_N, G_{HS})$ and $\mathbf{H} = (H_{EEZ,1}, \dots, H_{EEZ,N}, H_{HS})$, the steady-state condition for all stocks can be described by a single equation:

$$\frac{d\mathbf{X}}{dt} = \mathbf{G} - \mathbf{H} = 0 \quad (6)$$

This represents a system of $N + 1$ independent equations, i.e. stocks in different zones are not linked to each other. This assumption will be relaxed for the extension we consider next.

3.2.3 Migration Pattern: Technical Excludability

In this subsection, we take into account that zones might not be isolated due to spillovers related to the degree of technical excludability. In the case of fishery, this is called migration of fish, dispersal or diffusion and depends (linearly, in a first order approximation) on all stocks [45]. In order to account for dispersal, the steady state condition (6) has to be modified:

$$\frac{d\mathbf{X}}{dt} = \mathbf{G} - \mathbf{H} + D\mathbf{X} = 0 \quad (7)$$

The dispersal matrix $D = (d_{ij})$ contains all 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. In order to analyze the dispersal pattern in a simple 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 fisheries.¹²

[Figure 1 about here]

A paradigmatic example is the so-called “Donut Hole”. This area in the Bering Sea has the status of the high seas surrounded 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 other reasons) the United States to agree to a multilateral convention to protect the Bering Sea from the over-exploitation of fish as argued in [15]. The example stresses that the interconnection of EEZs and high seas crucially determines the strategic interplay between players.

With respect to the strength of interaction, we assume that dispersal is driven by differences in stock densities (e.g. [46]). 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 reasoning behind this assumption is that fish migrate from zone i to zone j if the competition for food and space in zone j is less fierce. Contrary to most articles capturing migration (e.g. [45],[46]), we are interested in a size dependent diffusion process which relates to areas of different size, i.e. different carrying capacities, as suggested by [29].

¹² Other possible arrangements as described in [45] include sink-source models which model dispersal as a unidirectional flow from a source to a sink and the fully integrated system in which all zones are directly connected to each other. The sink-source model, though it is relevant in the context of some specific fish species, would create some asymmetry which we try to avoid in this paper for analytical tractability. In contrast, the fully integrated system would preserve symmetry and might seem even more general at first sight. However, in the case of more than three players and hence $N + I > 4$ zones, it is impossible to arrange all zones such that every pair of zones share a border (see [20]). For the case of three players (to which we eventually have to revert in our analysis; see section 3.4), our circular arrangement is identical to the fully integrated system.

The following formal description of diffusion captures this idea. We specify the components of the vector $D\mathbf{X}$ (instead of the entries of the dispersal matrix, d_{ij}) because this directly defines how diffusion influences the temporal evolution of the stock in each zone as described by equation (7):

$$(D\mathbf{X})_i = d \left[k_{EEZ} \left(\frac{X_{i+1}}{k_{EEZ}} - \frac{X_i}{k_{EEZ}} \right) + k_{EEZ} \left(\frac{X_{i-1}}{k_{EEZ}} - \frac{X_i}{k_{EEZ}} \right) + \sqrt{k_{EEZ}k_{HS}} \left(\frac{X_{HS}}{k_{HS}} - \frac{X_i}{k_{EEZ}} \right) \right] \quad (8)$$

$$(D\mathbf{X})_{HS} = d \sqrt{k_{EEZ}k_{HS}} \sum_{i=1}^N \left(\frac{X_i}{k_{EEZ}} - \frac{X_{HS}}{k_{HS}} \right) \quad (9)$$

In equations (8) and (9) each summand accounts for one dispersal process between two adjacent zones. Dispersal takes place between each EEZ_i , $i \in \{1 \dots N\}$, and its neighbors EEZ_{i+1} , EEZ_{i-1} and the high seas.¹³ While each EEZ has three neighboring zones, namely two EEZs and the high seas, the high seas is connected to N EEZs as expressed by the sum in (9). The sign and intensity of diffusion is determined by differences in densities which is captured by the expressions in brackets. In order to include the size dependency of the process, each difference is multiplied by the square root of the carrying capacities of the two involved zones, similar as in [29]. The diffusion parameter d , which we assume for simplicity to be identical for all diffusion processes, is an indicator for the intensity of diffusion and thereby a measure for the degree of technical non-excludability (see, e.g. [26]).¹⁴

¹³ 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 .

¹⁴ The implication of the parameter d can be understood from considering a normalized example with carrying capacities $k = 1$. If the stocks in 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 $d\delta$. Note that the steady-state condition does not require diffusion to vanish but only to be balanced by growth and harvest in every zone.

3.3 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 private and public resource:

$$\Pi_i = pq \left(E_{EEZ,i} \frac{X_i}{k_{EEZ}} + E_{HS,i} \frac{X_{HS}}{k_{HS}} \right) - c(E_{EEZ,i} + E_{HS,i}) \quad (10)$$

where p is the fish price and c is the (constant) marginal cost of fishing effort, which is assumed to be identical for all players for simplicity.¹⁵ Each player i has to make two strategic choices: 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 that costs depend linearly on extraction efforts (e.g. [21],[45],[41]), though they are strictly convex when expressed in terms of harvests $H_{EEZ,i}$ and $H_{HS,i}$.

Cooperation among a group of players corresponds to the establishment of an 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. Moreover, states which decide against membership in an RFMO cannot be prevented from harvesting.

In order to capture these institutional features, we choose from the set of coalition formation games the single coalition open membership game due to d'Aspremont et al. [14] which has been frequently applied in the literature on IEAs (e.g. [7], [18] for overviews) but also in industrial economics (e.g. [6],[54] for surveys). This coalition game is a two-stage game.

¹⁵ 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. [6],[54] for an overview).

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 $K = \{C, \mathbf{1}_{(N-n)}\}$ where C is the set of n coalition members, $n \in \{0, 1, \dots, N\}$, and $\mathbf{1}_{(N-n)}$ 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 backward.

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, acting like one player, maximize the aggregate payoff of their coalition, $\Pi_C = \sum_{i \in C} \Pi_i$:¹⁶

$$\arg \max_{(E_{EEZ,j}, E_{HS,j})} \Pi_j(\mathbf{E}) \quad \forall j \notin C \quad (11)$$

$$\arg \max_{(\mathbf{E}_{EEZ,C}, \mathbf{E}_{HS,C})} \Pi_C(\mathbf{E}) \quad (12)$$

where $\mathbf{E} = (E_{EEZ,1}, \dots, E_{EEZ,N}, E_{HS,1}, \dots, E_{HS,N})$ denotes the vector of all fishing efforts whereas $\mathbf{E}_{EEZ,C} = (E_{EEZ,i})_{i \in C}$ and $\mathbf{E}_{HS,C} = (E_{HS,i})_{i \in C}$ denote the vectors of fishing efforts of the coalition members in the EEZs and in the high seas, respectively. The simultaneous maximization of (11) and (12) delivers the equilibrium fishing efforts $(E_{EEZ,j}^*, E_{HS,j}^*)$, $j \notin C$,

¹⁶ The assumption that members choose their fishing efforts cooperatively, both in the high seas and in their EEZs, is in line with FAO [16], p. 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”.

and $(\mathbf{E}_{EEZ,C}^*, \mathbf{E}_{HS,C}^*)$. We call this a coalitional Nash equilibrium in order to distinguish it from an ordinary 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, if coalition C comprises all players, $C = \{1, \dots, N\}$, the coalitional Nash equilibrium corresponds to the socially optimal fishing vector. Hence, the entire range from no cooperation, partial cooperation to full cooperation can be captured with this approach.

It is worthwhile to mention that the solution to (11) and (12) will be identical for every coalition $C \subseteq \{1, \dots, N\}$, 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 across players. In contrast, 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 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 $\mathbf{E}^*(C)$ derived from (11) and (12) together with the steady-state conditions of stocks in (7) have to be inserted into the payoff function (10) to determine individual payoffs $\Pi_{j \in C}^*(C)$ and the coalitional payoff $\Pi_C^*(C)$. Since we deal with symmetric players, we assume an equal sharing rule among n coalition members, i.e., $\Pi_{i \in C}^*(C) = \Pi_C^*(C) / n$.

Having determined equilibrium payoffs for every possible coalition structure in the second stage, we can now proceed to the first stage. 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. Moreover, the coalition structure of only singletons is stable by definition, which ensures existence of a stable coalition structure. This follows from the fact that this coalition structure can be supported by all players announcing not to be a member of the coalition, i.e. $C = \emptyset$, and hence a deviation by one player will make no difference.

When dealing with symmetric 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 (see [8]): if a coalition with n players is not internally stable, then coalition $n - 1$ is externally stable.

3.4 Solving Procedure

As mentioned above, the model is solved by backward induction. The most difficult part relates to the second stage in which optimal fishing efforts have to be determined for a given coalition structure. For this, the system of equations (7), which represents the steady-state condition, and the first-order conditions derived from (11) and (12) have to be solved simultaneously in order to obtain steady-state stocks and equilibrium fishing efforts for a given coalition structure. Due to the diffusion term, which links the steady-state stocks, we

face a highly nonlinear system of $3N + 1$ equations that cannot be solved analytically. Hence, we have to rely on numerical simulations.

It is evident that computing time and capacity requirements increase exponentially with the number of players. For this reason, we 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, this 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 coalitions 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 a non-member.

Simulations require the assumption of numerical values for the parameters of the model. Fortunately, a closer look at the system of equations reveals that results will only depend on few parameters. For the cost parameter c , the price p and the efficiency parameter q only the relation c/pq matters, which is known in the literature as the “inverse efficiency parameter” (see [36]). Hence, we normalize p and q to 1, and only vary c . Since prohibitive costs at which countries quit fishing are given by $c \geq 1$, irrespective of the scenario of cooperation, $c \in [0, 1]$. In our simulations, we set the base case value to $c = 0.5$ and conduct a sensitivity analysis for two other values: $c = 0.25$ and $c = 0.75$ (see Table II).

Results also depend on the growth rate r where we set the base value to $r = 0.5$ and also consider two other values in a sensitivity analysis: $r = 0.25$ and $r = 0.75$ (see Table II).¹⁷

As the total carrying capacity k_{tot} just represents a scaling factor it can be normalized to $k_{tot} = 4$ as there are four zones.¹⁸ The spatial allocation of property rights, as captured by the parameter α according to equation (1), is varied in the interval $\alpha \in [0, 1]$. Starting from a totally privatized resource ($\alpha = 0$), gradually increasing the degree of publicness in steps of $\Delta\alpha = 0.05$, we eventually end up in the case of a completely public resource ($\alpha = 1$). The variation also captures the case in which all zones are of equal size ($\alpha = 0.25$). Finally, we consider a wide range of sensible values for the diffusion parameter d with $d \in [0, d_{max} = 1.28]$ (see Table II).¹⁹

[Table II about here]

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 and the allocation parameter α , measuring the degree of technical and socially constructed excludability of the common property, respectively. In simulation run A, the values of the cost and growth parameter are set to their

¹⁷ Our base case values $c = 0.5$ and $r = 0.5$ are commonly assumed in the literature (e.g. [22],[52]). Note that a variation of the growth rate in the range $0.25 \leq r \leq 0.75$ (as e.g. considered in [40]) already has a significant impact on the outcome in terms of payoffs. For instance, in models with only a single zone (e.g. [41]), which correspond to $\alpha = 1$ in our model, aggregate payoffs in the Nash equilibrium at a growth rate $r = 2/3$ are already as high as in the social optimum at $r = 0.5$.

¹⁸ This is in line with the common normalization $k = 1$ in articles that deal with only a single zone (e.g. [41]). In our model, assuming no diffusion between zones with $k_{tot} = 4$ and setting $\alpha = 0.25$ results in four isolated zones with carrying capacities $k = 1$. See equation (1).

¹⁹ Strong diffusion makes the allocation of property rights, i.e. the value of α , irrelevant because all countries virtually exploit the same stock. Accordingly, all results converge towards the ‘only high seas’ limit ($\alpha = 1$) as d approaches infinity. Our choice of the upper bound $d_{max} = 1.28$ ensures sufficient convergence, as total efforts for $\alpha < 1$ and $d = 1.28$ differ less than 6% from the results for $\alpha = 1$.

base values, i.e. $c = 0.5$ and $r = 0.5$. In order to check the robustness of the results, a sensitivity analysis is conducted in simulation runs B and C, varying c while keeping r constant and vice versa. This also provides comparative static results with respect to c and r where the former may be viewed as an indicator of the economic attractiveness of fishing and the latter as an indicator of the degree of rivalry. All subsequent results are derived from all three simulation runs as summarized in Table II.

4. Results: Second Stage of Coalition Formation

In this section, we analyze how equilibrium fishing efforts, stocks and payoffs depend on the degree of cooperation and the crucial parameters of our model and how the various degrees of cooperation compare to each other. This will also provide helpful information for the interpretation of the incentive structure to form stable coalitions as analyzed in the first stage of coalition formation in section 5. 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 (no, partial and full cooperation).

Result 1: The Role of Diffusion and Allocation of Property Rights under Full Cooperation (Social Optimum)

The total fishing effort, total stock and total payoff are independent of the diffusion parameter d and the allocation parameter α where totals refer to aggregation over all players and zones.

In the social optimum, the distinction between high seas and EEZs does not matter for equilibrium strategies. Since in the social optimum externalities across all players are internalized, i.e. the social planner maximizes the aggregate payoff over all players and zones, diffusion does not matter either (cf. [12]). Hence, efforts, stocks and payoffs at the aggregate level depend neither on the diffusion parameter d nor on the allocation parameter α . Efforts are

distributed such that effort densities, i.e. the efforts per area $E_{EEZ,i} / k_{EEZ}$ and $E_{HS,tot} / k_{HS}$ are equal everywhere, irrespective of d and α . Accordingly, stock densities $X_{EEZ,i} / k_{EEZ}$ and X_{HS} / k_{HS} are the same in every zone and independent of d and α . In contrast, diffusion and the allocation of property rights matter under no and partial cooperation.

Result 2: The Role of Diffusion and Allocation of Property Rights under No Cooperation (Nash Equilibrium)

Individual and total fishing efforts increase with the diffusion parameter d and the allocation parameter α . Accordingly, the total stock in the entire fishing area decreases in d and α . The individual payoffs of players and the total payoff over all players decrease in d and α .

At the aggregate level, the higher the diffusion between zones, i.e. the lower the degree of technical excludability, the more will the fish stock be exploited (high fishing efforts), resulting in low stocks. This translates into low individual payoffs and a low total payoff. Similarly, a high value of α , i.e. a high degree of publicness (low socially constructed excludability), aggravates over-exploitation and leads to lower stocks and payoffs.

Whereas results at the aggregate level are clear-cut, a breakdown into efforts and stocks in the different zones would reveal the complexity of the underlying incentive structure. Since the equilibrium fish stock density 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 fishing in the high seas with fishing efforts increasing in the value of d . The mirror image is found in the EEZs which suffer from outgoing diffusion. The equilibrium reaction does not follow a simple pattern: 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 forces lead to some ambiguity in terms of equilibrium fishing efforts in the EEZ as a function of d which is not apparent from the aggregate values.²⁰

Viewed together, the results illustrate that there is an interesting and subtle incentive structure when players behave non-cooperatively if zones are linked through diffusion. This complex incentive structure carries over to the situation where some players behave cooperatively, but not all, as considered under partial cooperation.

Result 3: The Role of Diffusion and Allocation of Property Rights under Partial Cooperation

Consider a coalition with two players. Coalitional fishing efforts may increase or decrease in the diffusion parameter d , but they decrease in the allocation parameter α . Fishing efforts of outsiders increase in d and α . The total effort in the entire fishing area increases in d and α . Accordingly, the total stock in the entire fishing area decreases in d and α . The individual payoffs of signatories and the total payoff over all players decrease in d and α , though the outsider's payoff increases in d and α .

A general conclusion from Result 3 is that partial cooperation shares many features with no cooperation, quite different from those under full cooperation. 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 technical (i.e. high value of d) and socially constructed (i.e. high value of α) excludability has a detrimental effect on the total stock and total payoff. This is because the outsider, who is in the position of a free-rider, benefits from increased diffusion. Free-riding is particularly attractive the larger the area of the common property resource (high value of α). It is exactly then when, in equilibrium, the coalition chooses low fishing efforts to preserve the common pool resource. Only the optimal reaction

²⁰ Also in [26] it is recognized that a density-dependent diffusion process can create a destructive incentive to overexploit one's own fishing grounds in order to attract incoming diffusion.

of the coalition as a function of the diffusion parameter d is less clear-cut. On the one hand, high diffusion encourages exploitation of the high seas through the coalition; on the other hand, the inflow from the high seas comes from two EEZs belonging exclusively to its members.

The strategic interplay between players is also evident from the following results which compare individual equilibrium fishing efforts (Result 4 a), total equilibrium fishing efforts (Result 4 b), and total equilibrium stocks and payoffs (Result 5) for the three scenarios of cooperation.

Result 4: Individual and Total Fishing Efforts under Different Degrees of Cooperation

a) Let the individual total fishing efforts in all zones under full, no and partial cooperation be denoted by E_i^F , E_i^N , $E_{i \in C}^P$, and $E_{i \notin C}^P$, respectively, then

$$E_{i \notin C}^P \geq E_i^N \geq E_{i \in C}^P \geq E_i^F \text{ with strict inequalities whenever } d > 0 \text{ or } \alpha > 0.$$

b) Let the total fishing effort in the entire area under full, no and partial cooperation be denoted by E^F , E^N , and E^P , respectively, then $E^N \geq E^P \geq E^F$.

Compared to no cooperation, under partial cooperation the two-player coalition reduces its fishing efforts, 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 are increased compared to no cooperation. This “leakage effect” is due to the downward sloping reaction function of the coalition and of the outsider as fishing efforts are strategic substitutes as frequently observed in the context of public goods. However, despite this leakage effect, 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.

As will be analyzed in Section 5, the leakage effect is a driving force why self-enforcing cooperation proves difficult and will only be successful in a few cases. The next result compares fish stocks and payoffs at an aggregate level, resulting from fishing efforts under various degrees of cooperation. In order to measure the importance of cooperation as a function of our model parameters, we consider relative normalized differences related to the benchmark full cooperation.

Result 5: Total Stocks and Payoffs under Different Degrees of Cooperation

Let the total fish stock in the entire area and the total payoff under full, no and partial cooperation be denoted by X^F , X^N , and X^P , and Π^F , Π^N and Π^P , respectively, then

$$a) \quad X^F \geq X^P \geq X^N \text{ and } \frac{X^F - X^P}{X^F}, \frac{X^P - X^N}{X^F} \text{ and } \frac{X^F - X^N}{X^F} \text{ increase in } d \text{ and } \alpha;$$

$$b) \quad \Pi^F \geq \Pi^P \geq \Pi^N \text{ and } \frac{\Pi^F - \Pi^P}{\Pi^F}, \frac{\Pi^P - \Pi^N}{\Pi^F} \text{ and } \frac{\Pi^F - \Pi^N}{\Pi^F} \text{ increase in } d \text{ and } \alpha$$

with strict inequalities under a) and b) if either $d > 0$ or $\alpha > 0$.

Result 5 stresses that already partial cooperation can improve upon no cooperation, not only in terms of payoffs but also in terms of stock levels (cf. [42]). Moreover, the importance of cooperation, either partial or full, increases with the degree of interconnectedness between players. That is, the importance increases the lower the degree of technical and socially constructed excludability, i.e. the higher the diffusion parameter d and the higher the spatial allocation parameter α are. In other words, if d and/or α are high, we would hope that full cooperation or at least partial cooperation is stable which is tested in section 5. In contrast for low values, cooperation does not matter much anyway.

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 and our indicator of the degree of rivalry.

Result 6: The Role of the Cost Parameter c and the Growth Parameter r under Different Degrees of Cooperation

a) *Equilibrium efforts and payoffs decrease while stocks increase in the cost parameter c .*

This holds at the individual as well as at the aggregate level, irrespective of the diffusion parameter d , the allocation parameter α and the degree of cooperation. The differences

$$\frac{\Pi^F - \Pi^P}{\Pi^F}, \frac{\Pi^P - \Pi^N}{\Pi^F} \text{ and } \frac{\Pi^F - \Pi^N}{\Pi^F} \text{ as well as } \frac{X^F - X^P}{X^F}, \frac{X^P - X^N}{X^F} \text{ and } \frac{X^F - X^N}{X^F}$$

decrease in c whenever there is diffusion.

b) *Equilibrium efforts and payoffs increase in the growth parameter r . This holds at the individual as well as at the aggregate level, irrespective of the diffusion parameter d , the allocation parameter α and the degree of cooperation. Under full cooperation, equilibrium stocks are independent of r . Under no and partial cooperation the total stock increases in r*

whenever there is diffusion. The differences $\frac{\Pi^F - \Pi^P}{\Pi^F}$, $\frac{\Pi^P - \Pi^N}{\Pi^F}$ and $\frac{\Pi^F - \Pi^N}{\Pi^F}$ and the

differences $\frac{X^F - X^P}{X^F}$, $\frac{X^P - X^N}{X^F}$ and $\frac{X^F - X^N}{X^F}$ decrease in r whenever there is diffusion.

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 economic rents. Shrinking rents under all scenarios of cooperation with increasing costs also implies that the relative differences in

total payoffs between scenarios become smaller. Thus, the need for cooperation decreases in the cost parameter c .

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 efficiency of harvesting fish. Hence, a high price and technological efficiency are detrimental to the ecological system but conducive to economic rents and make cooperation particularly valuable from a normative point of view.

Also part b) of Result 6 is in line with intuition. A high growth rate encourages fishing and is associated with an economic advantage. However, higher fishing efforts do not necessarily imply lower stocks as the resource recovers more quickly with a high growth rate r . Only if diffusion is irrelevant, e.g. there is full cooperation or the entire fishing area is public ($\alpha = 1$), a higher growth rate is exactly balanced by higher fishing efforts and hence the equilibrium stock remains constant. However, if diffusion matters, e.g. there is no full cooperation, then the growth effect is stronger than the exploitation effect. Consequently, stocks and also payoffs increase with growth parameter r - our measure of rivalry and the need for cooperation decreases.

5. Results: First Stage of Coalition Formation

In this section we analyze stability of coalitions. As noted above in subsection 3.3, the all-singletons coalition structure, corresponding to no cooperation or the Nash equilibrium, is stable by definition. Hence, we are interested whether and under which conditions full or partial cooperation could be a second equilibrium. We start by considering the first-best solution of full cooperation, corresponding to the social optimum.

Result 7: Stability of Full Cooperation

The incentive to leave the grand coalition is always positive, except for $d=0$ and $\alpha=0$, irrespective of the values of c and r . If $d=0$ and $\alpha=0$, however, there is no gain from cooperation. The incentive to leave increases in d and α .

Result 7 is discouraging. Not only because full cooperation is never stable but also because the free-rider incentive is particularly pronounced under those conditions when it would matter most. This follows immediately from Result 5 which states that cooperation would be most desirable in the case of a strong externality as expressed by a high diffusion coefficient d and a large share of the public domain, corresponding to a high value of α . 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. Due to the lack of interdependency, there is no externality and hence full, no and partial cooperative fishing efforts coincide. Consequently, the incentive to deviate is zero but there is also no gain from cooperation. In a next step, we investigate whether partial cooperation can be stable.

Result 8: Stability of Partial Cooperation

The incentive to leave the two-player coalition is positive if either d or α are sufficiently large. However, for sufficiently small values of d and α , there is a range of parameter values for which partial cooperation is stable. This range increases in the cost parameter c and the growth parameter r .

In order to understand better the underlying driving forces of Result 8, Figure 2 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 7, allows us to conclude that a two-player coalition is always externally stable. Hence, Figure 2a focuses on

internal stability. Internal stability holds for all parameter combinations for which the incentive to leave a two player coalition is non-positive.

[Figure 2, a and b about here]

There are two countervailing effects. On the one hand, the larger α (d), the lower the degree of socially constructed (technical) excludability, the larger would be the gains from cooperation. On the other hand, with increasing α (d), also the incentive to deviate sharply increases, as already observed for the grand coalition in Result 7. Overall, a two-player coalition will only be internally stable, if α and d are sufficiently small.

A closer analysis of intermediate values illustrated in Figure 2b reveals that cooperation fails whenever $\alpha \geq 0.02$ or $d \geq 0.32$ for the base values of the cost parameter ($c = 0.5$) and the growth parameter ($r = 0.5$). The boundary value for d increases in c and r . Higher production costs discourage fishing (see Result 6a), and therefore lower the free-riding incentive and increase the upper bound of d for which partial cooperation is stable. Higher growth rates have a positive effect on stock levels (see Result 6b), and therefore lower free-riding incentives and hence also push the upper bound of d up for which partial cooperation is stable. Thus, the lower the degree of rivalry, the higher the likelihood of a stable coalition. However, even for high values of c and r , the range of stability remains rather small. Raising both base values of c and r from 0.5 to the maximum value 0.75 considered in our simulations, cooperation fails whenever $\alpha \geq 0.02$ and $d \geq 0.72$, corresponding to the larger triangle in Figure 2b.

6. Overall Results and Conclusions

In this section, we discuss our results by pulling the two stages of coalition formation together and relate them to a wider context.

Partial and full cooperation would make a big difference compared to no cooperation whenever the public domain of the resource is larger (large values of α) and the migration of fish stocks is large (high values of d) (Result 5). However, exactly under these conditions not even partial cooperation is stable (Result 8), let alone full cooperation (Result 7). Given this paradox of cooperation, one may derive some comfort from Results 2 and 3 which show that payoffs and stocks under no and partial cooperation decrease in α and d . Hence from a normative point of view, one would hope for small values of α and d as this has a positive effect on payoffs and stocks and increases the chances of at least partial cooperation.

The performance of some international fishery agreements seems to be in line with our model predictions. The agreement on the aforementioned “Donut Hole” appears to be stable and successful since the moratorium is respected by and large. It relates to a relatively small area of high seas (about 8 % of the entire Bering Sea) and regulates a species (Alaska Pollock) that does not belong to the list of highly migratory stocks. In contrast, the poor performance of most tuna-related RFMOs, such as the International Commission for the Conservation of Atlantic Tunas (ICCAT), represents a good example of failing cooperation (e.g. [24],[25]). It is in line with our results that failure occurs in the context of highly migratory species (which most tuna species are) and fishing areas that comprise a large portion of the high seas.

Though the degree of technical excludability is given, this is different for the degree of socially constructed excludability. Our results suggest that the declaration of EEZs was a sensible step in alleviating the tragedy of the commons in fisheries, at least if fish stocks are not highly migratory. Further expansion of these zones may be worthwhile to consider. Whether such an expansion would receive sufficient political support in an amended UN Convention is difficult to predict. In our simple model, the endogenous choice of α could be introduced by a voting procedure preceding stage 1 and 2. Two cases can be distinguished. If

all parameters except α are such that partial cooperation cannot be stable anyway (sufficiently large d ; small $\frac{c}{pq}$ and r ; see Result 8), all players would vote for $\alpha = 0$ as payoffs under no cooperation decrease with α (Result 2). In contrast, if partial cooperation is possible, then coalition members prefer $\alpha = 0$ and the free-rider prefers the maximum value of α which is still small enough such that stability of the coalition is not jeopardized (Results 3 and 8). On which of the proposals players will agree in this case depends on the voting rule. For instance, under unanimity voting, the free-rider would have veto power and could block any value of α below his optimum. Hence, not the entire fishing ground would be privatized.

In terms of the economic parameters (c =unit production cost, p =price and q =catchability coefficient), the higher the ratio $\frac{c}{pq}$, the higher are stocks regardless of the degree of cooperation (Result 6a), the higher are the chances to establish at least partial cooperation (Result 8), but the lower are economic rents and the need for cooperation (Result 6a). Hence, also with respect to this ratio, the paradox of cooperation is present. This is even more true because if this ratio is high, though partial cooperation may be possible and stocks are high, payoffs will be low. Hence, economic and ecological interests are opposed to each other.

Historically, the ratio $\frac{c}{pq}$ has fallen dramatically in the course of the last century. Fish prices have gone up due to scarcity and technical as well as economic efficiency of production have improved tremendously over time. Our results suggest that this could have aggravated the problem of overfishing – fish stocks have fallen and the need for cooperation has increased but the chances of establishing partial cooperation have deteriorated. Auctioning fishing quotas or imposing a tax would seem obvious measures to increase the ratio $\frac{c}{pq}$. However, this conclusion may be premature as it does not address the question of

how such a policy can be implemented self-enforcingly if a RFMO does not comprise all fishing nations. Moreover, technical progress will unavoidably continue to push for a lower c and higher q in the long term.

Finally, our results indicate that the higher the growth (which is inversely related to the degree of rivalry), the less vulnerable a stock is to overexploitation and the higher are economic rents irrespective of cooperation (Result 6b; see also, e.g. [16]). Hence, economic and ecological interests coincide. Moreover, the higher the growth rate, the higher are the chances to establish partial cooperation (Result 8), though again we face the paradox of cooperation as the need for cooperation becomes smaller (Result 6b).

Viewed together, our model facilitates to formally capture various degrees of technical and socially constructed excludability and rivalry, their impact on the absolute and relative differences between no, partial and full cooperation as well as on the success of stable cooperative agreements. We could confirm the expectation that the higher the degree of excludability, the closer is the non-cooperative equilibrium to the optimum and hence the smaller the gains from cooperation. Moreover, we could show that only if the cooperative gains are small due to a high degree of excludability, partial cooperation may be possible and full cooperation is only stable in the limited case if excludability is perfect but then cooperative gains are zero. A similar paradox of cooperation has been found for the degree of rivalry and the cost benefit ratio from production in our model. Hence, our model confirms the paradox of cooperation reported in the literature on international environmental agreements with respect to cost benefit ratio, and adds to other dimensions related to the degree of excludability and rivalry.

Our model also allows shedding light on the discussion of Sandler and Arce [49] mentioned in the Introduction about the duality between public good games (low degree of rivalry,

approximated by a high value of the parameter r in our model) and commons games (high degree of rivalry, approximated by a low value of the parameter r in our model) and their claim that cooperation is more difficult to establish for the commons than for public goods. In our model if the degree of socially constructed and technical excludability is not almost perfect, no cooperation is the only stable outcome, regardless of the value of r (Result 8). This suggests that the duality between public goods and the common pool resources holds, except that in the non-cooperative equilibrium, payoffs and stocks benefit from a high growth rate r and the relative difference between no and full cooperation becomes smaller (result 6b). If socially and technical excludability is sufficiently high, then the duality may break down: a high value of r may make partial cooperation possible whereas this may not be possible with a low value of r . Again, with a high growth rate r , the relative difference between no, partial and full cooperation diminishes.

This paper suggests several avenues for future research. For instance, Pintassilgo et al. [42] have shown that asymmetry (with respect to the cost parameter) can be conducive to cooperation if accompanied by an appropriate transfer scheme. Therefore, it seems promising to relax the restriction of identical countries and/or symmetric migration patterns. Finally, we expect that more cooperation might be possible if players not only consider the market-value of the resource but also its existence value.

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Table I: Classification of Impure Public Goods

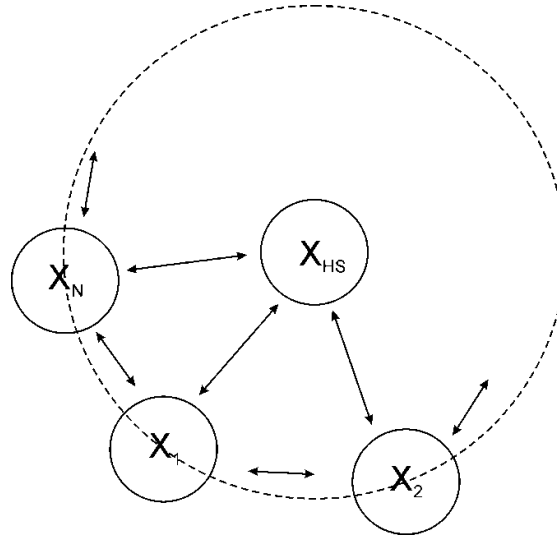
		High	←	Excludability	→	Low
		Low	←	Model Parameters α, d	→	High
Low ← Rivalry → High High ← Model Parameter r → Low		Private goods				Common pool resources
				International fisheries		Congestible public goods
		Club goods				Public goods

Table II: Simulation Runs*

Simulation Runs	c	r	d	α
A	0.5	0.5	0 – 1.28	0 – 1.0
B	0.25 - 0.75	0.5	0 – 1.28	0 – 1.0
C	0.5	0.25 - 0.75	0 – 1.28	0 – 1.0

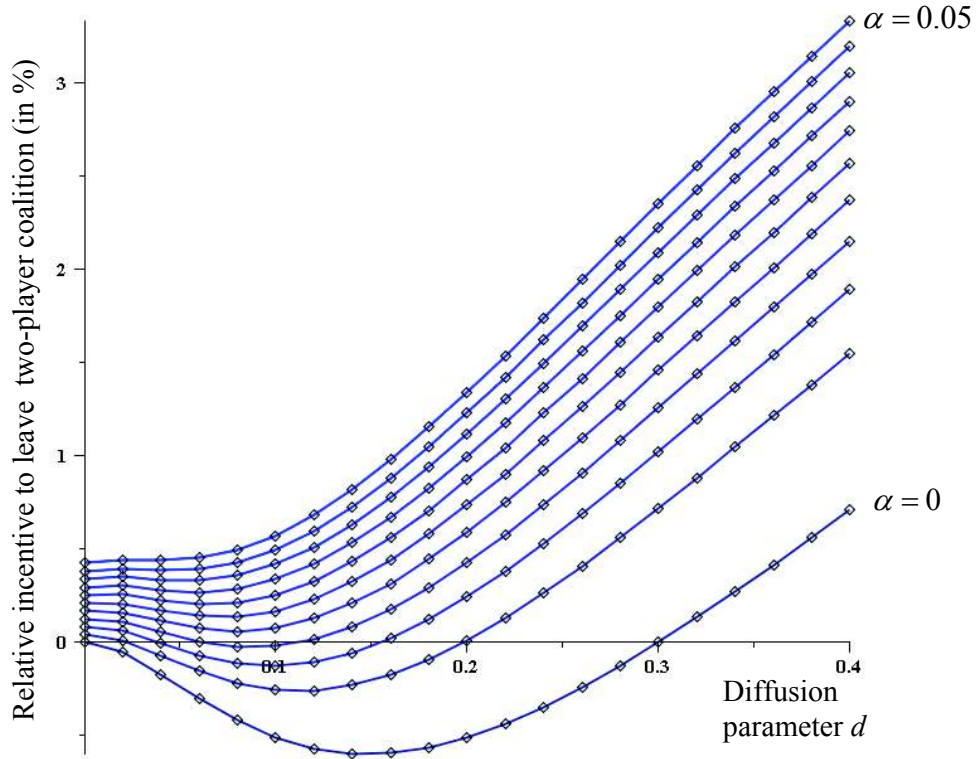
* Parameter variations in a simulation run are indicated bold; $p=1$, $q=1$ and $k_{tot}=4$ are assumed throughout.

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



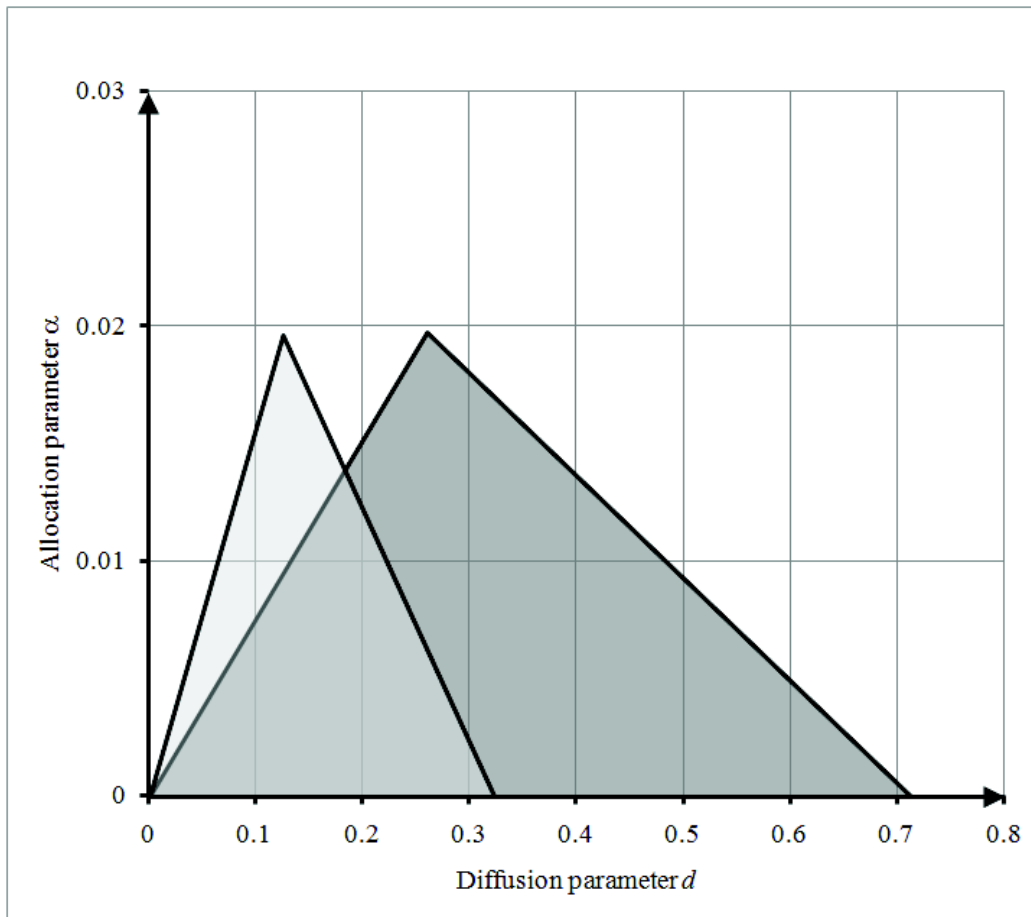
* Arrows indicate potential dispersal

Figure 2a: Incentive to Leave a Two-player Coalition*



* The incentive to deviate is expressed as a fraction of the payoff of a coalition member, i.e. $G_i := [\Pi_i^*(C \setminus \{i\}) - \Pi_i^*(C)] / \Pi_i^*(C)$. For the cost and growth parameter base case values are assumed ($c = 0.5$ and $r = 0.5$).

Figure 2b: Stability of the Two-player Coalition in Parameter Space*



- * Both triangles define parameter combinations (d, α) for which the two-player coalition is stable. The smaller, light shaded triangle refers to base case values for the cost and growth parameter ($c = 0.5$ and $r = 0.5$) whereas the larger, dark shaded triangle corresponds to the conditions that are most favorable for cooperation ($c = 0.75$ and $r = 0.75$).