Fishing is not an easy game: a short overview of game-theoretic resource modeling

Thomas 'Orlando' Da Costa

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Abstract

This note provides an overview of game-theoretic approaches to managing common-pool fisheries resources, emphasizing the strategic interactions among agents and their implications for ecosystem sustainability. Following on from the work of Bailey et al. (2010), it examines the challenges of cooperative and non-cooperative resource exploitation through dynamic and biological externalities. Models like those by Levhari and Mirman (1980) reveal how Cournot-Nash equilibria result in overfishing compared to cooperative solutions. Furthermore, multi-species frameworks as the one in Fischer and Mirman (1996) illustrate the nuanced effects of species interactions on exploitation dynamics. Recent developments, such as Doyen et al. (2018), introduce intermediate complexity models that highlight the importance of cooperation for biodiversity preservation. The paper then underscores the need for coalition stability, legally binding agreements, and innovative policy tools to reconcile economic objectives with biodiversity conservation in global fisheries management.

1 Game theory and the tragedy of the commons

In 1954, Howard Scott Gordon [1954] laid the cornerstone of the economic theory of common-pool resources, taking as example demersal fishes (which are not migratory). By introducing a mathematical conceptualization of what is an optimal exploitation based on fishing efforts, he opened the door to a wide field of research known as bioeconomics. More broadly, it allowed to reveal that common-pool resources are overexploited most of the time — what Hardin [1968] popularized as the tragedy of the commons. A year before, Harold Demsetz [1967] argued that property rights could internalize the externality caused by overexploitation driven by private benefits and collective costs. The idea that commons were unavoidably doomed to be overexploited unless they were privatized or regulated lasted until being challenged by Elinor Ostrom [1990], who issued eight principles that allow the existence of self-governing commons without private property or state intervention, based on a meta-analysis of empirical studies. In short, self-gouvernance can hold if:

1. there is a clear definition of the community and its members.
2. the exploitation rules are adapted to the resource.
3. users can adapt the exploitation rules.
4. there is a robust control of the resource exploitation.
5. the sanctions for not respecting the rules are graduated, with a low level at the beginning.
6. conflicts can be resolved quickly and at a low cost.
7. there is no tension between the self-organizing community and external authorities.
8. the organization is nested in several levels.

Unfortunately, it is easy to see how self-governance could not be applied to the current system of industrialized, globalized fishing. The first principle is compromised as actors and fish mobility increase in complexity. Bailey et al. [2010] classify shared fisheries resources into four categories: domestic shared stocks, transboundary shared stocks, straddling stocks, and discrete high seas stocks. While the first category could be compatible with self-governance, the second immediately adds a layer of complexity in the form of international agreements and raise a potential conflict between an international community and sovereignty. The third and fourth, as they involve highly migratories species that can travel across the high seas, would require a global gouvernance which cannot be achieved at the same time as low conflict resolution costs and easy democratic participation.

Beyond those arguments, overfishing is now vastly acknoledged (for instance, predatory fish biomass twenty years ago was already only about 10% of pre-industrial levels [Myers and Worm, 2003]) and has been internationally adressed since the 1982 United Nations Convention on the Law of the Sea.

While dynamic optimization models try to reveal the optimal exploitation of a resource, it does not necessarily take into account the strategic interactions between agents. This is where game theory can help explore and analyze the tragedy of the commons through non-cooperative games — the best example being the prisoner's dilemma: Nash equilibria are not Pareto-optimal, and the social optimum is not a Nash equilibrium. Nonetheless, cooperative games are not free of issues, as the phenomenon of free-riding can also emerge for more-than-two players game and undermine the cooperation.

Following Bailey et al. [2010], we will review how game theory has been applied to fisheries management since 1980, focusing on the evolution of the models and the results obtained. We will especially pay attention to Levhari and Mirman [1980], Fischer and Mirman [1996] and Doyen et al. [2018], expliciting how in standards model we very often find that non-cooperative catch rates are higher than cooperative ones and how adding complexity to a model makes its results more subtle.

2 Two-players game and dynamic externality

First and foremost, the game-theoretic approach to fisheries management is based on the assumption that players fall under the rational choice theory, *i.e.* they are rational and selfish, maximizing their own payoff with perfect anticipation and knowing that the other players will do the same.

The first paper that relied on this approach was published by Munro [1979]. He used cooperative game theory to study the management of transboundary fish stocks (the second category of shared fisheries resources) when (static) asymetry arises between countries in terms of discount rates, costs of fishing and consumers' preferences, and showed that joint-management would be greatly simplified with transferable utility, for instance with side payments.

One year on was introduced by Levhari and Mirman [1980] the concept of dynamic externality, a situation where externalities evolve over time and might involve intertemporal effects: the actions of an agent at the date t_0 can affect other agents' payoffs at some $t > t_0$, therefore allowing to look for an optimal exploitation path in the long-run.

The model is a two-players game involved in a Cournot competition. This statement implies that only one species is exploited (homogeneous product condition) competitively by the two rational players, who act strategically (as Cournot Duopolists). Players represent countries that compete in quantities rather than in price and maximize their sum of discounted utilities given the output of the other player. Some key assumptions of the model should be noted: on the biological side, rather than choosing a standard Gordon-Schaefer model [Schaefer, 1957], the fish stock dynamics follows $x_{t+1} = x_t^\alpha, \quad \alpha \in]0, 1[$. On the behavioral side, the player's actions affect the biomass stock, such that $x_{t+1} = (x_t - \sum_{i=1}^{2} c_i)^\alpha$. Only economic considerations count and threats are forbidden, such that actions based on the other player's past actions are not allowed (which could be questioned in a repeated game). The catch is only used for consumption, not for resale or profit. Countries i are differentiated by their discount rates β_i and the chosen utility function is logarithmic, $u_i = \ln c_i$. The competitive model is solved using dynamic programming through Bellman optimization, with the stock size as a state variable[1]. Considering that countries anticipate Cournot-Nash equilibrium in $t+1$, the authors find by recurrence the policy functions for a h-period horizon. It should be highlighted that the existence of heterogenous time-preferences still allows for the existence of a stable equilibrium. To find the steady-state of the Cournot-Nash problem, it suffices to study the analytical case where h tends to infinity. It is given by the equation (1).

$$\bar{x}^{(CN)} = \left(\frac{1}{\frac{1}{\alpha\beta_1} + \frac{1}{\alpha\beta_2} - 1} \right)^{\frac{\alpha}{1-\alpha}} \tag{1}$$

This steady-state depends only on the discount rates and the biological parameter α, is bounded between 0 and 1 and is independent of the initial stock size.

The cooperative case is computed by maximizing the discounted sum of both countries utilities, which implies a single discount rate β and a common catch $2c$. The authors find that the steady-state level of fish is higher under a cooperative solution than under a Cournot-Nash situation, as shown in (2).

$$\bar{x}^{(Coop)} = (\alpha\beta)^{\frac{\alpha}{1-\alpha}} > \bar{x}^{(CN)} \tag{2}$$

Levhari and Mirman explain that this higher stock size in the combined-management situation is related to a smaller total consumption, which makes it possible to obtain higher permanent catch levels in return.

Keeping the same Cournot-Nash framework, they study the effect of a what they call a linear growth function (which corresponds to an exponential growth of the stock size), $x_{t+1} = r(x_t - \sum_{i=1}^{2} c_i(x_t)), \quad r > 1$. Under an infinite horizon Cournot-Nash game, the stock growth is written as:

$$x_{t+1} = \frac{r x_t}{\beta_1^{-1} + \beta_2^{-1} - 1}, \quad 0 < \beta_1, \beta_2 < 1 \tag{3}$$

Based on equation (3), the stock grow infinetely if:

$$r > \beta_1^{-1} + \beta_2^{-1} - 1 \tag{4}$$

It tends to 0 otherwise. On the contrary, a cooperative solution (understood as a common exploitation with the same discount factor $\beta_1 = \beta_2 = \beta$) leads to $x_{t+1} = r\beta x_t$.

These competitive and cooperative solutions define a condition (5) for which the joint-management could allow for a infinite growth of the fish stock whereas the species goes extinct in a competition framework.

$$2\beta^{-1} - 1 > r > \beta^{-1} \tag{5}$$

It is important to highlight (as the authors forgot to precise) that this condition is only valid for a competitive situation where countries have the same discount factor. Moreover, the authors do not provide any analysis of this condition, although it is easy to show[2] that it holds for any $\beta < 1$, therefore implying that, in a case of linear growth function respecting condition (5) where countries have the same characteristics, the cooperative solution always leads to a growth in stock whereas the competitive solution leads to extinction.

To study another type of asymetry, the authors explored a Stackelberg competition model (or leader-follower game) where the market leader chooses its catches first and the follower adapts its own catches to the leader's choice. This model implies a perfect information assumption as the first country take into account the second country reaction, using its

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[1]
$$U = \max_{\{x_{t+1}\}_0^\infty} \sum_{t=0}^{\infty} \beta^t u(x_t, x_{t+1}) \text{ s.t. } \{x_{t+1}\} \in \Gamma(x_t)$$
$$V(x) = \max_{x' \in \Gamma(x)} [F(x, x') + \beta V(x')]$$
where $\Gamma(x)$ is the feasibility correspondance, *i.e.* the set of feasible choices.

[2]
$$\begin{aligned} & 2\beta^{-1} - 1 > r > \beta^{-1} \\ \Rightarrow & 2\beta^{-1} - 1 > \beta^{-1} \\ \Leftrightarrow & 2 - \beta > 1 \\ \Leftrightarrow & 1 > \beta \end{aligned}$$

Cournot policy function as an input. The equilibrium can be found by backward induction on the Bellman equation, and the steady-state is elicited as previously, giving the equation (6).

$$\bar{x}^{(Stack)} = (\alpha\beta_1 \cdot \alpha\beta_2)^{\frac{\alpha}{1-\alpha}} < \bar{x}^{(CN)} \tag{6}$$

Because of the starting advantage the leader has, it benefits from higher short-run catches than the follower. However, this situation leads to a lower steady-state stock size than under Cournot competition. This framework can be useful when studying countries with power asymetry, as the lower steady-state can be seen as a trade-off between the leader's short-run benefits and the two countries' long-run benefits. Bailey et al. [2010] argue that sequential games (*i.e.* games where players doesn't act simultaneously) are more realitistic than stage-games to represent transboundary fisheries management and can mimic the negociation of international agreements.

Since Levhari and Mirman [1980], many two-players game models have been developed, most of them building in the same direction while adding nuances and complexity. Clark [1980] concurs that non-cooperative behavior leads to overfishing in a limited entry system with at least two players. The use of stage-games, *i.e.* repeated games with a finite number of periods (unlike the infinite steady-state equilibria seen before), allows for a more precise accounting of the causality of events: for instance, in Sumaila [1995], the first stage is dedicated to the investment *ex ante* in fishing capacity, and on the second stage the resource exploitation (and therefore the competition) begins for 15 years. The study of a restricted fishery access and a single non-migratory species under this stage-game is then applied on a real situation, the Arcto-Norwegian cod fishery, to elicit the optimal capacity investments in terms of number of vessels that should be allocated between two actors.

3 From single to multiple species games

Game theory applied to the management of common-pool resources has revealed how the mechanisms of strategic interaction influence a stock of resources, but few articles extend their analysis to a multi-species context. Using a two-sector differential duopoly model, Fischer and Mirman [1992, 1996] include in their scope of research what they call a biological externality, which is the biological interdependence between the two species captured by two countries. In their first paper, the authors find that overfishing occurs in the non-cooperative problem because each country fails to take into account the effects each species has on the other. The stability of the steady-state and the optimal policies also depends on the type of interactions the two species face. In the second paper, they aim to integrate both the dynamic externality studied in Levhari and Mirman [1980] and the biological externality introduced in Fischer and Mirman [1992], looking for the closed-loop solution of the two-players two-species model and its efficiency.

The model defines two countries $i, i \in \{1, 2\}$, that compete for the same resource, composed of two species, (x_t, y_t). The stock of each species is affected by the stock of the other species, such that:

$$\begin{cases} x_{t+1} = x_t^{\alpha_1} y_t^{\beta_1} \\ y_{t+1} = y_t^{\alpha_2} x_t^{\beta_2} \end{cases} \tag{7}$$

In the equation (7), α_j captures the reproductive effect of species j whereas β_j represents the interaction effect of species j on species k, where $j, k,\ j \neq k$ take values in $\{1, 2\}$, with species x corresponding to $j = 1$ and species y to $j = 2$. Three typical types of biological interactions are modeled. A symbiotic relationship happens if $\forall j, \beta_j > 0$. On the contrary, a negative interaction, such as competition for a resource or mutual predation, is captured by a negative interaction coefficient: $\forall j, \beta_j < 0$. Eventually, a predator(j)-prey(k) relationship is modeled by opposite signs of β: $\forall k \neq j, \beta_j > 0, \beta_k < 0$.

The main biological assumption of the model is that the reproductive effect of a species is stronger than the one related to its interaction with the other species:

$$\alpha_j > |\beta_j| \tag{8}$$

On the players' side, the interactions are similar to the paper of Levhari and Mirman

[1980], with the stock size as a state variable affected by the catches $c_{j,t} \equiv \sum_{i=1}^{2} c_{i,j,t}$ of both countries i. The authors make the assumption that catch ratios γ are linear in stocks, *s.t.* $c_{i,j,t} = \gamma_{ij} s_t$, for $(s,j) \in \{(x,1),(y,2)\}$, $i \in \{1,2\}$. Equation (9) displays the stock dynamics taking into account biological and dynamic externalities and the assumption that catches are linear with respect to the stock.

$$\begin{cases} x_{t+1} = & \Big(x_t(1-\sum_{i=1}^{2}\gamma_{i,1})\Big)^{\alpha_1} \\ & \times \Big(y_t(1-\sum_{i=1}^{2}\gamma_{i,2})\Big)^{\beta_1} \\ y_{t+1} = & \Big(y_t(1-\sum_{i=1}^{2}\gamma_{i,2})\Big)^{\alpha_2} \\ & \times \Big(x_t(1-\sum_{i=1}^{2}\gamma_{i,1})\Big)^{\beta_2} \end{cases} \tag{9}$$

Finally, the utility function takes the form $u(c_{i,1,t}, c_{i,2,t}) = \nu_x \ln c_{i,1,t} + \nu_y \ln c_{i,2,t}$. It is a weighted sum of a standard logarithmic utility function for each species, with $\nu_x, \nu_y > 0$ the relative weights of the two species in the utility function.

The authors use the same dynamic programming approach as Levhari and Mirman [1980] to solve the model, *i.e.* Bellman optimization:

$$V_i(x,y) = \max\{u(c_{i,1}, c_{i,2}) + \rho_i V_i(x', y')\} \tag{10}$$

They impose the (logical) condition that $0 \leq c_x \leq x$, $0 \leq c_y \leq y$, *i.e.* the catches are non-negative and cannot be higher that the existing stock. The authors then assume that $V_i = A_i \ln x + B_i \ln y + D_i$, for some constants A_i, B_i, D_i depending on biological and behavioral parameters, and the discount rates. As the analytical solution doesn't say much about the roles of the parameters, they homogenize the consumption preferences for a species and the discount rate ($\forall i, \rho_i = \rho$ and $\nu_x = \nu_y = 1$), and they represent species with very similar characteristics, *s.t.* $\forall j, \alpha_j = \alpha$ and $|\beta_j| = \beta$. This simplification allows them to elicit two cases for catch ratios (which are now the same for both countries), one for symbiosis and negative interaction (*i.e.* $\beta_j = \beta$), and one for predator-prey relationship (*i.e.* $\beta_1 = \beta, \beta_2 = -\beta$).

Setting $\Delta = (1-\alpha\delta)^2 + (\beta\delta)^2$, the catch ratios are given by:

$$\begin{aligned} \gamma &= \frac{1-\delta(\alpha+\beta)}{2-\delta(\alpha+\beta)} \\ \gamma_{\text{predator}} &= \frac{\Delta}{\Delta+1-\delta(\alpha+\beta)} \\ \gamma_{\text{prey}} &= \frac{\Delta}{\Delta+1-\delta(\alpha-\beta)} \end{aligned} \tag{11}$$

Then, Fischer and Mirman [1996] analyze their results along two dimensions: a comparison with the single externality results from Fischer and Mirman [1992], and Levhari and Mirman [1980], and a comparison between cooperative and non-cooperative solutions. When both externalities are present:

- $\gamma_{\beta}^{(NC,both)} > \gamma_{\beta}^{(Coop,both)}$. The Nash equilibrium always lead to overfishing in negative interaction and symbiosis ($\beta_j = \beta$) compared to the cooperative solution.
- $\gamma_{\beta>0}^{(NC,both)} < \gamma_{\beta>0}^{(NC,dyn)}$. There is more overfishing in symbiosis ($\beta > 0$) when only the dynamic externality occurs.
- $\gamma_{\beta<0}^{(NC,both)} > \gamma_{\beta<0}^{(NC,dyn)}$. It is the contrary for negative interactions ($\beta_j < 0$): overfishing is a response to negative interaction.
- $\gamma_{\beta}^{(NC,both)} > \gamma_{\beta}^{(NC,bio)}$. The feasibility constraint (equation (8)) exacerbate the fact that overfishing (compared to a case of biological externality only) happens for symbiosis and negative interaction.
- $\gamma_{\text{predator}}^{(NC,both)} > \gamma_{\text{predator}}^{(NC,bio)}$. In a case of predator-prey, less fishing on the predator happens when only the biological externality occurs.
- $\gamma_{\text{prey}}^{(NC,both)} \gtrless \gamma_{\text{prey}}^{(NC,bio)}$, $\gamma_{\text{prey}}^{(NC,both)} > \gamma_{\text{prey}}^{(Coop,both)}$. The effect is unclear for the prey as the dynamic externality leads to overfishing but accounting for the biological externality pushes to preserve the prey. The prey is still overfished compared to a cooperation case.

It has to be noted that in a case of negative interaction with biological externality only, underfishing can happen as compared to the cooperative solution ($\gamma_{\beta<0}^{(NC,bio)} < \gamma_{\beta<0}^{(Coop,bio)}$). Because overfishing occurs when both externalities are present, the authors argue that the dynamic externality is stronger than the biological externality: the need to compete for the resource overwhelms the externality due to the biological interactions between the species.

From these results should be remembered that parameters of the biological interaction and the intertemporal discount rates matter to settle uncertain outcomes, and that two-players two-species game could bring more refined results. Before overviewing some works that focused on cooperation, we will take a closer look to a recent paper that studies the tragedy of the commons in a multi-players multi-species context, Doyen et al. [2018].

The authors generalize the model of Fischer and Mirman [1996] by using a bioeconomic model of intermediate complexity, a compromise between very stylized models and high dimensional ones, the former often expliciting a single mechanism while the latter attempt to capture the whole complexity of socio-ecosystems, sacrificing analytical clarity. They aim to investigate the effect of a dynamic multi-species (with interspecific relationships) and multi-agents framework on catch levels and on the ecosystem state and the biodiversity. To do so, they use on the biological side the multi-species Gompertz dynamics in discrete time[3].

$$x_j(t+1) = x_j(t) \cdot e^{(r_j + \sum_{k=1}^{n} \beta_{jk} \ln x_k(t))} \tag{12}$$

with:

- $x_j(t)$ the stock of species $j, j \in [1, n]$.
- r_j the intrinsic growth rate.
- β_{jk} the interspecies relationship, and $\beta_{kk} \in [-1, 0]$ to account for intraspecific competition. Also, $||S||_\infty = \max_{j,k} \mid \beta_{j,k}| < 1$.

On the behavioral side, the authors consider M identical agents who harvest $c_{i,j}(t)$, affecting the stock such that $x_j(t) \to x_j(t) - \sum_{i=1}^{M} c_{i,j}(t)$. Each of the fishers i follows a one-period utility function $U(c_i) = \sum_{j=1}^{n} \nu_j \ln c_{i,j}$, again a generalization of Fischer and Mirman's model. They also introduce the harvest rate $\gamma_{i,j} = \frac{c_{i,j}(t)}{x_j(t)}$ as a control variable. They rigorously justify this functional relationship by introducing the vector of shadow prices for different species w, whose expression can be found equation (13) (with I the identity matrix, ^{T} the transposition operation).

$$w = \nu(I - \rho(I + S)^T)^{-1} \tag{13}$$

w assesses the marginal contribution to the ecosystem services U of the different species j involved in the ecosystem. If w is well-defined and $(I + S)^T > 0$, the authors prove that the aggregate non-cooperative optimal catch for all species is linear: $\forall j, c_j = \gamma_j x_j$.

Using similar maximization programs and dynamic programming methods[4], they found the following optimal harvesting rates:

$$\begin{cases} \gamma_j^{NC} = \frac{M \cdot \nu_j}{M \cdot \nu_j + \rho((I+S)^T w)_j} \\ \gamma_j^{Coop} = \frac{\nu_j}{\nu_j + \rho((I+S)^T w)_j} \end{cases} \tag{14}$$

It should be highlighted that in this model, the optimal harvesting rates are not time-dependent, and that the cooperative case is a particular case of the non-cooperative one, where $M = 1$ (one single player). Therefore, $\forall M > 1, \forall j, \gamma_j^{NC} > \gamma_j^{Coop}$, *i.e.* the aggregate optimal non-cooperative harvest fraction is always strictly larger than the aggregate optimal cooperative harvest fraction.

Given the results in equation (14), the authors explore the potential gains from cooperation to the ecosystem state and the biodiversity according to the number of players. Let us introduce the species richness indicator, $SR(x) = \sum_{\text{species } j} \mathbf{1}_{\mathbb{R}_*^+}(x_j)$, that informs on extinction risks in a very simple manner by counting the number of species with a positive stock size.

First, when there is a large number of agents, *i.e.* $M \to \infty$, it is easy to show

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[3] Notations are homogenized with respect to Fischer and Mirman [1996] to ease the reading.

[4] For instance, the optimal harvest is found using the following Bellman equation:

$$V_i(x) = \max_{c_i} \{\nu' \ln(c_i) + \rho V_i(G(x - c_{i.} - c_{-i.}))\}$$

which can be rewritten as:

$$V_i(y) = \max_{\gamma_i} \{\nu' \cdot (\ln(\gamma_i) + y)$$
$$+\rho \cdot V_i \cdot (\mathbf{r} + (I + S)\mathbf{y} + (I + S) \ln(1 - \gamma_i - \gamma_{-i}))\}$$

with the system being log-linearized, $y = \ln x$

that $\forall \nu_j > 0, \gamma_j^{nc} \to 1$. Thus, it implies the depletion of every exploited stock, *i.e.* $\lim_{M\to\infty} x^{nc}(t) = 0$. On the contrary, when agents cooperate, the global catches of each species do not depend on the number of players, only the individual harvests share is reduced, such that $\lim_{M\to\infty} x^{c}(t) > 0$. Therefore, if $x_0 > 0$:

$$SR(\lim_{M\to\infty} x^c(t)) > SR(\lim_{M\to\infty} x^{nc}(t)) \qquad (15)$$

For any positive initial state, if the number of fishers is high, cooperation promotes the conservation of species, *i.e.* the ecosystem is more diverse.

However, Doyen et al. [2018] prove that the gains from cooperation for the ecosystem state turn out to be slightly more tricky when the number of agents remains limited, because they depend in a complex way on species interactions, species preferences, and future preferences based on the discount factor. Then, it exists situations where non-cooperation can lead to a greater species richness. The authors suggest that this phenomenon could occur under the mesopredator realease hypothesis, where the reduction in abondance of top-predators can lead to a growth of the mesopredators stock. This could imply more or less important dynamic perturbation of the trophic equilibria (for instance, it cannot be excluded that in the long term the overabondance of meso-predator leads to the loss of smaller species until their extinction).

A more general result is raised by using the second ecosystem state indicator. Defining the ecosystem as $Ecos(x) = w^T \ln(x) = \sum_i w_i \ln(x_i)$, they show that as long as $(I + S^T)^k w > 0$ holds, for any situation, the cooperative ecosystem is larger than the non-cooperative ecosystem:

$$Ecos(x^c(t)) \geq Ecos(x^{nc}(t)) \qquad (16)$$

Eventually, approaching the ecosystem value by the marginal value of a specie ($w = \frac{\partial V(y)}{\partial y}$), the authors are able to prove that the cooperative ecosystem performs better at the equilibrium.

Thus, by revisiting the tragedy of open access and overexploitation issues, Doyen et al. [2018] succeeded in extending the results of Fischer and Mirman [1996], even providing an analysis of the ecosystem state. Especially, their model of intermediate complexity allows to identify ambiguous situations where analytical solutions are not enough to predict the outcome of the game anymore. To deepen their analysis, authors suggest to extend the issue of cooperation in a multi-species context to a coalition problem, where players can form coalitions to maximize their utility.

4 On cooperation and coalitions

One cannot evoke cooperative games without citing *Two-person cooperative games* [Nash, 1953], in which Nash formally defines cooperation as the be ability of two players to discuss the situation and agree on a rational joint plan of action, therefore associating the concept of cooperation with communication, negociation and threats. We should also mention that a two-players stable cooperative outcome emerges under Pareto Optimality and Individual Rationality Constraint ($\forall i, u_i^{Coop} \geq u_i^{NC}$). In a more practical way, Miller and Munro [2004] suggested to consider a solution that incorporate flexibility — *e.g.* through side payments — in order to reach the resilience of the cooperative solution.

More broadly, the literature on applied cooperative game theory to fisheries management has been growing since the XXI$^{\text{st}}$ century. An interesting results raised by Hannesson [1997] in an infinite-duration repeated game is that there is a large incentive to deviate from cooperation given a sufficiently large number of players, because the payoffs associated with a non-cooperative solution are proportional with the number of players. Highly migratory stocks policies thus might be challenged by the issue of the number of countries involved in the stock management. While joint management is seen as an efficient response to the tragedy of the commons, its implementation is hampered by numerous obstacles.

For instance, when applied to study the efficiency of Marine Protected Areas (MPAs), Sumaila and Armstrong [2006] showed that besides the positive effects on fish stocks and rent from fisheries, the framing of the management plan before and after the MPA implementation could influence which countries may win or loose in the cooperation. At the individual level, cooperation between fishers depends on their attitudes towards risk, the costs they face, but also on the biological characteristics (*e.g* initial size and internal growth rate) of the fish population.

Between the strategic interactions involving two individuals and the global cooperation between all the players, there is a middle ground in which coalition slips in. A coalition can be defined as the cooperation of a subset of players, and can fall under the category of characteristic-function games (C-games) or of partition-function games.

Formally, we define a cooperative game as a pair (N, v), where N is the set of players and $v : 2^N \rightarrow \mathbb{R}$ is a characteristic-function assigning a payoff to each coalition $C \subseteq N$, with $v(\emptyset) = 0$. Let be (N, v) a coalitional game. An allocation $x \in \mathbb{R}^N$ is said:

$$\begin{cases} \text{feasible} & \text{if } x(N) \leq v(N) \\ \text{efficient} & \text{if } x(N) = v(N) \\ \text{individually rational} & \text{if } x_i \geq v(i), \forall i \in N. \end{cases}$$

In C-games, the value of a coalition $v(C)$ is the sum of the payoffs of the players involved in the coalition. The standard approach to solve a C-game is to compare the relative payoff of each coalition with respect to the grand coalition (*i.e* $C = N$), before setting a way of sharing the benefits between each player involved in the coalition. This is not a trivial question, and multiple rules have been proposed in the literature. The Nash bargaining solution maximizes the product of surplus utilities of each player and respects three axioms, namely invariance to affine transformations, symmetry (if i and j are identical, $\forall C \not\ni i, j, \quad v(C \cup \{i\}) = v(C \cup \{j\})$) and Pareto-optimality. The nucleolus method, introduced by Schmeidler [1969], seeks to distribute resources as fairly as possible, ensuring that the coalition with the largest dissatisfaction (or excess) is minimized first. It guarantees uniqueness and efficiency, but not necessarily symmetry neither linearity. Finally, the Shapley value attributes to the players their marginal contribution to the coalition, and is the only sharing rule that satisfies the following axioms: symmetry, linearity, efficiency and neutrality ($\forall i \notin C, \forall C$, a player i that does not bring any synergy to the coalition should only get its marginal contribution as a payoff: $v(C \cup \{i\}) = v(i)$), such that the value always exist and is unique. Let us note that reasoning in Shapley values for non-cohesive games could lead to results in which it may be more beneficial to involve in a coalition the players with the largest marginal contribution to cooperation rather than trying to include all the players in a grand coalition.

However, Bailey et al. [2010] argue that none of the above sharing rule guarantee a stable coalition. Defining core solutions as the set of all stable coalitions leads to the concept of stand-alone stable coalition, which is a coalition that is both internally and externally stable: no player can find an interest in leaving the coalition to become a singleton or a free rider, and no external player can find a benefit in joining the coalition [Pintassilgo, 2003]. Especially, the internal stability could be understood as $u_i^C \geq u_i^{\text{free rider}}$, which corresponds to the individual rationality constraint.

Charasteristic function games face a major limitation as they ignore the influence of coalition externalities, although the formation of a coalition can affect (positively or negatively) the payoffs of the non-members. To highlight externalities effects, some merges of coalitions can be done to observe potential variations in payoffs of the non-members. A free-rider can then be understood as a player that benefits from the coalition without being included in it.

Pintassilgo [2003] argues that the presence of externalities and free-rider incentives are generally present in the context of the management of high seas fisheries, through regional fishery organizations. To bypass C-games drawbacks, he turns to a partition function game. Let $N = \{1, 2, \ldots, n\}$ be a set of player and Ω the set of all partitions of N, and let a coalition structure $\mathcal{P} = \{S_1, S_2, \ldots, S_m\}$ be a partition of the set of players N. Then, a game in its partition function form specifies a coalition worth $V(S, \mathcal{P})$ for every partition $\mathcal{P}$ in Ω and every coalition S which is an element of $\mathcal{P}$. Thus, the value of a coalition S is determined by the overall partition $\mathcal{P}$ of the players, not just the set S. Applying this framework to the management of Northern Atlantinc bluefin tuna led to the fact that a fair sharing rule was not a sufficient condition for a stable coalition. The author called instead for the establishment of legally binding agreements.

The lack of enforcement power is indeed a major issue in the management of highly migratory stocks (*e.g.* tuna), not being included for instance in Regional Fisheries Management Organizations (RFMOs). These legal constraints seem more than necessary as Pintassilgo et al. [2010] identified that the number of countries involved in a competition for a fish stock is proportional to the relative gains from full cooperation, but inversely proportional to the likelihood of a large RFMO to be stable (a result that was already sensed by Hannesson [1997]). Using a game in partition function form based on the Gordon-Schaefer model, they found that new entrants increase the incentives of RFMO members to leave and decrease the incentives of non-members to join it.

The relationship between members in the coalition and outsiders is also captured in the "new member problem", where a player can choose to free-ride, *i.e.* practice unregulated fishing outside of the coalition, until the time when it becomes beneficial to join the coalition. Then, how can this player be taken responsible for the previous damage they caused, as RFMOs cannot exclude an interested party? Pintassilgo and Duarte [2000] suggests three solutions.

They consider setting up a fair sharing rule. However, in addition to the limitations we already presented, it might be unefficient in absence of complete information (how could potentially inefficient or free-riding new members be controlled?) and difficult to negociate for a large coalition of countries with potentially diverging interests. Nonetheless, in their simulation, the use of a Shapley value as a sharing rule preserves the individual rationality constraint.

The second solution is to impose a waiting period before a new member can join the coalition, in order to reduce their payoff, and therefore their threat. This idea might be particularly valid for players with a high discount rate; however, the authors' simulation using a five-year waiting period and a discount rate of 4% didn't eliminate the incentive of the Distant Water Fishing Nations to free-ride but only reduced the decrease of the payoff of the original members associated to the entry of the new one.

The final proposition bears in the idea of transferable membership through Individual Transferable Quota (ITQ). Actual members of the coalition would have *de facto* property rights, whereas prospective members could only have access to the fishery by acquiring the corresponding quota from the member countries. In practice, a two-stage allocation can be considered, where the allocation of quotas by regional organizations to countries happens first, followed by the distribution of quotas by countries to fishers. Therefore, the entry of new members would not change the cooperative and non-cooperative payoffs of the other players, and transfers will only take place if it is mutually beneficial for both parties.

Side payments are seen as a solution for many problems: for instance, using a stochastic incomplete-information harvesting game, McKelvey et al. [2003] argue that ITQ can encourage cooperative management in asymmetrical information situations. Their model is of great interest as most of the literature assumes perfect information: developing stochasticity analyses could enhance the study of resilient cooperative solutions that haven't been found yet. Bailey et al. [2010] also suggest using Principal-Agent analysis to integrate imperfect information and uneven power into the common-pool resources literature, with the aim of finding incentives that induce an agent to act in the best interest of a principal. Few studies have applied this model to fisheries management; nonetheless, policy instruments such as tax, property rights and catch privileges can enhance the principal's control over the agent.

5 Discussion

Many progress has been done from forty years of game theory applied to fisheries management and strong results has been uncovered.

Most of the theoretical results pushes for cooperation rather than competition to manage the commons, a result guessed since Hardin [1968] but supported by many works afterwards. This cooperation seeks to be translated in real policies, however many hurdles (*e.g.* free-riding and incentive for cooperation, straddling stock, high seas and international laws) remain to be overcome, some of them that game theory can address using coalition formation games.

One can regret that many papers assume the unicity of a Nash equilibrium. Admittedly, any given Nash equilibrium garantee the uniqueness of steady-states values, but solving the Bellman equation only ensure the existence of at least one Nash equilibrium. Hence, multiple equilibria could exist, although once a strategy profile is chosen, the long-run resource stock levels and payoffs are uniquely determined by the Bellman equation.

We could suggest that the next steps in the literature should be to develop more realistic models, especially by integrating stochasticity (*e.g.* potential dynamic changes in the payoffs due to environmental degradation) and heterogeneity in players (multi-heterogenous-agents models). The use of profit and the integration of effort costs instead of only considering the utility of catches would also improve the modeling work by better corresponding to well-known bio-economic MEY targets and better fitting to the economic reality of the fishery sector.

Finally, the field sometimes seem to lack imagination, often finding transferable utility as an ultimate solution to the tragedy of the commons. However, the use of ITQs is not without its critics, as it can for instance lead to the concentration of market power in the hand of the biggest firms, generate unemployment and more generally low social acceptability. Working on open vs. restricted membership coalitions, sharing rules and integration of imperfect information and non-rationality could maybe renew the potential of game theory in the management of common-pool resources.

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