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International Fisheries Agreements: A Game Theoretical Approach

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Abstract This paper surveys the application of game theory to the economic analysis of international fisheries agreements. The relevance of this study comes not only from the existence of a vast literature on the topic but especially from the specific features of these agreements. The emphasis of the survey is on coalition games, an approach that has become prominent in the fisheries economics literature over the last decade. It is shown that coalition games were first applied to international fisheries agreements in the late 1990s addressing cooperative issues under the framework of characteristic function games. Then, progressively, this cooperative approach was combined with non-cooperative elements such as the stability analysis of the agreements. Finally, partition function games, which model coalition formation endogenously, were introduced and became the standard approach to study the formation and stability of international fisheries agreements. A key message that emerges from this literature strand is that self-enforcing cooperative management of internationally shared fish stocks is generally difficult to achieve. Hence, the international legal framework and regulations play a decisive role on ensuring cooperation over the use of these resources.

Keywords International fisheries agreements · Game theory and fisheries · Regional fisheries management organizations · Shared fish stocks · Coalition games

JEL Classification C70 · F53 · Q22

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1 Introduction

The management of fish stocks shared by several countries is an important economic and political issue at the international level. According to Munro et al. (2004) the catches of these stocks account for about one third of world marine capture fishery harvests. Internationally shared marine capture fish stocks[1] present a large diversity and can be divided into three main categories (Munro 2007): transboundary fish stocks, which migrate across the Exclusive Economic Zone (EEZ) boundaries of two or more coastal states; straddling fish stocks[2], found both within coastal state(s) EEZ(s) and the adjacent high seas; and discrete high seas stocks, found exclusively in the high seas.

The cooperative management of international shared fish stocks has proven to be difficult and led the United Nations to take a few initiatives. The 200 nautical miles coastal state Exclusive Economic Zones (EEZs) established by the UN Convention on the Law of the Sea (United Nations 1982) was a major step towards assigning property rights on fish stocks. Many stocks which were previously disputed by several countries become property of a single coastal state. Despite this new legal regime, disputes persisted over transboundary fish stocks and especially over straddling fish stocks. The successive cases of overexploitation of the latter stocks led the United Nations to convene a conference which resulted in an international agreement, popularly known as the UN Fish Stocks Agreement (United Nations 1995). This agreement supplements the UN Convention on the Law of the Sea regarding the conservation and management of straddling fish stocks. According to article 8 of the agreement, all coastal states and distant water fishing states (DWFSs) with "a real interest in the fisheries concerned" should pursue cooperation on the management of straddling fish stocks directly or through regional fisheries management organizations (RFMOs) or arrangements.

Munro (2007) points out that the UN Fish Stocks Agreement left a few problems unsolved regarding the cooperative management of straddling fish stocks under RFMOs. One problem is the possibility of prospective new members wanting to join these organisations and share the harvest following recovery of the stocks. In fact, according to article 8, the terms to join a RFMO are close to open membership. Another problem, labelled as unregulated fishing, is the possibility of non-members operating in the high seas, in contravention of the RFMOs' management regimes (for a comprehensive discussion on the limitations of the UN Fish Stocks Agreements see Bjørndal and Munro 2003). These problems have frequently surfaced in the management of RFMOs and undermined its cooperative efforts.

Under the framework of the UN Convention on the Law of the Sea and the UN Fish Stocks Agreement, many International Fisheries Agreements (IFAs) have been established worldwide on internationally shared fish stocks in the form of RFMOs. Examples of such organisations are the Northwest Atlantic Fisheries Organization (NAFO), the South Indian Ocean Fisheries Agreement (SIOFA) and the South Pacific Regional Fisheries Management Organisation (SPRFMO).

The literature on the economics of IFAs has evolved in parallel with the literature on what is usually termed as International Environmental Agreements (IEAs), which is largely dominated by agreements related to the emission of greenhouse gases and other atmosphere

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[1] Hereafter, these stocks will be simply referred as internationally shared fish stocks. Thus, our analysis is restricted to marine capture fish stocks, which are by far the most important internationally shared fish resources. The main principles discussed also apply generally to shared inland water fisheries.

[2] This broad category includes what, in the terminology of the Food and Agriculture Organization of the United Nations, is called highly migratory fish stocks, such as the main tuna species. According to Munro (2007), there is no meaningful difference between straddling fish stocks and highly migratory fish stocks as far as economic analysis is concerned.

pollutants. Both types of agreements share natural similarities, as they basically aim to foster cooperation and therefore avoid the consequences of non-cooperative use of the resources. However, there are notable differences. First, IFAs deal with renewable resources which are usually impure public goods with varying degrees of rivalry and excludability. In the case of IEAs, environmental quality is non-rival and non-excludable due to its public good nature. Second, the spatial distribution and migration of the fish stocks is of utmost importance in IFAs, as it determines the bargaining power of each fishing state. In IEAs, the roles of the spatial and diffusion processes are very different. For instance, the emission of greenhouse gases to the atmosphere affects global climate irrespective of its source. Third, IFAs are generally regional issues which only involve the countries harvesting specific species on a particular area. Many IEAs, such as climate agreements, on the contrary, are global by nature. Fourth, the number of potential countries involved in an IFA may change over time due to shifts in the spatial distribution of the stocks or the emergence of DWFSs with a "real interest" to join the fisheries. In an IEA the number of countries with a stake in the issue is generally more stable. In the case of climate agreements, for example, all countries in the world are interested parties.

The economics of IFAs, as that of IEAs, is anchored on game theory as the management of internationally shared fish stocks involves the strategic interaction between several countries. Since the seminal paper by Munro (1979) a large bulk of literature on IFAs has developed, using both cooperative and non-cooperative games. The formation of IFAs involves several countries joining together, hence the introduction of coalition games in the fisheries literature by Kaitala and Lindroos (1998) was a major step forward. These authors used a characteristic function game (C-game), which belongs to the domain of cooperative games, to study the sharing of the surplus from cooperation in straddling stock fisheries. This paper triggered a whole branch of literature on the application of characteristic function games to IFAs. Another major development was the introduction of partition function games by Pintassilgo (2003). These non-cooperative games of coalition formation allowed to overcome the limitations of characteristic function games and became the standard approach in addressing the formation and stability of IFAs.

The applications of game theory to fisheries have been surveyed by a few authors. Sumaila (1999) review the main game theoretical models of fishing before the introduction of repeated and coalition games. Lindroos et al. (2007) focus on coalition games applied in fisheries economics, exploring both cooperative and non-cooperative approaches. Lindroos and Pintassilgo (2009) provide a selection of simple non-cooperative and cooperative games to show fundamental principles in the strategic interactions between fishery agents. Bailey et al. (2010) present the history of game theory and fisheries since the landmark paper by Munro (1979). It encompasses all domains of this field in a non-technical way. Hannesson (2011) does a very comprehensive survey on the economics of shared fish stocks. It highlights the main strands in the literature and the respective results. In particular, it explores the "beginnings" of game theory in the fisheries literature, in the late 1970s, and two main methodological strands: repeated games and coalition games. It also deeply explores issues such as the choice of the strategic variable in fisheries games, imperfect information and the problems associated to high seas fisheries. Miller et al. (2013) is an example of a specific survey focusing on the lessons that the literature provides regarding the challenges that climate change will present for the management of internationally shared fish stocks.

The present paper aims to survey the literature on the economics of IFAs and differentiates from previous ones by focusing mainly on coalition games. Compared to Hannesson (2011) and Bailey et al. (2010) it expands the approach to coalition games by exploring systematically the settings and applications of characteristic and partition function games. Lindroos et al.

(2007) also focused on coalition games, however did not thoroughly review partition function games, which meanwhile became the standard non-cooperative approach to the formation of IFAs. Thus, our survey represents a significant advance in this domain. All the other surveys referred above do not explore much the issue of coalition games.

The survey is organised as follows. Section 2 presents the application of characteristic function games to the analysis of IFAs. After defining the concept, the main contributions to the literature are briefly discussed and the link between the characteristic and partition functions is explored. Section 3 addresses the partition function games. It includes the concept, the first applications to IFAs, a standard model and recent developments. Section 4 presents an overview of other game theoretical approaches to IFAs, which include a wide set of frameworks. Section 5 shows avenues for future research in the field of IFAs. Finally, Section 6 concludes the survey by highlighting the core ideas and making a brief parallel with the literature on IEAs.

2 Characteristic Function Games

For decades it has been well-known that the joint exploitation of shared fish stocks is economically preferable over its competitive use. The latter is likely to lead to rent dissipation and the tragedy of the commons, while a joint exploitation of the resources leads to full rent maximization (see for example Warming 1911; Gordon 1954; Scott 1955 and Munro 1979). Since the late 1990s, the joint management of shared fish stocks has been approached through coalition games, which allows groups of countries to join in IFAs (see Lindroos et al. 2007 for an overview). In these agreements, participants aim at finding a fair sharing of the resources such that all are satisfied. This sharing can be modelled as a characteristic function game and applied to analyse, for instance, the sharing of total allowable catches (TACs).

2.1 The Concept

A characteristic function game or C-game is a purely cooperative game, where the agreement originally is assumed to be binding. Assume that a resource is shared by a set of n players, where $N = \{1, 2, \ldots, n\}$ is the grand coalition formed by all players. Let $S \subseteq N$, where $S = \{1, 2, \ldots, s\}$ is any of the 2^n sub-coalitions of N, which consists of s players.[3] By applying the C-games it is possible to find a fair distribution, called sharing imputation or sharing rule, of the aggregate worth from cooperation among players in any sub-coalition S, assuming transferable utility. For instance, the Nash bargaining solution, the Nucleolus and the Shapley value are commonly used fair sharing rules, which are based on different fairness concepts. The Nash bargaining solution with equal weights yields an egalitarian imputation of the gains. The Nucleolus maximizes the minimum gains to any possible coalition, that is, the gains of the "least satisfied coalition". The Shapley value divides the gains according to each player's average contribution to the coalitional worth.

To solve a C-game, a characteristic function is determined by assigning to each coalition S the associated benefits from cooperation. This is equivalent to the total worth of the coalition minus the sum of the payoffs of its members under full non-cooperation, that is, when all act as singletons (Mesterton-Gibbons 2000). Hence, a typical characteristic function applied to IFAs looks like follows:

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[3] The number of sub-coalitions, 2^n, also includes the empty coalition (Ø) and the grand coalition.

$$\bar{v}\,(S) = \pi\,(S) - \sum_{i=1}^{s} \pi\,(\{i\}) \tag{1}$$

where $\bar{v}\,(S)$ is the characteristic function (C-function) and $\pi\,(.)$ are the net-benefits of the coalition or the singleton. The C-game, in its original form, does not consider any effects to or from the $n - s$ players outside the coalition, S. According to Chander and Tulkens (1997), the game between coalitions and singletons can take different forms. The most commonly applied in IFAs is the so-called γ-type, where singletons and the coalition interact according to Nash strategies (Chander and Tulkens 1997).[4] Within the γ-characteristic function it is assumed that coalition and singletons adopt a mutually best response, i.e. playing a Nash game. The γ-characteristic function is argued to be the rational approach (Chander 2007) but can be argued to impose a weak punishment on deviators compared to other characteristic functions (e.g. the α-characteristic function Finus 2003).

The distribution, or sharing imputation, describes the fraction of the benefits of cooperation allocated to each player inside the coalition. It can be seen that the sharing imputation applying the characteristic function depends on the members of the coalition only and not the players' behavior outside the coalition. To compute the sharing imputation, it is sometime convenient to normalize the characteristic function as a fraction of the benefits from full cooperation, that is, the grand coalition:

$$v\,(S) = \frac{\bar{v}(S)}{\bar{v}(N)} = \frac{\pi(S) - \sum_{i=1}^{s} \pi(\{i\})}{\pi(N) - \sum_{i=1}^{n} \pi(\{i\})} \tag{2}$$

where $v\,(S)$ is the normalized C-function. With the normalised C-function the sharing imputations are restricted between 0 and 1.

Only in cases where the characteristic function is positive, $\bar{v}\,(S) > 0, \quad S \subseteq N$, hence there is a positive exceess worth of the coalition compared to the aggregate worth of the singletons, is it meaningful to find a distribution of benefits. Regarding the grand coalition, the sharing imputation is referred to as a n-dimensional vector $X = (x_1, x_2, x_3, \ldots, x_n)$ where x_i is the allocation of the benefits to player i. There are many sharing rules in the literature, being the Nash bargaining solution, the Shapley value and the nucleolus some of the most popular (for a thorough description of these and other sharing rules see Kronbak and Lindroos 2013). The main problem with the characteristic function approach in applying these sharing imputations is that the worth of a coalition does not depend on how the other players form coalitions, hence if there are externalities from coalition formation these are ignored.

2.2 Applications to IFAs

The first application of characteristic function games to fisheries is due to Kaitala and Lindroos (1998). They assumed a binding agreement in the Norwegian spring-spawning herring fishery and analysed the sharing of benefits. The application of the C-game approach to fishery economic problems took a major leap forward with a special issue of Marine Resource Economics in 2000. This issue consisted of a series of papers which analysed the sharing of the benefits from cooperation in different fisheries and also the stability of the agreements,

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[4] In addition to the γ-characteristic functions there are the α- and ß-characteristic functions, which presume strategies to make the other players worse off.

which were not assumed to be binding. Thus, these papers used in fact a combination of C-games and non-cooperative coalition games. Lindroos and Kaitala (2000) and Arnason et al. (2000) analysed the Norwegian spring-spawning herring fishery whereas Duarte et al. (2000) and Brasão et al. (2001) the Northern Atlantic bluefin tuna fishery. The papers used fairly disaggregated bio-economic models, derived characteristic functions and different sharing imputations. The overarching conclusion in these papers is that the application of standard sharing rules usually is not sufficient to stabilise the grand coalition, where stability is defined by the common concepts of internal and external stability (d'Aspremont et al. 1983). Stability of coalition S, is defined by:

$$\begin{aligned} v_i\left(S\right) &\geq v_i\left(S\backslash\left\{i\right\}\right), \quad \forall i \in S \quad \text{(internal stability)} \\ v_j\left(S\right) &\geq v_j\left(S\cup\left\{j\right\}\right), \quad \forall j \in N\backslash S \quad \text{(external stability)} \end{aligned} \tag{3}$$

The coalition S is stable when no one inside the coalition has the incentive to leave it (internal stability), and no one outside the coalition has incentive to join it (external stability). Brasão et al. (2001), for example, recognized the internal instability of a cooperative agreement for the Northeast Atlantic bluefin tuna under the Shapley value, due to the free rider incentives. Kennedy (2003) also applies a variant of characteristic function game. It addresses the Northeast Atlantic mackerel fishery and derives similar conclusions concerning the stability of cooperative agreements. Lindroos (2004) analyses the Norwegian spring-spawning herring, introducing the concept of safe minimum economic stock level (SMEL) in a characteristic function game framework. The model included an age-structured biological model, with uncertain recruitment. The author concludes that, under the Shapley value, introducing the SMEL reduces the probability of the grand coalition being unstable.

In all these applications, the presence of strong free rider incentives was the driving factor behind the instability of IFAs, even with side payments. The main reason for these conclusions is that when players join into a coalition then that increases the payoffs of non-members. This emerges as coalitions typically adopt more conservative harvesting strategies than players acting non-cooperatively. The more conservative a coalition is (e.g. coalition consisting of diverging players in terms of for example catchability or harvesting costs), the more likely free rider incentives are.

2.3 The Link to the Partition Function Approach

A major characteristic of IFAs is the presence of externalities from coalition formation, that is, a merger of coalitions affects the payoffs of the non-merging players. However, these externalities are not considered in pure C-games.

Kronbak and Lindroos (2007) use a combination of a C-game and a non-cooperative coalition game to analyse the consequences of externalities to cooperative agreements. The authors reformulated the nucleolus sharing imputation, where the nucleolus if found by asking each coalition S about its dissatisfaction with the proposed sharing imputation and then by minimizing the maximum dissatisfaction from the sharing imputation. The reformulation by Kronbak and Lindroos (2007) included taking free rider incentives into consideration, rather than the non-cooperative Nash solution. They called this adjusted approach the satisfactory nucleolus. They applied the alternative approach to the Baltic Sea cod fishery and demonstrated that this approach may stabilize an agreement, also in cases where the traditional sharing imputations such as the Shapley and the nucleolus cannot stabilize it.

The applications of C-games to IFAs evolved into combinations of cooperative and non-cooperative coalition games. The cooperative part involved the application of fair sharing rules and the non-cooperative part the use of stability analysis on IFAs. This was followed by the use of partition function games, which are addressed in the next section.

3 Partition Function Games

According to Bloch (2003), cooperative games are centred on the question: how to divide the coalitional worth among coalition members? Non-cooperative games of coalition formation answer two other fundamental questions: which coalitions will form? and, how does the presence of other coalitions affect the incentives to cooperate? Partition function games, which model the formation of coalitions endogenously, emerged as the main approach to answer these questions. Introduced in the early 1960s by Thrall and Lucas (1963), these games would only be revived in the 1980s (e.g. d'Aspremont et al. 1983; Hart and Kurz 1983, 1984) and 1990s (e.g. Bloch 1996; Yi 1996; Ray and Vohra 1997).

3.1 The Concept

A partition function game $\Gamma\,(N, \Pi)$ is fully defined by the set of players, $N = \{1, 2, \ldots, n\}$, and the partition function, Π. Following Bloch (2003), a partition function can be defined as a mapping which associates to each coalition structure $C = \{S_1, S_2, \ldots, S_z\}$ a vector in $\Re^{|C|}$ representing the worth or aggregate payoff of all coalitions in C. A coalition structure $C = \{S_1, S_2, \ldots, S_z\}$ stands for a partition of the set of players, that is, a set of coalitions that altogether integrates all the players, with each player belonging to only one coalition. Thus: $\bigcup_{k=1}^{z} S_k = N$ and $S_i \cap S_j = \varnothing, \forall i, j \in \{1, \ldots, z\} \wedge i \neq j$.

In a partition function the worth of a coalition depends on the overall coalition structure: $\Pi\,(S, C)$. Thus, it is a generalization of the characteristic function, in which the worth of any coalition does not depend on how the remaining players form coalitions: $v\,(S)$.

The worth of a coalition is generally affected by the merger of other coalitions. Hence, mergers generate positive or negative externalities for non-members. The partition function captures these externalities across coalitions, which are assumed to be absent in the characteristic function. Hence, the advantage of the partition function approach, compared to C-games, is that it captures externalities across players compactly and allows one to analyse also the formation and stability of subcoalitions. Fisheries games are generally positive externality games as when players join into coalitions they usually find it optimal to decrease their aggregate fishing effort, which increase the payoff of the remainder players.

According to Yi (2003), the formation of economic coalitions with externalities has opened a new strand of literature on the non-cooperative theory of coalition formation. This has been applied to a wide range of phenomena, such as firm mergers, cartel formation, custom unions and environmental agreements (see Yi 2003 for a survey). Most studies (e.g. Bloch 1996; Yi 1996) assume symmetric players, are centred on finding the equilibrium number and size of coalitions and share a common two-stage game framework. In the first stage, players form coalitions, which in fishery games take the form of agreements between the fishing parties. In this stage, it is commonly assumed that only one agreement forms. Thus, players have to choose whether to join the agreement or to remain outside as non-members. In the second stage, the coalition(s) and non-members decide on their fishing strategies, usually defined in terms of fishing effort or harvest. These games are solved by backward induction.

The first applications of partition function games in the field of environmental and natural resource economics are due Carraro and Siniscalco (1993) and Barrett (1994) and both address the formation of international environmental agreements (IEAs). Since these seminal papers a vast literature has been developed on the application of partition function games to IEAs (for surveys see, for instance, Barrett 2003 and Finus 2003, 2008).

3.2 The First Applications to International Fisheries Agreements

Pintassilgo (2003) introduced partition function games to the field of IFAs. The author modelled straddling stock fisheries as a partition function game and derived general results regarding externalities, stability of coalition structures and the equilibrium of the game. In particular, he derived a condition under which there is no sharing rule that can make a coalition internally stable (as defined in Sect. 2.2). The framework used was that of a two-stage game, where in the first stage each country decides whether to join a Regional Fisheries Management Organization (RFMO) or to remain outside as a free rider. In the second stage, the RFMO chooses the fishing effort strategies of its members that maximize the aggregate payoff, whereas non-members choose the strategies that maximize their payoffs.

The paper also contains an empirical application to the North Atlantic bluefin tuna fishery, modelled through a dynamic age-structured, multigear bioeconomic model. The payoffs of the harvesting countries are represented by the net present value of profits. In the first stage countries decide whether to join the relevant RFMO, the International Commission for the Conservation of Atlantic Tunas (ICCAT), or not. In the second stage the RFMO and the non-members decide their optimal fishing effort that maximizes their net present value of profits over a 25-year period, given the behaviour of the others. The results for this species show a typical picture of the high seas fisheries: the simultaneous presence of strong externalities in the coalition structures and the absence of internal stability for the grand coalition. A fundamental conclusion of the paper is that in order to guarantee the stability of IFAs, usually it is not sufficient to implement a fair sharing rule for the distribution of the returns from cooperation. Stability requires a legal regime preventing players that engage in non-cooperative behavior from having access to the resource.

Pham Do and Folmer (2006) model fisheries through a general static bioeconomic model where payoffs represent steady state profits. This setting is used to study the feasibility of coalitions. According to the authors, a coalition is feasible if its payoff is larger or equal than the sum of the payoffs of its members under full non-cooperation. Pham Do and Folmer (2006) also suggest a modified Shapley value as an appropriate device for the division of the gains from cooperation (further explored in Pham Do and Norde 2007). The authors conclude that, in many circumstances, even with this sharing rule is not sufficient to discourage free-riding.

Kwon (2006) extends the great fish war model of Levhari and Mirman (1980) by considering multiple symmetric countries and investigates the formation of coalitions. In this model, players maximize intertemporal utility functions and thus payoffs are the sum of discounted lifetime values. Based on this dynamic bioeconomic model, a two stage partition function framework is set, in which players decide whether to join a fishery agreement in the first stage and choose their optimal harvesting strategies in the second stage. Using the internal and external stability concepts, the author shows that no coalition with more than two member countries can be sustained under a Nash-Cournot behavior. That is, in the second stage, both the coalition and the singletons decide simultaneously their harvesting strategies. Kwon (2006) also explores Stackelberg behaviour in the second stage. In this setting, the harvesting strategies are defined sequentially, with the coalition playing the leader role by deciding before the singletons. The results show that under Stackelberg behaviour there always exist one or two stable non trivial coalitions and its size depends on the biological and economic parameters. This result emerges from the fact that, under Stackelberg leadership, coalition members have a strategic advantage over the singletons. The coalition has an incentive to expand harvest in order to lead singletons to reduce their harvest. Consequently, free rider incentives are reduced and larger coalitions forms, compared to the Nash-Cournot assumption.[5]

3.3 A Standard Model

Having presented the first applications of partition function games to fisheries, we now explore in more detail a model that has been widely used in the literature. This standard model, due to Pintassilgo and Lindroos (2008), is used to illustrate the main concepts and the solution of a partition function game.

Pintassilgo and Lindroos (2008) modelled the management of internationally shared fish resources through a coalition game in partition function form, assuming *ex ante* symmetric players and the classical Gordon-Schaefer bioeconomic model (Gordon 1954; Schaefer 1954). Due to its simplicity, this bioeconomic model has been frequently used for game-theoretic analyses of internationally shared fish resources (e.g. Ruseski 1998; Lindroos 2008). It captures the relation between the fish stock, X, the harvest of an individual player i, H_i, with the set of players $N = \{1, \ldots, n\}$, and the fishing effort exerted by player i, E_i, by the following three equations:

$$\frac{dX}{dt} = G(X) - \sum_{i=1}^{n} H_i \tag{4}$$

$$G(X) = rX\left(1 - \frac{X}{k}\right) \tag{5}$$

$$H_i = qE_iX \tag{6}$$

where r denotes the intrinsic growth rate of fish, k the carrying capacity of the ecosystem (and thus the equilibrium level of X in the absence of harvesting), q the catchability coefficient, which constitute the parameters of the model, and t denotes time.

The steady state or equilibrium stock is as function of the total fishing effort that is constant through time:

$$X^* = \frac{k}{r}\left(r - q\sum_{i=1}^{n} E_i\right). \tag{7}$$

The economic rent or payoff of fishing state i, Π_i, is defined as:

$$\Pi_i = pH_i - cE_i \tag{8}$$

where p is the price for fish and c the individual cost per unit of effort.

The authors use the standard two-stage stage exposed in Sect. 3.1. In the first stage, each player decides on its participation: join the IFA (coalition) or be a non-member and act as singleton. It is assumed that only one coalition forms and that any player (country) is allowed to join it. This framework, known as the single coalition open membership game was introduced by d'Aspremont et al. (1983) and is dominant in the literature on IFAs. The justification for this framework lies in the legal setting of the UN Convention on the Law of the Sea (United Nations 1982) and the UN Fish Stocks Agreement (United Nations 1995).

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[5] Finus (2003) also concludes that for the standard models on the formation of International Environmental Agreements (IEAs) the equilibrium coalition size and global welfare are at least as high under the Stackelberg than under the Nash-Cournot assumption, due to the strategic advantage of participants over non-participants.

According to this setting an internationally shared fish stock should be managed through a Regional Fisheries Management Organization (RFMO), which justifies the use of a single coalition. The assumption of open membership is based on article 8 of the UN Fish Stocks Agreement, which states that participation in an RFMO should be open to all countries with "a real interest in the fisheries concerned".

In the model introduced by Pintassilgo and Lindroos (2008), first stage decisions lead to a coalition structure $C = \left\{S, 1_{(n-m)}\right\}$ where S is the non-empty set of m coalition members, $m \in \{1, \ldots, n\}$, and $1_{(n-m)}$ is the vector of $n - m$ singletons. Given the simple structure of the first stage, a coalition structure is fully characterized by coalition S. In the second stage, players chose their fishing effort strategies. In each stage, strategies (participation and fishing effort) form a Nash equilibrium. The game is solved backward for the subgame-perfect equilibrium.

Assuming that a coalition, S, has formed in the first stage, Pintassilgo and Lindroos (2008) show that the equilibrium fishing effort strategies in the second stage lead to the following equilibrium payoffs of coalition members ($i \in S$) and singleton ($j \notin S$):

$$\Pi^*_{i\in S}(S) = \frac{rpk}{m(n-m+2)^2}(1-b)^2 \tag{9}$$

$$\Pi^*_{j\notin S}(S) = \frac{rpk}{(n-m+2)^2}(1-b)^2 \tag{10}$$

where $b = \frac{c}{pqk}$, which always lies in the range [0; 1], is usually called an "inverse efficiency parameter" (Mesterton-Gibbons 1993) because it increases with the cost per unit of effort and decreases with the price and the catchability coefficient.

As players are ex ante symmetric, the payoffs of coalition members are obtained by an equal sharing of the coalitional worth. In the first stage, a coalition S is an equilibrium if it is internally and externally stable.

This game is characterized by positive externalities, that is, the merger of coalitions increases the payoffs of the non-merging players. A key result is that, apart from the case in which the number of players is only two, the grand coalition is not a Nash equilibrium outcome. Furthermore, in the case of three or more players the only Nash equilibrium coalition structure is the one formed by singletons. Thus, it can be concluded that the prospects of successful IFAs are low if players can adopt a free rider behaviour. Yi (1997) reaches a similar conclusion for two other partition function games with symmetric players in the context of positive externalities: output cartels and coalitions formed to provide public goods.

3.4 The Role of Asymmetry

Pintassilgo et al. (2010) extend the analysis of Pintassilgo and Lindroos (2008), by relaxing the assumption of symmetric players. This is undertaken by allowing for different costs per unit of fishing effort. Thus, the payoff of fishing state i, Π_i, is now defined as:

$$\Pi_i = pH_i - c_i E_i \tag{11}$$

where c_i the individual cost per unit of effort of player i.

Assuming, interior solutions, that is, strictly positive fishing efforts for all possible coalition structures, the equilibrium payoffs of coalition S and singleton j are given by:

$$\Pi_S^*(S) = \frac{rpk}{(n-m+2)^2}\left(1-(n-m+1)\,b_S^{\min}+\sum_{j\notin S} b_j\right)^2 \tag{12}$$

$$\Pi_{j\notin S}^*(S) = \frac{rpk}{(n-m+2)^2}\left(1-(n-m+1)\,b_j+b_S^{\min}+\sum_{k\neq j\notin S} b_k\right)^2 \tag{13}$$

where n is the number of players, m the size of coalition S, $b_i = c_i/pqk$, and $b_S^{\min}$ the lowest b among the members of coalition S.

As players are asymmetric, an equal sharing of coalitional worth is not appropriate. Therefore, the authors adopt the "almost ideal sharing scheme" (AISS) proposed by Eyckmans and Finus (2009). This scheme allocates to each coalition member his free-rider payoff, plus a share of the surplus of the coalitional worth over the sum of free-rider payoffs. This scheme is called "almost ideal" because it stabilises those coalitions generating the highest possible global worth among the set of all "potentially stable coalitions".

Through Monte Carlo simulations Pintassilgo et al. (2010) estimate the probability of a given coalition being stable or, in other words, its stability likelihood. Three main results were obtained. First, the larger the number of fishing states that compete for the fish stock, the higher are the relative gains from full cooperation, but the lower is the likelihood of a large coalition being stable.[6] This is connected to the new entrant problem: the possibility of a new country joining the fishery of an internationally shared fish stock. The results showed that new entrants, joining the RFMO or not, increase the incentive of RFMO members to leave and decrease the incentive of non-members to join it. Second, the higher the overall efficiency of all fishing states in harvesting, the lower the relative success of coalition formation. Third, the higher the cost asymmetry among fishing states, the higher the relative success of RFMOs. Cost asymmetries increase the potential gains from cooperation through a cost-effective allocation of fishing efforts. This potential is fully exploited through the "almost ideal sharing scheme". An important implication of this "optimistic" result is that cost asymmetries, e.g. between coastal and DWFSs, may not be an obstacle to the formation of cooperative agreements but, on the contrary, can foster it.

3.5 Recent Developments

Long (2009) uses a partition function game to explore the relevance of minimum participation clauses and enforcement costs on the formation of RFMOs. The author uses the classical Gordon-Schaefer bioeconomic model with symmetric players, as in Pintassilgo and Lindroos (2008), and assumes that a RFMO only enters into force if the number of members is higher or equal than a threshold. This threshold is chosen endogenously, such that the payoff of a member country cannot be lower than under full non-cooperation. The author concludes that a minimum participation clause increases the prospects of cooperation. The equilibrium is full cooperation if the number of players is less than five and partial cooperation, with more than 80% of the players, if the number of players is five or higher. The mechanism behind this result is that the endogenously chosen minimum number of players works as a coordination device. Moreover, under the minimum participation clause, the existence of enforcement costs, faced by RFMO members to ensure compliance within the coalition, typically have a positive impact on participation. The explanation lies in the fact that compliance costs reduce

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[6] Thus whenever cooperation would be needed most, it achieves only little. This paradox was first described in the context of International Environmental Agreements by Barrett (1994).

the payoffs of coalition members, for a given coalition size. Therefore, it (weakly) increases the minimum coalition size for which a coalition member gets a payoff not lower than under full non-cooperation.

Long and Flaaten (2011) extend the model in Pintassilgo and Lindroos (2008) by considering a Stackelberg behaviour instead of the standard Nash-Cournot. In this setting, the fishing effort decisions in the second stage are taken sequentially: the coalition plays the leader role and decides first, followed by the singletons. The authors conclude, in line with Kwon (2006), that under Stackelberg leadership the prospects of cooperation are higher. They show that if the number of players does not exceed four then the grand coalition is the stable outcome and that, for larger number of players, stable partial cooperation always exists.

Breton and Keoula (2012) approach IFAs through a partition function game based on the bioeconomic model introduced by Levhari and Mirman (1980), as in Kwon (2006). They extend Kwon's paper, which adopts the classical internal and external stability analysis, by using the concept of farsighted stability. This assumes that players are symmetric and have rational conjectures, acknowledging that a deviation from a player may trigger successive moves of the other players leading to the formation of a new coalition structure. The results are in line with those obtained for IEAs (e.g. Eyckmans 2001; Diamantoudi and Sartzetakis 2002; de Zeeuw 2008) in particular that farsightedness leads to more optimistic cooperation levels than the standard internal and external stability assumption. The intuition behind this result is that under rational conjectures players are able to foresee that by deviating from a coalition they may trigger the deviation of the other coalition members, making free riding less appealing.

Breton and Keoula (2014) use the bioeconomic model by Levhari and Mirman (1980) and set a partition function approach in a context where players are asymmetric in terms of their time preferences and use different discount rates. The authors use the concepts of internal and external stability and assume no transfers. They conclude that if players are divided in two broad groups with similar discount rates and take harvesting decisions simultaneously, i.e. in a Nash-Cournot game, then the equilibrium coalition size is generally small. This means that this type of asymmetry is not sufficient to solve the puzzle of small coalitions, although it affects significantly the way the resource is shared.

Punt et al. (2013) extend the RFMO formation model from Pintassilgo et al. (2010) to allow for the formation of Marine Protected Areas (MPAs). They investigate the effects of fish growth enhancing MPAs on IFAs over highly migratory fish stocks. The MPA formation is an additional stage in their model between coalition formation and the fisheries game. The results show that MPAs generally increase the size of stable RFMOs and thus can enhance the success of IFAs. The authors justify this by arguing that the benefits from an MPA can be better reaped by a coalition than by free-riders, because coalitions tend to have cost advantage in a context of asymmetric costs.

Finus et al. (2011) use international fisheries as a prime example where multiple characteristics affect the incentive structure of non-cooperative and cooperative impure public good provision. The degree of socially constructed excludability is captured by the distinction between the internationally accessible domain of high seas and the state-owned exclusive economic zones. The degree of technical excludability is related to the pattern of fish migration between various zones and the degree of rivalry is reflected by the growth rate of the resource. The authors set a partition function game over the fishing of an internationally shared stock, migrating over the exclusive economic zones (EEZs) and the high seas. A stylized geographical setting is adopted, where the EEZs are arranged in a circle with the high seas at its center. Among other results, it is shown that the spatial allocation of property rights is crucial for cooperation, as long as the migration rate of the stock is not sufficiently high. In particular, under a low migration rate, partial cooperation is achieved if the high seas zone is small compared to the EEZs. Moreover, the "paradox of cooperation" (Barrett 1994) holds, that is, when the relative difference in terms of global payoffs between the full and no cooperation is large, stable coalitions achieve relatively little.

Recently, empirical applications of partition function games have emerged in the literature. Ekerhovd (2010) applies it to the blue whiting fishery in the Northeast Atlantic. Through a 5-player partition function model the author studies the effects of two scenarios of spatial distribution of the stock on coalitional stability. The results show that the spatial distribution area of the blue whiting has a key role on the stability of a cooperative agreement. This is due to the fact that when the spatial distribution of the stock expands it reaches the EEZ of a country that previously only harvested in the high seas. Therefore, this country becomes a coastal state and in this setting a larger coalition size emerges.

Kulmala et al. (2013) studies the management of the Atlantic salmon stocks in the Baltic Sea by combining a two-stage game of four asymmetric players with a comprehensive bioeconomic model. The results show that cooperation under the harvest allocation rules of the European Union's Common Fisheries Policy is not a stable outcome. However, partial cooperation can be sustained under alternative sharing schemes, such as the "almost ideal sharing scheme" (AISS). Thus, in a context of asymmetric players an appropriate transfer scheme can enhance the prospects of cooperation. This result, obtained from a fairly disaggregated bioeconomic model, is in line with the outcomes of Pintassilgo et al. (2010) using the classical Gordon-Schaefer model. The empirical application by Kulmala et al. (2013) highlight an interesting feature: although there are significant global welfare gains by departing from full non-cooperation to stable IFAs, this does not ensure the biological management goals set for the Atlantic salmon stocks in the Baltic Sea by the International Council for the Exploration of the Seas (ICES).

Another recent empirical application is due to Ellefsen (2013a), who investigates the IFA on the mackerel stock in the Northeast Atlantic. It addresses the problem of a new entrant into the fishery due to a change in the migratory pattern of the stock. This highlights the relevance of the spatial and migratory dimensions of fisheries, in aspects such as the number of harvesting countries. The results show that the new entrant leads to a decrease in the stability of the IFA, which is in line with the general result obtained by Pintassilgo et al. (2010).

4 Other Approaches

The economic analysis of IFAs has not only resorted to characteristic and partition function games. In this section, we present the main alternative approaches. This section aims to analyse the main differences and similarities between these alternative approaches and coalition games.

4.1 Dynamic Games

The beginning of game theory applied to fisheries was dominated by dynamic games. There are two not very much linked strands here, the continuous time differential games and discrete time dynamic games.

The pioneer works on continuous time differential fishery games are due to Munro (1979) and Clark (1980). Munro (1979) studies a two-player dynamic bargaining game inspired by the UN Convention on the Law of the Sea. In the analysis cooperative agreements are assumed to be binding, that is, free-riding incentives do not to exist. He shows how side payments could be used to share the benefits from cooperation. Clark (1980), on the other hand, analyses a two-player dynamic non-cooperative game. He shows that the feedback equilibrium is such that players harvest at maximum capacity.

Kaitala and Pohjola (1988), using the framework of Clark (1980), shows that cooperation can be sustained for a low enough discount rate through trigger strategies. Under these strategies, players cooperate until someone fails to cooperate, which triggers a switch to non-cooperation. The new member problem was also addressed in this framework by Kaitala and Munro (1997). In this work, inspired by the UN Fish Stocks Agreements, the authors show that having new players in the game is a problem in the sense that the existing cooperative equilibrium could be switched to non-cooperative behaviour. In the same framework, Kaitala and Lindroos (2004) analyse the timing to sign an agreement. They show in a two-player dynamic game that some parameters may yield cases of immediate ratifying, lagged ratifying and never ratifying. These early dynamic models did not include any coalitional analysis, as countries were assumed not be able to form any partial cooperative agreements. This gap was filled by the work of Kaitala and Lindroos (1998), which computed a characteristic function for a three-player game.

The other important strand of literature on dynamic fishery games is the discrete time models initiated by Levhari and Mirman (1980). A major difference to the dynamic games by Munro (1979) and Clark (1980) is the absence of economic parameters such as prices and costs. Whereas in the models by Munro and Clark net revenues are maximised the Levhari-Mirman model maximises the logarithm of harvests. They show that the two-player Nash-Cournot equilibrium is a steady state. They compare this non-cooperative equilibrium to the cooperative outcome and show that the former implies larger harvest and lower steady state fish stock level. Later this framework was also used in a coalition approach by Kwon (2006), Rettieva (2012), Breton and Keoula (2012, 2014). The multi-species models by Fischer and Mirman (1992, 1996) also follow this basic discrete time model.

4.2 Repeated and Multi-stage Games

The most important application of repeated games to IFAs is by Hannesson (1997) who shows, in an infinite horizon repeated game, that only a limited number of countries can be supported in a cooperative agreement over shared fish stocks. This paper uses a specific form of asymmetry and transfers: there is one low cost agent, all others are symmetric high cost players, and the coalition payoff is split equally. Moreover, it considers trigger strategies: if one player deviates from the cooperative solution then when that is detected the other players will retaliate and fish down the stock until further depletion becomes unprofitable. In this setting, cost asymmetry increases the gains of defectors and therefore is detrimental for the success of cooperation. This contrasts with the finding by Pintassilgo et al. (2010) who concludes, in the context of a two-stage partition function game, that larger cost asymmetries lead to larger gains from cooperation and more successful coalitions, as long as an optimal sharing scheme is adopted.

An early contribution of multi-stage games, in which there is more than one decision level, is due to Ruseski (1998), followed by Quinn and Ruseski (2001). Note that the previously analysed partition function games are just one branch of multi-stage games, in which players decide in the first stage whether to join an IFA or not. In the case of Ruseski (1998) there are two decisions levels: the country level and the firm level. He founds that countries either choose to license too many domestic fishers or give too large subsidies, resulting in lower than efficient fish stock levels. Quinn and Ruseski (2001) extend the approach to include asymmetric players. In this setting, for example, entry deterring strategies may become relevant. As in the Kaitala and Pohjola (1988) framework, more efficient players would then find it optimal to deter entry of less efficient players.

Kronbak and Lindroos (2006) use a four-stage game where they include a three-player government coalition game in addition to a three-player fisher coalition game. They analyse an enforcement game in the first two stages and a harvesting game in the last two stages. Under some circumstances, it is shown that a stable grand coalition in the fisher game may exist, hence making enforcement unnecessary. Munro et al. (2013) continue this analysis in the context of rights based fishing.

4.3 Games under Uncertainty

Strategic interaction between countries harvesting shared stocks in a context of uncertainty is an underexplored area. Kaitala (1993) is an early application of stochastic methods to fisheries games. He studies a stochastic differential game where countries use trigger strategies for possible retaliation. He shows how uncertainty may trigger cooperative and non-cooperative phases, a tendency that is clearly visible in IFAs. This is due to imperfect observation of other player's behaviour. Similar modelling could be used in dynamic coalition games where, non-cooperation, partial cooperation and full cooperation could be solutions at different time periods.

Laukkanen (2003) studies the Baltic salmon fishery through a stochastic sequential game, where the players are different groups of fishers within one country, namely offshore and inshore fishers. She shows how stochastic shocks in recruitment may trigger phases of non-cooperation. Her results state that the larger the uncertainty the less likely is cooperation. Also here one reason for this is the imperfect ability to observe competitor's behaviour. McKelvey et al. (2003) study a two-country stochastic split stream model, that is, a spatial stochastic dynamic game. Their simulations show how removing uncertainty may be detrimental to cooperation. In this game, the main driver of the results is that with better information the players are able to target their fishing to seasons where the available stock size is higher. Similar results have been found in the IEAs literature (see for instance, Na and Shin 1998; Kolstad 2007).

4.4 Ecosystem Games

Issue linkage, where concessions in one agreement are exchanged by concessions in another agreement (Finus 2003), may be useful in analysing multi-species or ecosystem games. For instance, agreements on the harvest of several species may be linked and considered simultaneously. In this setting, countries may be part of multiple coalitions (agreements). Moreover, for some species there may be a cooperative fishing behaviour whereas for others non-cooperation may prevail. The question arises: how the ecosystem should be managed from the international perspective? An agreement governing all species, part of the species or one species per agreement.

Ellefsen et al. (2013) compare multi-species management to single-species management and, on the other hand, cooperative to non-cooperative management. The authors apply the concept of issue linkage by combining agreements on different species in a multispecies fishery. They conclude that there are significant gains by departing from single-species management to multi-species management. The theory of issue linkage has been explored in the IEAs literature and was originally proposed by Folmer et al. (1993). The advantage of issue linkage is that it can induce cooperation as it provides a form of transfers (Finus 2001). The results obtained by Ellefsen et al. (2013) are in line with this general principle.

The interaction between the species may play an important role in IFAs. Kronbak and Lindroos (2011) analyse the critical number of players from the biological point of view. The question addressed was: what is the maximum number of players for which the ecosystem can sustain all original species? They show in a non-cooperative game setting that sometimes open access is not a problem, and in other cases even very few players may already extinct one of the species. Hannesson (2013) is a recent example of including migratory aspects into a two-player game model. He shows that stock migration affects the bargaining position of the players. The minor player is shown to gain from random migrations and constant migrations, but in the case of stock-dependent migrations it is optimal for the major player to fish down the stock to a level where it does not migrate at all.

4.5 Climate Change and Fisheries

There are a few recent models that explicitly take into account climate change effects to international fisheries. The main idea is that climate change can affect, for instance, the distribution and reproduction of the fish stocks. This may have positive or negative effects to the countries involved and impact on the stability of IFAs. Further, the number of players may also change as a result of fish stocks migrating to the Exclusive Economic Zones of new coastal states. Miller et al. (2013) provide a review of how game theory can be used to address such problems.

Liu and Heino (2013) study the effect of changing stock distribution, due to climate change, on optimal fishing policies in a two-player dynamic non-cooperative model. They show that under reactive management, in which future distributional shifts of the stock are ignored, it is optimal to harvest aggressively if the fish density is decreasing. Proactive management, in which such shifts are considered, may help in conserving schooling species. This occurs as the distributional shift of the stock increases its ownership by one of the players, who has then an incentive to preserve the stock.

Connected to climate change, Ellefsen (2013b) discusses the case of the Northeast Atlantic mackerel, which has changed its migratory pattern being now available in Icelandic waters. The author uses a game-theoretic model of entry deterrence to determine whether the original fishing parties have an advantage from fishing the stock down to a smaller size to prevent another party from entering into the fishery. The results show that if the change in the migratory pattern of the stock is temporary then the optimal strategy for the original players is to fish such that they just deter entry to a potential entrant. If the change is permanent, then the new entrant will have a greater bargaining strength and will obtain a larger share of the aggregate payoffs, when compared to a temporary change.

Brandt and Kronbak (2010) show that climate change may have a negative impact on the stability of international fisheries agreements. They use an age-structured bioeconomic model of Baltic Sea cod and analyse the internal stability of the grand coalition. In their case, climate change means a negative shock to the recruitment via decreased salinity. Finally, Ekerhovd (2013) concludes in a two-player dynamic game that the increased productivity of the North-East arctic cod in the Barents Sea, due to climate change, favours cooperative possibilities.

5 Avenues for Future Research

Having surveyed the main contributions to the game theoretical analysis of IFAs, we now highlight some of the most promising avenues for future research.

The impact of the spatial dimensions of shared fish stocks on IFAs is a vast domain to explore, for instance dimensions such as migration and distributional area. In particular, Hannesson (2011) suggests that whether a stock is fished sequentially by separate national fleets or simultaneously in separate areas may have important consequences for the success of an IFA. Another relevant topic are the challenges to the stability of IFAs posed by changes in the spatial distribution of the stocks, due for instance to climate change.

The dynamic aspects of coalition formation, allowing for renegotiations if exogenous ecological or economic changes occur is an area that still needs more attention. This includes studying the formation of IFAs as dynamic games of coalition formation, in which players can revise their membership over time. This would allow analysing the interaction between current members and new entrants in a more sophisticated but also more realistic way. In this field, knowledge may be drawn from the IEAs literature (see Rubio and Ulph 2007). It should be noted that many internationally shared fish stocks are overexploited (FAO 2005) and this may have important consequences for the stability of IFAs. Hence, in this context, the use of static coalition games focused on steady-state stock levels may lead to misleading results.

To study the role of uncertainty and learning in the formation of IFAs, using the framework of partition function games, is another field that could benefit from more attention. Internationally shared fisheries are subject to considerable uncertainty both on its biological and economic dimensions. This uncertainty may play a role on the success of IFAs. This topic has been deeply explored in the IEA literature. For instance, Na and Shin (1998) and Kolstad (2007) show that, in the context of climate agreements, removing the "veil of uncertainty", through learning, is usually detrimental for the success of cooperation. Finus and Pintassilgo (2013) qualify this result and show that the conditions under which it holds are rather the exception than the rule. The application of this framework to fisheries presents some peculiarities, as fisheries uncertainty surrounds parameters common to all players (e.g. biological aspects, such as recruitment or stock growth) and also individual parameters (e.g. prices and harvesting costs).

Including multiple or overlapping coalitions is a further important extension of the current literature in IFAs. It is not unlikely that countries could join more than one coalition at the same time. For example, countries could cooperate (or free ride) with respect to different issues in the game, such as research, conservation, monitoring, different species, and enforcement.

Another extension to the literature on IFAs is to model the behaviour of coalition members as a bargaining process, instead of assuming that they maximise the sum of the individual payoffs. Finally, as suggested by Sumaila (1999) and by Kronbak and Lindroos (2013), a broader system approach in fisheries game theoretical modelling, including for instance species interaction, has a great potential to shed light on IFAs.

6 Conclusion

In this survey, we reviewed the rapidly expanding literature on the application of game theory to international fisheries agreements (IFAs) aiming to shed some light on the international conflicts and cooperation over shared fish resources. Our main focus was on the use of coalition games to model IFAs. We show that the earlier contributions use characteristic function games to analyse the sharing of cooperative benefits via appropriate cooperative solutions. Then, non-cooperative elements such as the stability of the agreements were progressively combined with the cooperative approach set by the characteristic function games. Finally, partition function games were introduced, allowing to address the endogenous formation of IFAs.

The literature on IFAs developed separately to the literature on international environmental agreements (IEAs) during the 1990s and only recently there has been some confluence between them, through standardized concepts, notation and methods. IFAs present many specific aspects compared to IEAs and therefore the lessons learned from the IFAs may be of particular relevance to the general theory of coalition formation over natural resource management.

Among the specific aspects of IFAs, we can highlight the following. First, internationally shared fish stocks are impure public goods, which exhibit varying degrees of rivalry and excludability. Second, the spatial distribution and migration of the fish stocks play a crucial role on the bargaining power of each fishing state. Third, IFAs are generally regional issues involving countries harvesting specific species in a particular area. Fourth, the number of countries involved in an IFA may change over time. These particular aspects, which generally do not apply to international climate agreements, may however be quite relevant for other international environmental agreements on regional issues, such as for instance water sharing and environmental pollution.

Finally, there are also many developments in the IEAs literature which have not yet been applied to IFAs. In our opinion, two deserve special attention. One is to model shared fisheries as dynamic coalition formation games. This has the potential to show the driving forces that lead countries to revise their participation in IFAs. The other development is to incorporate uncertainty and learning in fishery coalition games. This setting can be used to explore the role played by the economic and biological uncertainties surrounding fisheries on the formation and success of IFAs.

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