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Original research article

Dilemma of total allowable catch (TACs) allocated as shareable quotas: Applying a bio-economic game-theoretical approach to euro-mauritanian fisheries agreements

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ABSTRACT

The recent fisheries management approach by Mauritania recommends that Total Allowable Catch (TAC) quotas, identified as essential for maintaining fish stocks, be shared (allocated) among fishing fleets operating in Mauritanian waters. However, the efficiency of such management regulations is debated. This issue can be identified as the typical dilemma between distant-fishing countries and coastal countries. We developed a theoretical model to determine how to allocate TAC quotas between the fishing fleets of Mauritania (RIM) and the European Union (EU). We discuss the various procedures and conditions for optimizing the allocation of fishing quotas (by country) in context of the Nash equilibrium. We found that both equilibria are characterized by strategic interactions of the exploitation that influence both the supply of TAC quotas available on the market and the cost of externalities due to RIM's dependence on financial compensation by the EU and available TAC quotas.

1. Introduction

A sharp decline in marine biodiversity has been observed off the Mauritanian continental shelf over the past three decades (Labrosse et al., 2010), which is a highly productive upwelling area (Auger et al., 2016; Diogoul et al., 2021). Demersal fishes, the most valuable target species of industrial and artisanal fisheries in Mauritania, have been particularly impacted by overfishing, which has led to a decline in their productivity and the degradation of their habitat (Beyah & Gascuel, 2014). To prevent further habitat impacts and improve stocks, it is imperative to develop a sustainable fishery that can both provide economic benefits and maintain exploited fish populations.

A suite of public policies was endorsed in the late 1970s to institute more sustainable fishing and limit negative impacts on biodiversity (Kane, 2007). For example, since the early 1980s, fisheries policies have been based on fisheries agreements, from fishing control to fishing licenses. However, part of the fish stocks exploited by the "national" fishery (industrial and artisanal) has been given to foreign industrial vessels, especially after the emergence of a new artisanal fishery after the "octopus war" (Kane, 2007).

The Mauritanian Institute of Oceanographic and Fisheries Research (IMROP) estimates that more than 60% of fish stocks off the Mauritanian waters are either fully exploited or overexploited (IMROP, 2014) or reached or exceeded Maximum Sustainable Yield (MSY). For example, overexploitation of octopus (*Octopus vulgaris*) exceeds MSY by more than 17% (IMROP, 2014), illustrating an example of the "Tragedy of the Commons" (Hardin, 1968). Belhabib et al. (2015) assumed that the EU fleet under-reported their catch in the East-central Atlantic by 71% (1.6 million tons reported) between 2000 and 2010, whereas the Chinese fleet under-reported their catch by 92% (2.3 million tons reported), which would make overexploitation estimates lower than reality. Therefore, fish catch from Mauritanian waters by these two fleets likely threatens the food security of nations in the West African sub-region.

There is an abundance of literature using game theory (Nie et al.,

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2014) as a framework for analyzing fisheries and their externalities. Traditionally, fisheries economists use bio-economic models to analyze the cost-benefit or profitability of fishing methods and gear types (Cunningham et al., 1985), determine sustainable levels of catch and effort, and the method of exploitation to reach equilibrium levels, particularly in rebuilding overexploited stocks (Gordon, 1954; Schaefer, 1954, 1957; Hannesson, 1993; Knowler, 2002; Anderson & Seijo, 2009). Increasingly, bio-economic models are being used to assess the impact of policies governing natural resource exploitation and human welfare (Prellezo et al., 2012; Ba et al., 2018; 2019). Typically, these models simulate a variety of potential management scenarios, allowing decision-makers to compare the relative advantages and disadvantages of various combinations of stock preservation strategies and income flows. One of such model is game theory, which can be an effective approach for determining how fishermen behavior and fisheries management regulations impact shared fish stocks (Guillotreau & Vallée, 2005; Bailey et al., 2010). Game theory could be used to ensure compliance with Mauritania's fisheries regulations relating to the creation, implementation, and management of TAC quotas in accordance with Mauritania's fisheries development plans.

Based on negotiation theory (a subset of game theory), Munro (1979) showed that successful transboundary management of fish stocks requires a cooperative approach. Consequently, Munro was the first statistician to demonstrate how fisheries policy and management can be applied theoretically in the context of game theory.

The literature has expanded considerably to incorporate other properties of fisheries, such as multispecies fisheries (Le Manach et al., 2013; Doyen & Péreau, 2012; Bailey et al., 2010; Fischer & Mirman, 1996), exploitation of migratory species (Costa Duarte et al., 2000), and consideration of market externalities (Feichtinger and Mehlman, 1989). In the latter case, the price of fish varied in a duopolistic framework according to the quantity caught by each player. As the technologies of the two players differ, a Stackelberg-type information disadvantage can be compensated for by technology that is more efficient.

The most recent contributions in this theoretical framework combine bioeconomics and game theory to incorporate coalition games that affect stability (Lindroos and Kaitala, 2001; Costa Duarte et al., 2000; Pintassilgo, 2003; Lindroos et al., 2007). In their work, Lindroos and Kaitala (2000) study a cohort model for the Norwegian herring fishery. Nash equilibrium are computed for each possible coalition for fishing mortality (two players or countries joined in a cooperative strategy). The challenge is to study the conditions of coalition stability and very few studies show stability in the grand coalition (Lindroos et al., 2007). However, when a player joins the coalition, the gains increase systematically, as well as the value of the fishery (Brasão et al., 2000). Stability will then depend on the shared rules adopted by the players, where, in particular, the gains of the cooperative players (or countries) must exceed those of the free riders. However, in fisheries agreements, shared quota systems generally involve more than two players (Guillotreau & Vallée, 2005; Kane, 2007; Vallée et al., 2009). Sumaila (1999) developed a model that integrates more than two competitors in the management of shared stocks. Establishing quotas to maintain sustainable fisheries and monitoring compliance of fishing fleets (domestic and foreign) is extremely difficult for fisheries regulators. In Mauritania, the Minister of Fisheries and Maritime Economy of Mauritania (MPEM) that manages the stocks. The enforcement of compliance by foreign fishing fleets is particularly crucial as foreign vessels account for more than two-thirds of the catches withdrawn from Mauritania's Exclusive Economic Zone (EEZ).

This paper adds to the literature, which is focused on an application of two-player game theory to fisheries management, e.g., Levhari and Mirman (1980), highlighted how a fish stock is affected by the decisions of two competitors and how each competitor integrates the actions of the other into its strategy. From this, we draw new lessons regarding the role of financial compensation in the sharing of TAC quotas between Mauritania (RIM) and the European Union (EU).Historically, cooperation between the African, Caribbean, and Pacific (ACP) countries and the current European Union dates back to the first Convention signed in Lomé on 28 February 1975 and then revised regularly in 1979, 1984, 1990, and in 1995 (Kane, 2007). The Economic Partnership Agreements came after the Lomé Convention was initiated in 1975 and the Cotonou Agreement was signed in 2000. The Cotonou arrangement removed tariff barriers to ACP exports while allowing ACP countries to maintain tariffs on their imports from the EEC. These non-reciprocal trade preferences expired on 1 October 2014, following an earlier extension in 2007. The objective of Cotonou was also to allow the EU to negotiate with sub-regional groups. This last point is particularly resisted by developing countries and the EU still negotiates access to fishing grounds with individual ACP countries on behalf of the Member States. The quotas obtained by the EU are then distributed among the Member States, which in turn grant these rights to national companies. This article attempts to shed new light on these issues at a time when new constraints and opportunities are emerging. The reformations of the Mauritanian fisheries policy (MPEM, 2000) and that of the Common Fisheries Policy (CFP) of the European Union since 2002 are now based on the search for sustainable fisheries and not simply on the security of supply to the European market. The current EU bilateral fisheries agreements, based on "payment for access" and the payment of a fishing license, are gradually evolving towards fishing quota agreements that promote responsible fishing in the mutual interest of the parties involved. Central questions need to be asked in this context: (1) to what extent can the European Union's stated desire for more sustainable fishing modify the strategies of each player in the search for a compromise favorable to the conservation of natural stocks? (2) How will it preserve the economies of developing countries? (3) Is Mauritania, the owner of the resources, able to restore its negotiating power in fisheries agreements despite its macroeconomic dependence on monetary compensation?The known model of the "fish war" in game theory (Levhari & Mirman, 1980) is modified here to account for the macroeconomic dependence of the country owning the fishery resources on the financial manna proposed by the European Union in exchange for access to the resources. The hypothesis adopted is that of an asymmetry of temporal preferences between the EU and Mauritania, the latter giving greater importance to the future state of its resources. The state of the stocks thus becomes dependent on the level of the TAC and the effort adopted by each of the stakeholders, but it is also jointly influenced by the weight of financial compensation in the negotiation process.

Levhari and Mirman (1980) developed a simple logarithmic game model in their "Fish War Game" scenario. We added a term this dynamic fish stock assessment model to account for financial compensation paid by the EU to Mauritania for fishing access rights. The model involves only two competitors, the European Union (EU) and Mauritania (RIM), in the joint exploitation of a total allowable catch, defined and allocated by a Mauritanian mediator or negotiator. The utility functions of each entity that share TACs are expressed as quotas (by country) as a function of financial compensation (alpha) paid by the EU. The model is primarily used to analyze the rules of negotiation in the search for an optimal fishing quota or simply to jointly improve negotiation outcomes (Ehtamo et al., 1999). In this study, we outline a series of steps that can be used to determine optimal fishing quotas, based on a two-dimensional diagram developed by Ehtamo et al. (1999), which plots the number of fish extracted by Mauritania against number of fish extracted by the EU (Fig. 1). Then, we determine a Pareto-optimal agreement and the Pareto-efficient border for the extraction of fish resources (Heiskanen et al., 2001; Ehtamo et al., 1996; Lou & Wang, 2016). The method of Ehtamo et al. (1999) is a constrained optimization problem that Mauritanian mediators intend to use to determine the incremental steps needed to reach quota Pareto-optimal agreement. Although both countries must move in the direction of compromise imposed by the mediator, the usefulness of the agreement to one country depends on the choices made by the other country in the negotiation. We adopted the hypothesis that, although there is an asymmetry in the

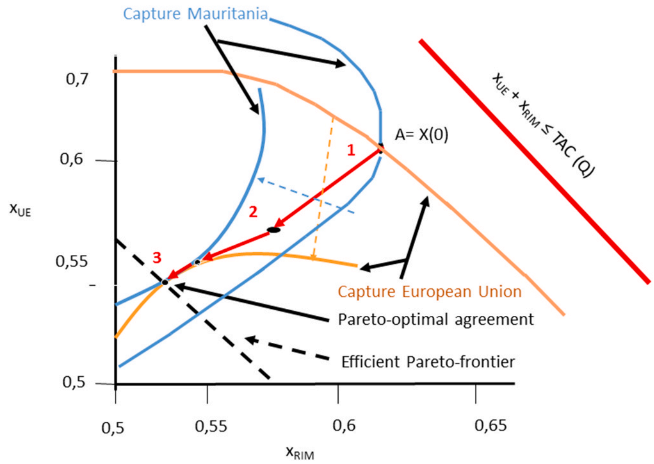

Fig. 1. Illustration of negotiating procedures leading to Pareto-optimal quota levels in two iterative steps (from 1 to 3) representing a series of negotiated, tentative agreements. Point 3 represents the optimal Pareto agreement. A Pareto optimum is a situation in which one cannot improve the fate of one agent without reducing the fate of the other. The points are limits that provide the maximum of satisfaction for two competitors (i.e., the Pareto-efficient frontier). Abbreviations: A = TAC at point X_0, X_{EU} = Quota for European Union, and X_{RIM} = Quota for Mauritania. Source: Vallée et al. (2009).

temporal preferences between the EU and the RIM in extracting its share of the TAC, there is also a desire among fishermen that the stock to be managed so that it can replenish itself by the next fishing season (t_{+1}). We will use decision processes leading to the Nash equilibrium for the game scenario and then compare our results with the cooperative equilibrium. Both of these approaches are politically acceptable relative to problems normally associated with establishing global quota systems while simultaneously maximizing national fishery incomes under sustainable fishing practices.

Game theory can provide the theoretical strategy a regulator can use to allocate fishing quotas (and hence incomes) of the fishing fleets it is empowered to regulate. Representatives of the regulated fleets can choose one of two approaches for negotiating its share of TAC – they can either cooperate or compete. However, in reality, negotiations for TAC shares are really in one part a cooperation and in another part a competition, which complicates the application of game theory models. However, the models (and model structure) can provide useful insights into the complexities inherent in real incomes sharing negotiation processes (e.g., Cournot competition (Ha et al., 2011).

Here, we revisit the game of fish war (Levhari-Mirman 1980) and negotiations between two players within the same fishery, and highlight the economic incentives underlying a quota management program in fisheries agreements. The main goal of this study is to determine a bio-economic model to analyze of the welfare gain/loss and Total Allowable Catch 'TAC' redistribution of quotas between Mauritania and the European Union.

2. Material and methods

2.1. Equations for utility functions

The issue in this paper is solved by optimization and game theory is a mathematical tool that is rapidly expanding in fisheries management. It can be used to assist in the theoretical resolution of the negotiation of fisheries agreements. The functions used here are utility functions, where one party's action may affect the other's action in sharing a TAC. Utility functions, by country (EU and RIM), are as follows:

$$U_{EU} = log[(1-\alpha)x_{EU}] + \beta_{EU} log(Q - x_{EU} - x_{RIM})^{\tau} \quad (1)$$

$$U_{RIM} = \log(x_{RIM} + \alpha x_{EU}) + \beta_{RIM} \log(Q - x_{EU} - x_{RIM})^{\tau} \quad (2)$$

where $0 \leq \alpha < 1$, $0 \leq \beta_{EU}, \beta_{RIM} \leq 1$, $0 < \tau < 1$, $0 < Q \leq +\infty$, and

$$(x_{EU}, x_{RIM}) \in D = \{(x_{EU}, x_{RIM}) : x_{EU} \geq 0, x_{RIM} \geq 0, x_{EU} + x_{RIM} \leq Q\} \quad (3)$$

The parameters β_i ($\beta_{EU\ and}\ \beta_{RIM}$) represent the desires of the two competitors (EU and RIM) to sustain exploited fish stocks over the long-term, whereas τ is the stock recruitment rate for the resource (fish population). The parameters x_{RIM} and x_{EU} designate the catch of each country, whereas Q is total allowable catch and alpha (α) represents the monetary transfer (financial compensation) between countries, which in this case is proportional of the TAC allocated to the EU. Therefore, it represents the reduction in the utility value of a given quota to the EU. Although the EU's quota contributes to Mauritania's national budget, the TAC quotas limit fish extraction for Mauritanian fleets (this ensures a sustainable exploitation of fishery resources in short and medium-term time frames). The table below describes the parameters and variables of the model (Table 1).

We describe alpha values (financial benefits of EU and Mauritania catches), based on the "Fish War" game simulation. Two scenarios are compared. The mediator uses the method called the "little steps method" of Ehtamo et al. (1999, 2001) (Fig. 1) where the mediator seeks a mutually beneficial direction and proposes to each group of fishermen (RIM and EU) this direction via "small steps" of compromise (Supplementary 1). This scenario describes the Nash equilibrium situation, whereas the second scenario describes a cooperative situation where in the regulator seeks to maximize financial gain and consequently income in a sustainable fishery.

2.2. Nash equilibrium

The Nash equilibrium (Nash, 1950; Kreps, 1989) considers the power relationship between competitive players. Finding the equilibrium that consists of determining the point at which none of the players (countries) desires to modify their strategies unilaterally. The optimality of the Nash equilibrium shows that any game with opposing strategies has a Nash equilibrium (Holt & Roth, 2004) that is a proposed solution of a non-cooperative game involving two or more players in which each player is assumed to know the equilibrium strategies of the other players, and no player has anything to gain by changing only his own strategy. Mathematically, this equilibrium can be solved using the Lagrange multiplicator:

Table 1
Parameters Used in TAC Sharing Utilities Functions. RIM: République Islamique de Mauritanie; EU European Union.

Symbol	Description
U_{EU}	European Union Utility
U_{RIM}	Mauritanian Utility
β_{EU}	Preference for the future of sustainable fisheries in the European Union
β_{RIM}	Preference for the future of sustainable fisheries in the Mauritanian (RIM)
τ	Stock recruitment rate
x_{EU}	Quotas or catch of European Union
x_{RIM}	Quotas or catch of Mauritania
α	Financial compensation paid by the EU to the Mauritanian Public Treasury.
Q	Fish stock or allowable catch rate (TAC)
D	Improved leadership of negotiators in the determination of their quotas
T	Optimum utility at Nash equilibrium
λ	Lagrange multiplier
L	Collective utility function
x^C_{EU}	Catch EU for cooperative strategy
x^C_{RIM}	Catch RIM for cooperative strategy
x^N_{EU}	Catch EU Nash equilibrium
x^N_{RIM}	Catch RIM Nash equilibrium
R	Player reaction function i

$$\underset{x_i \lambda_{i,1}, \lambda_{i,2}}{\mathrm{Max}}\, L_i \;\; \textit{with}\; L_i = \; U_i e \lambda_{i,1}(Q - x_{EU} - x_{RIM}) + \lambda_{i,2} e_i \tag{4}$$

where each λ_{ij} is a Lagrange multiplier associated with the constraints of the equation (Kuhn & Tucker, 1951). To solve problems of optimization under non-linear constraints of inequality, the conditions of Kuhn-Tucker or Karush-Kuhn-Tucker are used (Chung, 2009). The possible solutions provided by Kuhn-Tucker conditions are:

$$\partial L_i \big/ \partial X_i = 0, \lambda_{i,1}(Q - x_{EU} - x_{RIM}) = 0, \lambda_{i,2} x_i = 0 \tag{5}$$

Given the above constraint, any equality in Equation (5) makes it possible to reduce the conditions of maximization optimal under those constraints to the satisfaction of the model:

$$x^*_{EU} = T_{EU}(x_{RIM}) \Leftrightarrow \frac{\delta U_{EU}}{\delta x_{EU}} = 0 \tag{6}$$

$$x^*_{RIM} = T_{RIM}(x_{RIM}) \Leftrightarrow \; \frac{\delta U_{RIM}}{\delta x_{RIM}} = 0 \tag{7}$$

For the EU:

$$x_{EU} = \frac{(Q - x_{RIM})}{1 + \beta_{EU}\tau} \equiv T_{EU}(x_{RIM}), \lambda_{EU,1} = 0, \lambda_{EU,2} = 0 \tag{8}$$

For the RIM:

$$\left\{ \begin{array}{l} x_{RIM} \geq 0 \, and \, x_{RIM} = \dfrac{Q - x_{RIM} - \alpha x_{RIM}\beta_{RIM}\tau}{1 + \beta_{RIM}\tau} \\ \quad = T_{RIM}(x_{EU}), \lambda_{RIM,1} = 0, \lambda_{RIM,2} = 0 \\ x_{RIM} = 0 \, and \, \lambda_{RIM,1} = 0, \lambda_{RIM,2} = \dfrac{\beta_{RIM}\tau}{Q - x_{EU}} - \dfrac{1}{\alpha x_{EU}} \end{array} \right\} \tag{9}$$

The results of the collective simulation show that the quota restrictions granted to the EU (e.g., those represented by the non-negative quota constraints for Mauritania) are no longer verified. In this case, the implicit price of Mauritania's fishing quotas becomes non-zero.

If the EU's response function is not affected by the classic Levhari and Mirman (1980) model, Mauritania's response to restrictions is commensurate with the importance it attaches to the financial compensation provided by the EU. We have:

$$\frac{\partial T_{RIM}(x_{EU})}{\partial \alpha} < 0 \tag{10}$$

In other words, the more the EU gives up the large share of the TAC to Mauritanian fishermen, then the mediator will encourage local fishermen to benefit more from the allocated TAC. However, a monetary value can be determined for this fishing quota allocated to the Mauritanian (i.e. the amount of compensation that Mauritanian fishermen will agree to pay and/or to stop fishing). The value of this quota (which would be paid by EU fishers) is:

$$x_{EU} \geq \frac{Q}{1 + \alpha\beta_{EU}\tau} \tag{11a}$$

This value of this quota declines as the amount of the asset available (1.259) available for redistribution increases.

Nash equilibriums are such that $(x^N_{EU}, x^N_{RIM}) \in T_{EU} \cap T_{RIM}$ for either

$$\left\{ \begin{array}{l} x^N_{EU} = \dfrac{Q\beta_{RIM}}{\beta_{EU} + \beta_{RIM} - \alpha\beta_{RIM} + \tau\beta_{EU}\beta_{RIM}}, x^N_{RIM} \\ = \dfrac{Q(\beta_{EU} - \alpha\beta_{RIM})}{\beta_{EU}(1 + \beta_{RIM}\tau) + (1 - \alpha)\beta_{RIM}}, \textit{if}\; \alpha < \dfrac{\beta_{EU}}{\beta_{RIM}} \\ \\ x^N_{EU} = \dfrac{Q}{1 + \beta_{EU}} \; \textit{and}\; x^N_{EU} = 0, \; \textit{if}\; \alpha \geq \dfrac{\beta_{EU}}{\beta_{RIM}} \end{array} \right\} \tag{11b}$$

At the Nash equilibrium, the condition under which a non-zero fishing quota exists for Mauritanian fishermen can be reduced to the following condition:

$$\alpha < \frac{\beta_{EU}}{\beta_{RIM}}.$$

For any value, $\alpha < \frac{\beta_{EU}}{\beta_{RIM}}$ the properties of the Nash equilibria are:

$$\frac{\partial x^N_{EU}}{\partial \alpha} = \frac{Q\beta^2_{RIM}}{(\beta_{EU} + \beta_{RIM} - \alpha\beta_{RIM} + \tau\beta_{EU}\tau\beta_{RIM})^{\,2}} > 0 \tag{12}$$

and

$$\frac{\alpha x^N_{RIM}}{\partial \alpha} = -\frac{Q(1 + \tau\beta_{EU})\beta^2_{RIM}}{[(\alpha - 1)\beta_{RIM} - \beta_{EU}(1 + \tau\beta_{RIM}\,)]^2} < 0 \tag{13}$$

3. Results

3.1. Nash equilibrium

Mathematically, this equilibrium can be solved using the Lagrange multiplicator:

$$\underset{x_i \lambda_{i,1}, \lambda_{i,2}}{\mathrm{Max}}\, L_i \;\; \textit{with}\; L_i = \; U_i e \lambda_{i,1}(Q - x_{EU} - x_{RIM}) + \lambda_{i,2} e_i \; \partial L_i \Big/ \partial X_i = 0, \lambda_{i,1}(Q$$
$$- x_{EU} - x_{RIM}) = 0, \lambda_{i,2} x_i = 0 x^*_{RIM}$$
$$= T_{RIM}(x_{RIM}) \Leftrightarrow \; \frac{\delta U_{RIM}}{\delta x_{RIM}} = 0 x_{EU} = \frac{(Q - x_{RIM})}{1 + \beta_{EU}\tau} \equiv T_{EU}(x_{RIM}), \lambda_{EU,1} = 0, \lambda_{EU,2} = 0 \frac{\partial T_{RIM}(x_{EU})}{\partial \alpha} < 0 x_{EU}$$
$$\geq \frac{Q}{1 + \alpha\beta_{EU}\tau} \left\{ \begin{array}{l} x^N_{EU} = \dfrac{Q\beta_{RIM}}{\beta_{EU} + \beta_{RIM} - \alpha\beta_{RIM} + \tau\beta_{EU}\beta_{RIM}}, x^N_{RIM} \\ = \dfrac{Q(\beta_{EU} - \alpha\beta_{RIM})}{\beta_{EU}(1 + \beta_{RIM}\tau) + (1 - \alpha)\beta_{RIM}}, \textit{if}\; \alpha < \dfrac{\beta_{EU}}{\beta_{RIM}} \\ \\ x^N_{EU} = \dfrac{Q}{1 + \beta_{EU}} \; \textit{and}\; x^N_{EU} = 0, \; \textit{if}\; \alpha \geq \dfrac{\beta_{EU}}{\beta_{RIM}} \end{array} \right\} \frac{\partial x^N_{EU}}{\partial \alpha} = \frac{Q\beta^2_{RIM}}{(\beta_{EU} + \beta_{RIM} - \alpha\beta_{RIM} + \tau\beta_{EU}\tau\beta_{RIM})^{\,2}} > 0 \frac{\alpha x^N_{RIM}}{\partial \alpha}$$
$$= -\frac{Q(1 + \tau\beta_{EU})\beta^2_{RIM}}{[(\alpha - 1)\beta_{RIM} - \beta_{EU}(1 + \tau\beta_{RIM}\,)]^2} < 0$$

In this case, the quota requested by a foreign fleet (e.g., the EU) will be greater than he agree to compensate the host country (e.g., Mauritania) in return for a larger part of the TAC. Symmetrically, this same coefficient reflects the arbitration of the Mauritanian mediator between the options of exploiting the TACs by the national fishery (low value of alpha) or allowing the EU fleets to operate, hence the negative derivative of the TAC level of the Mauritanian fisheries relative to the alpha parameter. Finally, as already stated, more the rate of alpha quickly increases, more the TAC quota limit is quickly reached; then Mauritanian fishermen will no longer share in allocated TACs. In addition, we can check the following signs of the EU derivatives:

$$\frac{\partial x_{EU}^{n}}{\partial \beta_{EU}} < 0, \frac{\partial x_{EU}^{n}}{\partial \tau} < 0 \tag{14}$$

This is illustrated by the two inequalities above: (1) if the EU's desire is for sustainable fisheries in the future, then its current catches and quotas will decrease and (2) if the instantaneous growth rate of the resource (fish) increases, then EU catches will be the same in the first scenario because biological recovery of stock populations is desired by the EU.

For Mauritania, with $\alpha < \frac{\beta_{EU}}{\beta_{RIM}}$, we always have:

$$\frac{\partial x_{RIM}^{N}}{\partial \beta_{RIM}} < 0, \frac{\partial x_{RIM}^{N}}{\partial \tau} = \frac{Q\beta_{EU}\,\beta_{RIM}\,(\alpha\beta_{RIM} - \beta_{EU})}{[(\alpha - 1)\beta_{RIM} - \beta_{EU}(1 + \tau\beta_{RIM})]^2} < 0 \tag{15}$$

which means that (1) if Mauritania wants its catch to increase in the future, then its current catch must decline and (2) if the instantaneous growth rate of the resource (fish) increases, then current catch by Mauritanian fishermen must decline.

The analysis of the model results at equilibrium (is a proposed solution for a non-cooperative game involving, in which each country is supposed to know the equilibrium strategies of the other, and no country has anything to gain by only changing its own strategy.) can be illustrated numerically with the following values:

If Total Allowable Catch If Total Allowable Catch $Q = 1.259$, $\tau = 0.2852$, $\beta_{EU} = 0.4$, and $\beta_{RIM} = 0.9$, then:

(1) If $\alpha = 0$, then $x_{EU}^{N} = 0.807$, $x_{RIM}^{N} = 0.359$, $U_{EU}^{N} = -\ 0.485$, $U_{RIM}^{N} = -\ 1.636$, then the global fishing TAC = 1.166;
(2) If $\alpha = 0.2$, then $x_{EU}^{N} = 0.926$, $x_{RIM}^{N} = 0.226$, $U_{EU}^{N} = -\ 0.555$, $U_{RIM}^{N} = -\ 1.463$, then the global fishing TAC = 1.153;
(3) If $\alpha = 0.5$, then, $x_{EU}^{N} = 1.13$, $x_{RIM}^{N} = 0$, $U_{EU}^{N} = -0.805$, $U_{RIM}^{N} = -1.096$, then the global fishing TAC = −1.90.

With the above-assigned values, if the mediator wants to rebuild stocks, then the mediator should not allocate a quota to Mauritanian fishermen if compensation (α) >0.444. Logically, the presence of a strictly positive redistribution of quotas (α >0) will reduce the TAC of Mauritanian fishermen and increase the TAC of EU fishermen. Mauritania is in a better situation when the redistribution increases and the total number of fish caught declines. Therefore, establishing Total Allowable Catch (TAC) quotas makes it possible to reduce pressure on fish stocks, even if neither country agrees with the established quotas. However, reducing catch leads to a deterioration in the utility (satisfaction) for the EU.

3.2. Cooperative game equilibrium

At the equilibrium point in a cooperative game scenario, Mauritania and EU (cooperators) focus on how to share catch quotas (in contrast to strictly competitive scenarios, where each competitor focuses on choosing a stable strategy. Assuming that sharing a global quota is in the best interest of both parties, quota sharing depends on cooperation that is considered an "external" element of the game (i.e., it defines the objective of the game, in this case, the sustainability of the fishery). The maximum value for the collective utility (satisfaction) in a cooperative game is defined as:

$$\underset{x_{EU},\ x_{RIM},\ \lambda_{C1}\ \lambda_{C2}\ \lambda_{C3}}{Max} L_c \text{ With } L_C = U_{EU} + U_{RIM} + \lambda_{C,1}(\mathcal{Q} - x_{EU} - x_{RIM}) + \lambda_{C,2}x_{EU} + \lambda_{C,3}x_{RIM} \tag{16}$$

If the conditions of the first order are:

$$\left\{ \begin{array}{l} \frac{\delta L_C}{\delta x_{EU}} = 0, \frac{\delta L_C}{\delta x_{RIM}} = 0 \\ \\ \lambda_{C,1}(\mathcal{Q} - x_{EU} - x_{RIM}) = 0, \lambda_{C,2}x_{EU} = 0, \lambda_{C,3}\, x_{RIM} = 0 \end{array} \right\}$$

Then the coupled solution, called the cooperative solution, is:

$$\left\{ \begin{array}{l} x_{EU}^{C} = \frac{Q}{(1-\propto)(2+\beta_{EU}\tau+\beta_{RIM}\tau)}, x_{RIM}^{C} \\ = \frac{Q(1-2\alpha)}{(1-\alpha)(2+\beta_{EU}\tau+\beta_{RIM}\tau)}, \text{ if } \alpha < 0.5 \\ x_{RIM}^{C} = \frac{2Q}{2+\beta_{EU}\tau+\beta_{RIM}\tau} \text{ and } x_{RIM}^{C} = 0, \text{ if} \alpha \geq 0.5 \end{array} \right\}$$

$$\left\{ \begin{array}{l} x_{EU}^{C} = \frac{\mathcal{Q}}{(1-\alpha)(2+\beta_{EU}\tau+\beta_{RIM}\tau)}, x_{IRM}^{N} \\ = \frac{\mathcal{Q}(1-2\alpha)}{(1-\alpha)(2+\beta_{EU}\tau+\beta_{IRM}\tau)}, \text{if } \alpha < 0.5 \\ x_{RIM}^{C} = \frac{2\mathcal{Q}}{2+\beta_{EU}\tau+\beta_{RIM}\tau} \text{ and } x_{RIM}^{C} = 0, \text{ if } \alpha \geq 0.5 \end{array} \right\}$$

For a value α = 0, then the cooperative solution (i.e., the case without transfer) applies:

$$x_{EU}^{C} = \frac{\mathcal{Q}}{2\ +\ \beta_{EU}\tau\ +\ \beta_{RIM}\tau} = x_{RIM}^{C}$$

In order to illustrate results obtained in the cooperative solution, the previous numerical values of the Nash equilibrium are used. This gives three results:

(1) If $\alpha = 0$, then $x_{EU}^{N} = 0.807$, $x_{RIM}^{N} = 0.359$, $U_{EU}^{N} = -0.485$, $U_{RIM}^{N} = -1.636$ then the global fishing TAC = 1.166.
(2) If $\alpha = 0.2$, then $x_{EU}^{N} = 0.926$, $x_{RIM}^{N} = 0.226$, $U_{EU}^{N} = -0.555$, $U_{RIM}^{N} = -1.463$, then the global fishing TAC = 1.153;
If $\alpha = 0.5$, then $x_{EU}^{N} = 1.13$, $x_{RIM}^{N} = 0$, $U_{EU}^{N} = -0.805$, $U_{RIM}^{N} = -1.096$, then the global fishing TAC = −1.90.

Indeed, the mediator modifies the distribution of TACs based on the alpha value determined, but does not change the utilities because (by definition) the overall optimal quota has already been defined.

For the EU (wherein α < 0.5), we can verify that:

$$\frac{\partial x_{EU}^{C}}{\partial \alpha} > 0, \frac{\partial x_{EU}^{C}}{\partial \beta_{EU}} < 0, \frac{\partial x_{EU}^{C}}{\partial \tau} < 0$$

which means that: (1) If the cash payment from EU to Mauritania increases, then there is an incentive for the EU to request a larger share of the allocated quota, thus allowing it to increase its catch; (2) If the EU's desire is to increase its future catches, then its current catches will decrease; and (3) If the instantaneous growth rate of a target fish species increases, the EU catch allocation will decrease.

For Mauritania:

$$\frac{\partial x_{RIM}^{C}}{\partial \alpha} > 0, \frac{\partial x_{RIM}^{C}}{\partial \beta_{RIM}} < 0, \frac{\partial x_{RIM}^{C}}{\partial \tau} < 0$$

Therefore, if the payment to Mauritania by the EU increases, then the catch quota allocated to the Mauritanian fleet decreases, if the preference of Mauritania is to increase catches in the future then its current catch quota will decline, and if the instantaneous growth rate of the resource increases, catch quotas for Mauritanian fishermen will decline.

4. Discussion

We revised the model of Levhari and Mirman (1980) to take into account financial compensation provided by the European Union when determining a global TAC at the scale of a fish stock, which is in this case subdivided into individual quotas for RIM and EU. Thus, the bio-economic model of game theory focused on the sustainability of exploiting fish stocks and Mauritania's reliance on financial compensation that strongly influences how Total Allowable Catch is shared.

At the most recent round of negotiations between Mauritania and the EU, the final objective of the Sub Regional Fisheries Commission (SRFC) focused on restoring the bargaining power of its member nations in fish allocation talks [i.e., to analyze the effects and identify alternatives to the financial dependence of national institutions relative to fishery agreements (CSRP, 2005)]. The Mauritanian Chief Negotiator and the SRFC clearly indicated that the main obstacles to member nations agreeing on a coherent strategy for negotiating quota allocations lies less on the effects of fishing quotas that on the objectives of fishery policies (e.g., sustainable yields) then on how member nations will be monetarily compensated. Therefore, it is difficult to envisage how any quota policy, which conserves fishery resources by imposing quotas on powerful foreign industrial fleets (e.g., European, Chinese, and Russian fishing fleets) would reserve part for domestic fishing fleets. Such quota sharing negotiations impose a dual externality in utility functions (U_{EU} *and* U_{RIM}), which lead to the classical stock externality situation that results from a sharing of total allowable catches (TAC) (e.g., between fleets of coastal nations and European fleets) and from the monetary compensation provided by foreign fleets or the share of TAC allocated to foreign fleets. The Nash equilibrium can be used to determine how much of the TAC should be reserved for its own fleet (i.e., where $\alpha < \frac{\beta_{EU}}{\beta_{RIM}}$). Catches by the EU and RIM fleets represent the isovalue elements of the utility values for the two countries, which represents sustainable fishing in Mauritanian waters. Therefore, the isovalues represent the fish population required to rebuild the stock adequately:

$$\left(x^N_{EU}, x^N_{RIM}\right) \in T_{EU} \cap T_{RIM}$$

The total EU catch plus the total RIM catches is equal to the TAC set by a mediator; see Fig. 2. The function of the collective utility (T) allows the mediator to find a compromise condition under a maximized utility constraint. On the other hand, if the desire for future catches of the EU is much lower than the desire of Mauritania, then Mauritania will have to reconsider its desire based on the reduced financial compensation that would be offered by the EU. However, an increase in the transfer coefficient, which represents a tax on the exploitation of an individual quota, has positive effects on the long-term conservation of the fish stock. In spite of this, the Nash equilibrium based on the bilateral negotiation of a TAC shows that Mauritania will financially gain by coming to the negotiating table with a less demanding conservation policy (Low β_{RIM}) and/or higher financial demands (high α) for compensation or its quota share. By switching to a cooperative solution to determine a TAC, a transfer mechanism always determines the equilibrium solution of the game (i.e., elevating the coefficient does not change the total magnitude of the TAC, but rather gives the EU fishing fleet a greater share of the TAC).

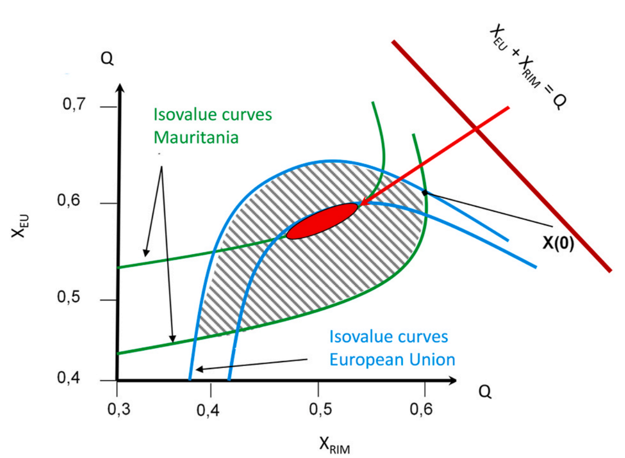

Fig. 2. Quota isovalue curves for the European Union (blue lines, EU) and Mauritania (green lines, RIM). The area of overlap (red) between isovalue curves represents the number of fish that can be sustainably fished by both fishing fleets (European Union and Mauritania). Abbreviations: X_0 = TAC at point O, X_{EU} = Quota of European Union, and X_{RIM} = Quota for Mauritania. Adapted from Ehtamo et al. (1999).

Karush-Kuhn-Tucker or Kuhn-Tucker conditions allow solving optimization problems under nonlinear inequality constraints. In general, Kuhn-Tucker conditions are necessary conditions for the optimization treatment of utility functions, i.e., if we are at an optimum point, they are always realized. However, it is not because they are realized at a point (x, λ) that this point is necessarily an optimum. Nevertheless, there is at least one situation in the allocation of n quotas where it can be affirmed that they are indeed sufficient. This is the case in particular when Mauritania's utility function is concave and the functions of the European Union are convex. Kuhn-Tucker conditions are necessary and sufficient conditions of optimality. In this situation, a point is optimal if and only if the conditions of the Lagrange multipliers associated with the constraints are realized.

A number of important components of realistic TAC sharing processes in fisheries agreements are not taken in account by the model and they must still be categorized and described by our theoretical model, such as differences in the size of fishing vessels, the biological rest period, and boarding the sailors and observers on board and so one. One problem with any theoretical modelling effort is in comparing results of simulations against real data. To be useful in the allocation of TAC quotas, any bio-economic modelling must be based on the description of the fisheries, accurate data on population size, biomass of managed fish stocks, and reliable statistical data on the economic performance of the fishing fleets.

Sharing Total Allowable Catch (TAC) among fishing fleets may appear to be an applicable management strategy, among others, for sustaining equitably (fairly) allocating fishing incomes between fishing fleets, e.g., between the EU and the RIM. Any allocation of catch should link financial compensation to one part of the TAC in a way to maximize the number of fish caught in Mauritanian waters. If the Nash equilibrium result for the EU-RIM is not in accordance with the cooperative equilibrium describing the sharing of the TAC in Mauritania, we can assume that the sharing of the TAC in the cooperative equilibrium is mismatched with the integration of the sector in the national economy and in conflict with the policies initiated in particular within the framework of the landing of catches in RIM.

In fisheries management, economists assign the TAC a fundamental role. The individual quota sharing approach incorporates the concept of capitalism in the commercial exploitation of a common resource (e.g., fish) by an industry (e.g., a fishery). Theoretically, in a competitive and deterministic world the individual quota system is equivalent to a per unit tax that encourages an extractive industry to quickly reach a socially optimal allocation of the exploited resource. However, in reality, many externalities related to either the resource or the behavior of its users (e.g., fishermen) may prevent this optimum allocation from occurring.

A Total Allowable Catch sharing policy is not focused on achieving a general long-term equilibrium, but rather its goal is to restore a renewable fish resource that has become over-exploited in a competitive environment. The sharing of TAC quotas protects a fish species by taxing catch in a way that establishes a short-term social optimum for fishing industry participants more concerned with maximizing their short-term profits than in maximizing the long-term well-being of the resource or other participants in the fishing industry. Although managing fisheries by establishing quotas on individual fish species may benefit the fishery over the long term, not every participant in the fishery can be guaranteed success. Furthermore, enforcement of TAC quotas has had a limited success in effectively managing fish resources, which is known to those who evaluate fish populations. For one, establishing quotas requires both an accurate assessment of the fish population available for exploitation and no fishing-under-declaration regulations. There are two problems with the fair distribution of individual quotas: (1) the establishment of the duration of quota allocation and (2) the acquisition of most of the quota shares by the most influential ship-owners (because they have more economic power or better capacity to lobby the regulators than small scale fishermen). Some fisheries experts believe that the concentration of quota shares in the hands of foreign fishing fleet owners will generate economic efficiency gains in the sector. However, it is difficult to determine the actual effects that TAC allocation will have on the social utility of fishing for local societies or how the distribution of monetary gains varies between categories of fishermen, even if the EU fishing agreements are, without doubt, the most transparent worldwide. Therefore, the sharing of fish quotas in Mauritania should only be considered after weighing potential impacts, even though quota sharing is generally recognized as a sustainable way to manage fisheries and the maritime economy and it is partially financed by aid programs or by multilateral cooperation.

The FAO of the United Nations states that responsible fisheries management should follow "principles and international standards of behavior to ensure responsible practices for effectively ensuring the conservation, management, and development of bio-aquatic resources, while respecting ecosystems and biodiversity." (FAO, 1995). Mauritania's current national strategy for managing its fishery sustainably provides it an opportunity to control the distribution of Total Allowable Catches (TAC) in its territorial waters. Such a transboundary fisheries management strategy will gain in importance as climate changes (Sarré et al., 2017; Fernandes & Fallon, 2020) and should be useful for establishing quota sharing strategies in the future at a sub-regional scale (Hieu et al., 2018) avoiding as far as possible bilateral agreement with foreign country for transboundary sharing stocks.

Declaration of competing interest

All authors must disclose any financial and personal relationships with other people or organizations that could inappropriately influence (bias) their work. Examples of potential competing interests include employment, consultancies, stock ownership, honoraria, paid expert testimony, patent applications/registrations, and grants or other funding. Authors must disclose any interests in two places: 1. A summary declaration of interest statement in the title page file (if double anonymized) or the manuscript file (if single anonymized). If there are no interests to declare then please state this: 'Declarations of interest: none'. This summary statement will be ultimately published if the article is accepted. 2. Detailed disclosures as part of a separate Declaration of Interest form, which forms part of the journal's official records. It is important for potential interests to be declared in both places and that the information matches.

Credit authorship contribution statement

E.A. Kane: Conceptualization, the work, Formal analysis, Redact the paper and edit the revision and figures. **A.C. Ball:** Reviewed the first version. Redact the paper and edit the revision and figures, and. **P. Brehmer:** Redact the paper and edit the revision and figures.

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Appendix A. Supplementary data

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