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Management of the Northern Atlantic Bluefin Tuna: An Application of C-Games

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Abstract *This paper considers the prospects for cooperative multilateral management of the North Atlantic bluefin tuna fisheries in accordance with the United Nations (UN) Agreement on Straddling Fish Stocks and Highly Migratory Fish Stocks signed in December 1995. A three-players characteristic function game (c-game) is used to analyze the cooperative agreements. The analysis focuses on the sharing of total net returns from cooperation. Three sharing rules are calculated; namely, the Nucleolus, the Shapley value, and the Nash bargaining solution. The analysis is based on simulation and optimization results from a multi-gear, age-structured, bioeconomic model developed for the North Atlantic bluefin tuna fisheries, East and West stocks.*

The results show, as expected, that significant gains can be attained from cooperation. The different sharing rules for the distribution of gains provide different returns to each player. Nonetheless, the basic transfer payments structure is rather stable. This case study points out some particular situations where these solutions are not enough to guarantee cooperation between all the coastal states.

Key words Bluefin tuna, cooperative games, high-seas fisheries, highly migratory fish stocks, Nash bargaining solution, Nucleolus, Shapley value.

Introduction

The management of highly migratory species has become one of the most important problems in the management of ocean fisheries (Munro 1998).

Under the 1982 Law of the Sea, high seas were considered to be international common property, being open to the fishing activities of any distant water fishing nations. In the past decade, several examples of conflicts between fishing nations and the severe depletion of many highly migratory fish stocks proved that this legal setting was inadequate to deal with the sustainable management of these resources (Munro 1998, 1999).

In an attempt to solve this problem, the UN in December 1995, signed the Agreement on Straddling Fish Stocks and Highly Migratory Fish Stocks. The UN Agreement suggests that the management of highly migratory species should be car-

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ried out by a Regional Fisheries Management Organization (RFMO) and that only the nations that follow its management regime will have access to the resource. Also, as stated in Tahindro (1999), the agreement establishes that, "Coastal States and States fishing in the high seas are required to cooperate for the adoption of measures aimed at insuring the long term sustainability of these stocks and at promoting the objective of their optimum utilization."

This new setting can be interpreted as establishing a legal obligation to cooperate within a RMFO; therefore, cooperative games can help us examine the economics of cooperative management. In fact, several authors have already suggested this as an adequate framework to study the negotiation process of cooperative agreements within an RFMO (Kaitala and Lindroos 1998; Li 1998; and Munro 1999).

In particular, Kaitala and Lindroos (1998) and Li (1998) used a c-game approach to study this problem. The c-game approach is based on the fundamental assumption that the players have already agreed to cooperate, and that side payments among the players are possible. The problem to be solved in this setting is the distribution of the gains of cooperation in a fair way. Three solution concepts are proposed as possible solutions for this problem: the Nucleolus, the Shapley value, and the egalitarian, or Nash, bargaining solution. These solutions are based on different fairness concepts. The Nucleolus maximizes the benefits of the coalition that present the minimum gains, the Shapley value divides the gains in accordance to each player's average contribution for the coalition payoffs, and the Nash bargaining solution yields an egalitarian imputation of the gains.

In the two aforementioned papers, all the solutions are in the core of the game, so it is not clear which of these solutions will be most likely realized in practice. In fact, different solutions will treat players differently, so that each player will favor the solution that maximizes its payoffs.

This paper presents a case study where a c-game approach is applied to the cooperative management of the North Atlantic bluefin tuna. For this fishery, a three players' game is defined. For the East stock, it is considered that all the countries participating in the fishery are represented in the regional organization by one of the three members, the EU (European Union), OCS (other coastal states), and DWFNs (distant water fishing nations). For the West stock, the three members considered are: the USA (United States), CAN (Canada), and DWFNs.

The simulation of possible outcomes of this fishery is based on a multi-gear, age-structured, bioeconomic model developed for the North Atlantic bluefin tuna fisheries (Pintassilgo, Brasão, and Duarte 1998). The overall fishery comprises a number of sub-fisheries, defined geographically and by fleet/gear, operating out of many countries. Different fishing gears target different quality and size specimens, which also have different market values. The complexity of the bioeconomic model used reflects most of these aspects. The optimal strategies are assumed to be fixed strategies, either constant level of effort or constant level of catch, that maximizes the total net present values of profits for a 25-year period.

This paper differs from the two mentioned above in two aspects. First, the analysis is not based on a theoretical framework, but is applied to a real fishery. Second, the players do not differ in costs (or efficiency), but in dimension and composition of gear structure. This case study points out one possible source of weakness in the UN agreement. None of the solutions is in the core of the game, meaning that some players can do better outside the grand coalition. This may be a serious threat to the cooperative arrangement, and it certainly creates an incentive to cheat. Note, however, that in the UN Agreement, it is established that nations that do not follow the RMFO regime will not have access to the resource. This legal restriction is, therefore, essential for increasing the effectiveness of this management solution, and it can deal with the DWFNs. The possible free rider problem remains with the coastal states, as they can always fish in their EEZ.

This paper is organized as follows. First, a brief description of the fishery is provided, and the bioeconomic model is defined. Second, the setting and structure of the characteristic function game is settled for the East stock. Third, the three solution concepts, Nucleolus, Shapley value, and egalitarian, are calculated for this game. A similar analysis is then presented for the West stock. Finally, the main results are discussed together with the scope for further work.

The Fishery

The North Atlantic bluefin tuna fishery is a paradigmatic example of the difficulties faced in managing highly migratory species. Many countries, both coastal and distant water, capture this species in the North Atlantic and the Mediterranean Sea. Recent stock assessments report that both the East and the West stocks are severely depleted and face an acute risk of extinction.[1]

There exists two major spawning areas, both characterized by warm waters that reach 24ºC. In the West Atlantic, the spawning area is in the Gulf of Mexico and in the Florida Straits. In the East Atlantic, the spawning area is located in the Mediterranean around the Balearic Islands and the southern Tyrrhenian Sea.

Bluefin tuna is distributed on the West, from Brazil to Labrador; on the East from the Canary Islands to Norway; in the North Sea; in the Mediterranean; and in the southern Black Sea. Occasionally, it reaches Iceland and Murmansk.

North Atlantic bluefin tuna fisheries are characterized by a variety of vessel types and fishing gears operating out of many countries. Different types of fishing gear target different quality and sizes of bluefin tuna, which have different market values. The prices for large, high-quality specimens are significantly higher.

The most important fishing gears in the East Atlantic are: purse seine, longline, trap, and baitboat. In the West Atlantic, the prevailing gears are: purse seine, longline, and rod and reel. These gears differ according to the location of the fishery, and differences in efficiency may also be found.

Throughout the years, the importance of each gear has changed. Certain fisheries, such as traps, go back to ancient times. Other fisheries, such as the Atlantic longline and the Mediterranean purse seine, reached full development in the mid-1970s. The spatial distribution of the different gears in the Atlantic and the Mediterranean Sea has also changed over time. One of the most relevant changes has been the reallocation of the longline fishery, mainly Japanese, from the West to the East Atlantic. The distribution of the main fisheries following 1970 is shown in figure 1.

The management of North Atlantic bluefin tuna falls under the aegis of the ICCAT (International Commission for the Conservation of Atlantic Tunas). This Commission, created in 1969, is comprised of twenty-three fishing nations and is responsible for collecting information and proposing scientific-based management measures. Several conservation measures have been proposed by the ICCAT in order to preserve these stocks from a serious risk of extinction, but without much success. The common property of high seas allowed any country to extend its fishery, making noncooperation the natural outcome. In this setting, the individual countries involved had no clear incentives to adhere to restrictive measures. This is also predicted by economic theory of shared stocks where noncooperative management results in a situation equivalent to open-access equilibrium (Kaitala and Munro 1997).

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[1] For a detailed description of the historical and present situation of this fishery see Costa Duarte, Brasão, and Pintassilgo 1998.

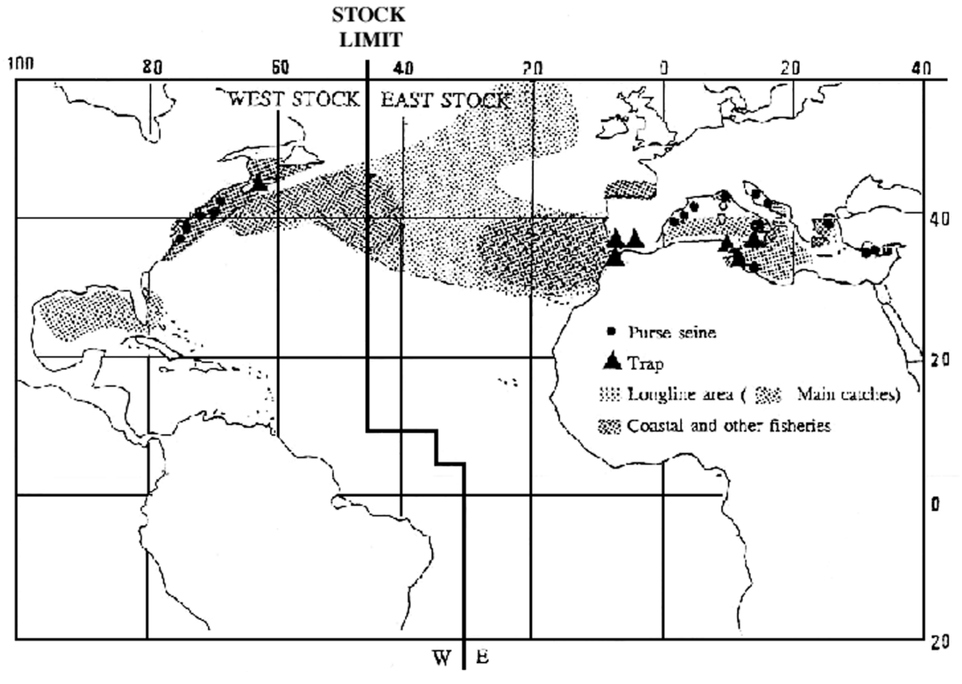

Figure 1. North Atlantic Bluefin Tuna Main Fisheries (Source: ICCAT)

The Model

To simulate the possible outcomes of this fishery, we use an age-structured, multi-gear bioeconomic model developed for both the East and the West stocks. This model is presented in Pintassilgo, Brasão, and Duarte (1998) and Pintassilgo (1999). The model was used to simulate an open-access outcome and study the optimal use of the resource.

The model was extended in order to obtain outcomes by nations. In this approach, it was assumed that the fishery was composed of only three members: the EU, OCS, and DWFNs, for the East stock, and the USA, CAN, and DWFNs, for the West stock. Taking into account that the countries involved in this fishery use more than one type of gear, the relative importance of the three members in each sub-fishery was based on the values of catches by gear and country published by the ICCAT for the base year 1995 (ICCAT 1996). A general description of the model is presented in the Appendix.

The open-access dynamics were modeled assuming that effort changes according to the signs of profits and a given adjustment coefficient. The optimal management of this fishery is considered to be the constant fishing strategy for each gear (either constant level of effort or constant level of catch) that maximizes net present value of profits (NPV) over a 25-year period.[2] It turns out that, in this setting, constant effort strategies always provide higher NPV than the constant catch strategies.

[2] Throughout this paper, net present value of profits is calculated assuming a 4% discount rate. This discount rate was considered reasonable according to other applied studies using similar investment horizons, such as the "Final Environmental Impact Statement for the Western Atlantic Bluefin Tuna" (U.S. Department of Commerce 1995) and long-run interest rates published in FMI reports.

The optimal management solution in this model is much more difficult to establish than those derived from aggregated bioeconomic models. The optimal management solution has to determine not only the optimal level of effort, but also the optimal mix of gears. This is due to the fact that different gears result in different profits, therefore affecting the maximum level of profits attainable by the entire fishery. In order to assess the importance of gear structure in the optimal management solutions, two scenarios are presented in Pintassilgo (1999). In one, the strategies are restricted to a fixed gear structure. In the other, the strategies are unrestricted.

This paper uses the first scenario, which imposes some restriction to the optimal management of this stock, but it is certainly a realistic base for a cooperative agreement. This analysis was extended to the other scenario, but the results were not significantly different.

The Setting of the Game

Let us consider that the actual situation of this fishery is the noncooperative outcome, as simulated by the open-access. In this outcome, the stock of bluefin tuna is expected to be extinct in five years, and the NPV obtained by all gears is US$7.6 million. This value is divided by the three members according to fleet activity and is presented in the first row of table 1. The open-access simulation implies a negative NPV for the EU and the OCS members, but a positive NPV for the DWFNs.[3]

The optimization routine of the model establishes that the optimal management strategy would be a 50% effort reduction for all gears (Pintassilgo 1999).[4] By doing so, stock and catches for all gears would grow progressively throughout the entire simulation period. The NPV accumulated in 25 years will be US$1,292 million. The NPV earned by the fleets of three members is divided and presented in the second row of table 1.

As can be seen, the total benefits from cooperation are very significant for all members, but they are not evenly distributed. More than half of the profits from this cooperative solution will be due to EU fleets. This occurs because the most profitable gears in the long run (trap and remainder) belong to EU fleets. In fact, the catch function representing those gears has the highest catch-stock elasticity. Therefore, as the stock recovers, those catches grow faster than do those harvested by the other gear types.

Now, let us assume that an RMFO is established for the East stock and that all three members participating in the fishery agree to cooperate. Suppose that all players agree to restrict their effort by 50% for all gears and that they have to decide how the benefits from cooperation should be divided.

A characteristic function game approach (c-game) is then applied to this setting in order to study the possible solution for the distribution of gains.

Following the notation used by Kaitala and Lindroos (1998), let $w(X_{95})$ denote the global economic return from this fishery under a cooperative agreement. In particular, the value reflects the NPV obtained by following the optimal management strategy for 25 years, starting at the stock level of the base year (X_{95}).

Let $e(X_{95})$ denote the net global returns to be shared by the three members. These are equal to the present value of the optimal management strategy, $w(X_{95})$, subtracting from it the sum of the threat points of each member. The sum of the threat points is the NPV resulting from the noncooperative fishery.

[3] The negative NPVs are due to losses that some gears experience when the stock collapses.
[4] The solution used here assumes also that the total catch of the remainder is restricted to 5,000 metric tons.

Table 1
Coalition Simulation Outcomes—East Stock

Strategy	E/E_{95}	NPV	EU	OCS	DWFN	NPV Coalition
Noncooperative		7.6	–13.8	–5.0	26.4	–
Cooperative	0.50	1,291.7	727.1	337.1	227.6	1,291.7
{EU, OCS}	0.28	991.8	107.3	46.9	837.5	154.2
{EU, DWFN}	0.34	976.4	155.7	752.4	68.3	224.0
{OCS, DWFN}	0.68	19.9	5.0	–4.1	19.0	15.0
{EU}		7.6	–13.8	–5.0	26.4	–13.8
{OCS}		7.6	–13.8	–5.0	26.4	–5.0
{DWFN}		7.6	–13.8	–5.0	26.4	26.4

Note: Values of NPV in 10^6 USD

$$e(X_{95}) = 1{,}291.7 - 7.6 = \text{US\$}1{,}284 \text{ million} \qquad (1)$$

Let (M,v^*) denote the characteristic function form of the game, where $v^*(K)$ is the value of coalition K that measures the increase in NPV achievable with this coalition, and M is the set of all possible coalitions.

Let the value of each coalition $v^*(K)$, be equal to its own payoffs less the sum of the noncooperative payoffs of its members (Mesterton-Gibbons 1992). Also, the normalized values are given by: $v(K) = v^*(K)/e(X_{95})$.

The set of all the possible coalitions for this game is: ({EU,OCS,DWFN}, {EU,OCS}, {EU,DWFN}, {OCS,DWFN}, {EU}, {OCS}, {DWFN}, {Ø}).

Calculating $v^*(K)$ for all coalitions requires the use of the bioeconomic model to simulate these outcomes. The outcome of the grand coalition is the optimal management simulation outcome. Also, the coalition of each individual member generates less profit than in open-access, being $v^*(K)$ equal to 0.

To simulate the outcomes of the two-member coalitions, it was assumed that the two members of the coalition maximize the joint NPV, assuming that the third member is acting according to market dynamics.[5] It turns out that the optimal strategy for all coalitions is also a constant effort strategy. The optimal effort reductions for each coalition, as well as the NPV obtained by each member, are presented in table 1.

All three possible two-player coalitions will increase NPV as compared to the noncooperative solution. However, the greater impact occurs with the coalitions that include the EU. Note also that the member excluded from the coalition is the one that gains the most. This happens because the stock recovery that occurs will be most beneficial to the member that is free to increase its own effort. Recall that in this situation, the member that is out of the coalition is able to increase its effort whenever there are profits. Moreover, in all the partial coalition simulations, the stock will still be extinct before the end of the simulation period, although later than in the open-access simulation. This means that only the grand coalition is able to provide sustainable stock management.

Table 1 also shows that coalition {OCS, DWFN} is not able to do better than the noncooperative case. In fact, the NPV generated by this coalition is less than the sum of the threat points. It is then assumed that this coalition will never take place.

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[5] Market dynamics were defined in the bioeconomic model for the open-access simulation, increasing effort whenever there are profits and decreasing it whenever there are losses (see Pintassilgo 1999).

Table 2
Coalition Values—East Stock

Coalition	$V^*(K)$	$V(K)$
{EU, OCS, DWFN}	1,284.1	1.00
{EU, OCS}	173.1	0.14
{EU, DWFN}	211.4	0.17
{OCS, DWFN}	0	0
{EU}	0	0
{OCS}	0	0
{DWFN}	0	0
{Ø}	0	0

Note: Values of $V^*(K)$ in 10^6 USD

The values of the coalitions $v^*(K)$ and the normalized values $v(K)$ are presented in table 2. It shows that in this game, most of the sub-coalitions have a zero value, meaning that they are not able to do better than the noncooperative setting. Only the two coalitions that include the EU will have a positive value.

The Solution

Suppose now that the members within the RMFO have to agree on a distribution of benefits. The most common sharing rules used in the c-game approach (*e.g.*, Li 1998; Kaitala and Lindroos 1998) are: the Nucleolus, the Shapley value, and the Nash bargaining solution. All three solutions define a share imputation of the gains $Z = (Z_1, Z_2, Z_3)$ that must satisfy the following conditions: (*i*) $Z_i \geq 0$ (individual rationality); (*ii*) $Z_1 + Z_2 + Z_3 = 1$ (group rationality). For the particular game structure of this applied study, these three solutions exist and are unique.

The Sharing Rules

The idea behind the Nucleolus concept is to find a payoff vector that maximizes the minimum gains of cooperating. Thus, the benefits of the "least satisfied coalition" are maximized. More specifically, it maximizes the minimum gains to any possible coalition, and can be defined as follows (Friedman 1986):

Definition: For a set of imputation vectors X, the Nucleolus over X is:

$$\text{Nuc}\ (X) = \{Z \in X \mid Z' \in X \text{ implies } \theta(Z) <_L \theta(Z')\} \tag{2}$$

where $\theta(Z)$ is the function:

$$\theta(Z) = [\theta_1(Z), \theta_2(Z), \dots, \theta_8(Z)] \tag{3}$$

and

$$\theta_j(Z) = Exc(K_j, Z), \text{ and } \theta_j(Z) \geq \theta_{j+1}(Z) \text{ for } j = 1, 2, \dots, 8. \tag{4}$$

here K_j represents a coalition, and *Exc* the excess function defined as:

$$Exc(K_j, Z) = v(K_j) - \sum_{i \in K_j} Z_i \tag{5}$$

The relation denoted $\theta(Z) <_L \theta(Z')$ defines a lexicographic ordering. Under this ordering, $\theta(Z)$ is smaller than $\theta(Z')$ if $\theta_1(Z) < \theta_1(Z')$ or, for $j > 1$, $\theta_j(Z) < \theta_j(Z')$ and $\theta_i(Z) = \theta_i(Z')$, for $i = 1,\ldots, j - 1$.

The Shapley value is based on the average contribution that each member makes to the set of possible coalitions (Kaitala and Lindroos 1998).

Definition: Let the Shapley value be the imputation $Z = (Z_1, Z_2, Z_3)$ given by:

$$Z_i = \sum_{K \subset M} [v(K) - V(K - \{i\})] \frac{(k-1)!\,(m-k)!}{m!} \tag{6}$$

Here, *K* includes all the coalitions to which member *i* belong, *M* is the set of all possible coalitions, *k* denotes the number of elements in *K*, and *m* is the total number of players. Also, $v(K - \{i\})$ defines the value of coalition *K* excluding the member *i*. Therefore, $[v(K) - v(K - \{i\})]$ represents the contribution of member *i* to the coalition *K*.

The Nash bargaining solution for an m player bargaining game can be defined as follows:

Definition: The Nash bargaining solution is the vector **u** that maximizes the Nash product:

$$\Pi_{i \in m}(\mathbf{u}_i - d_i) \tag{7}$$

where $\mathbf{u}_i$ is the payoff of player *i* in the grand coalition, and d_i is the payoff of player *i* in the case of noncooperation.

This solution yields an egalitarian imputation for all the players and completely ignores the possibility of cooperation among subsets of players (Myerson 1991).

The Solutions

The solutions for the three sharing rules were calculated for the East Atlantic and are presented in table 3. Each solution establishes a possible way for Regional Organization Members to agree on redistribution of the benefits from cooperation, given by $e(X_{95})$.

They show that for this particular game, the three concepts give similar imputations. The Nucleolus imputation is even equal to the Nash bargaining solution. This is due to the low value of $v(K)$ for all the two-member coalitions. In fact, if all the two-player coalitions present a $v(K) \leq 1/3$, then the Nucleolus is equal to the Nash bargaining solution. Thus, if the value of the two-player coalitions is not very high, the Nucleolus approaches the egalitarian solution.

The Shapley value, reflecting the average contribution of each player in the set of possible coalitions, gives the highest share to the EU, which is, in this sense, the player with some bargaining power.

By comparing the gains from cooperation attributed to each member with its NPV in the cooperative scenario, we can determine the side payments necessary for implementing the agreement. Table 4 shows that for all three sharing rules, the coop-

Table 3
The Sharing Rules—East Stock

	EU	OCS	DWFN
Nucleolus	0.33	0.33	0.33
Shapley	0.38	0.30	0.32
Nash	0.33	0.33	0.33

Table 4
Side Payments for the Three Solutions—East Stock

	EU	OCS	DWFN
NPV-Coop.	727.1	337.1	227.6
Nucleolus	312.8	–85.9	–226.9
Shapley	248.7	–44.3	–204.4
Nash	312.8	–85.9	–226.9

erative agreement implies that the EU member will have to transfer to the other two members part of the NPV generated by its own fleets. Nonetheless, these transfers decrease substantially by adopting the Shapley value instead of the other sharing rules. Note that the values of the payments shown in table 4 represent the net present value of the sum of the transfers for 25 years. Also, the distribution of the payments according to any of the solutions will vary significantly throughout the simulation years.

Interpreting the Results

This case study points out one possible source of weakness in the UN agreement. None of these solutions is in the core of the game, meaning that some players can do better by free riding the grand coalition. In fact, if we compare the gains from cooperation attributed to "OCS" and "DWFN," with the gains of the outcomes of the coalitions {EU, DWFN} and {EU, OCS}, it can be seen that those members gain a lot more if they do not participate in the grand coalition. This seems to be a serious threat to the cooperative arrangement, and certainly creates an incentive to cheat.

Note, however, that the UN Agreement establishes that the nations that do not follow the RMFO regime will not have access to the resource. This legal restriction is, therefore, essential for increasing the effectiveness of this management solution, and it can deal with the DWFNs.

The possible free rider problem remains with the coastal states. In this case, it is not possible to prevent them from fishing this resource in their coastal waters; therefore, a sustainable management of the resource is more difficult to attain with a distribution of gains according to any of the three sharing rules.

As a final remark, note that this analysis is based on a complex bioeconomic model and that the model structure and parameters determine the values presented. Nonetheless, sensitivity and retrospective analyses of the model presented in Brasão, Pintassilgo, and Costa Duarte (1999), shows that the optimal policies are generally not very sensitive to the model parameters.

In the specific setting of this paper, the impact of changes in the discount rate in the game solutions was also analyzed. Discount rate increases of 10% and 20% were considered.

Table 5
Impact of the Discount Rate on the Sharing Rules—East Stock

	r = 4% {EU, OCS, DWFN}	r = 20% {EU, OCS, DWFN}	rDWFN = 20% {EU, OCS, DWFN}
Nash	{0.33, 0.33, 0.33}	{0.33, 0.33, 0.33}	{0.33, 0.33, 0.33}
Shapley	{0.38, 0.30, 0.32}	{0.43, 0.29, 0.28}	{0.38, 0.31, 0.31}
Nucleolus	{0.33, 0.33, 0.33}	{0.33, 0.33, 0.33}	{0.33, 0.33, 0.33}

The simulation results show that increasing the discount rate for all the players will affect the NPV, but will not significantly affect optimal policies. Therefore, there is a considerable impact on the gains from cooperation, but the structure of the game and the relative position of the players is rather stable. Regarding the sharing rules, table 5 shows that for a 20% discount rate, the Nucleolus remains equal to the Nash bargaining solution. For the Shapley value, the results show that the EU share increases with the discount rate, while the share of the OCS, and especially the DWFNs, decreases.

It order to assess the importance of different discount rates for the players, a scenario was considered in which the EU and the OCS have a 4% discount rate, while the DWFN has a higher rate (20%). The results for the three sharing rules are presented in the 4th column of table 5. In this case, the Nucleolus remains equal to the Nash bargaining solution, but the Shapley value gives a lower share to the DWFNs. Therefore, the player with a higher rate of discount would have a lower share in Shapley value.

The C-Game Analysis for the West Stock Fishery

An analysis similar to the one presented in the previous section for the East stock was also developed for the West stock. The optimal reductions in effort for each coalition, as well as the NPV obtained by each member in that outcome, are presented in table 6.

In the noncooperative outcome, the stock would be extinct in 12 years, with a negative NPV for all gears (Pintassilgo, Brasão, and Costa Duarte 1998).[6] The optimal management strategy in this case is a 24% reduction in all gears (Pintassilgo 1999).

All of the two-member coalitions will increase the NPV.[7] However, the higher gains occur with the coalitions that include the USA.

The values of each coalition are presented in table 7, and the imputation for each of the sharing rules in table 8. As in the East case, the benefits from cooperation would be redistributed among the RMFO members according to the sharing rules. Recall that the gains from cooperation are defined as the difference between the sum of the payoffs in the grand coalition and the noncooperative scenario.

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[6] Note that the West stock is severely depleted, but the fisheries are restricted, and actual catch and effort are at low levels. This implies that the effort in 1995 was very low, so that an open-access simulation takes longer to lead the stock to extinction.

[7] The sum of the net present value of the three players is higher in the case of the coalition {USA,DWFN} than in the grand coalition, which seems to be a contradiction. Recall that the optimal strategies in this case are restricted to constant strategies and constant shares. In the two-member coalition outcomes, the third player is allowed to increase its effort gradually, introducing some additional flexibility, which explains the higher total net present value.

Table 6
Coalition Simulation Outcomes—West Stock

Strategy	E/E_{95}	NPV	USA	CAN	DWFN	NPV Coalition
Noncooperative		–3.737	–1.596	–1.016	–1.125	–
Cooperative	0.76	67.271	33.978	19.947	13.346	67.271
{USA, CAN}	0.48	44.025	12.777	6.614	24.634	19.391
{USA, DWFN}	0.71	69.014	25.656	33.002	10.357	36.012
{CAN, DWFN}	0.42	19.976	15.793	2.091	2.092	4.183
{USA}		–3.737	–1.596	–1.016	–1.125	–1.596
{CAN}		–3.737	–1.596	–1.016	–1.125	–1.016
{DWFN}		–3.737	–1.596	–1.016	–1.125	–1.125

Note: Values of NPV in 10^6USD

Table 7
Coalition Values—West Stock

Coalition	$V^*(K)$	$V(K)$
{USA, CAN, DWFN}	71.0	1.00
{USA, CAN}	22.0	0.31
{USA, DWFN}	38.7	0.55
{CAN, DWFN}	6.3	0.09
{USA}	0	0
{CAN}	0	0
{DWFN}	0	0
{Ø}	0	0

Note: Values of V*(K) in 10^6 USD

Table 8
The Sharing Rules—West Stock

	USA	CAN	DWFN
Nucleolus	0.43	0.23	0.34
Shapley	0.45	0.22	0.33
Nash	0.33	0.33	0.33

The results of this game show some differences when compared to the East case. The Nucleolus is significantly different from the Nash bargaining solution. This is because there is a two-player coalition, formed by the USA and the DWFN, that presents a high value, $v(K) = 0.55$. The Nucleolus is now closer to the Shapley value, although the latter still yields a higher share for the player with the highest bargaining power (the USA).

The side payments necessary to implement each of the proposed solutions are presented in table 9. It can be seen that, for all the three sharing rules, the USA is a net contributor and the DWFN a net receiver. Canada, on the other hand, is a net receiver with the Nash bargaining solution and a net contributor with the Nucleolus and the Shapley value.

Table 9
Side Payments for the Three Solutions—West Stock

	USA	CAN	DWFN
NPV-Coop.	34.0	19.9	13.3
Nucleolus	5.2	4.8	–10.0
Shapley	3.9	5.5	–9.4
Nash	11.9	–2.7	–9.2

Also, for the West stock, none of these solutions is in the core of the game. If we compare the gains from cooperation attributed to "CAN" and "DWFN," with the gains of the outcomes of the coalitions, {USA, DWFN} and {USA, CAN}, it can be seen that those members gain a lot more if they do not participate in the grand coalition. Here again, the obligation to follow the RMFO regime in order to have access to the fishery can solve the free rider problem of the DWFNs. However, this problem remains for Canada.

Conclusions

This paper studies a possible cooperative solution for a high-seas fishery management problem to be undertaken by a RFMO, as proposed by the 1995 UN Agreement. Namely, the cooperative management of the North Atlantic bluefin tuna is presented.

A characteristic function game (c-game) approach is applied to describe the sharing of the benefits of cooperation. This approach assumes that the grand coalition exists and that the problem lies in how benefits from cooperation should be distributed among members in a "fair" way. Three sharing rules are calculated: the Nucleolus, the Shapley value, and the Nash bargaining solution. None of these solutions is in the core of the game, meaning that it is not clear which will be most likely realized in practice. In fact, different solutions will treat players differently, so that each one will favor the solution that maximizes its payoffs.

In the East Atlantic, the Nucleolus is equal to the Nash bargaining solution, as there is no coalition with considerable bargaining power. In all three sharing rules, the cooperative agreement implies that the EU member will have to transfer part of its returns from the fishery to the other members. These transfers decrease if the Shapley value is adopted.

In the West Atlantic, the Nucleolus is significantly different from the Nash bargaining solution, owing to the significant bargaining power of the coalition formed by the USA and the DWFN. According to the sharing rules, the USA is a net contributor and DWFN a net receiver. Concerning CAN, it is a net receiver when the Nash bargaining solution is applied. However, it is a net contributor with the Nucleolus and the Shapley value.

The results obtained for the two stocks illustrate some characteristics of the different sharing rules. The Shapley value always gives the largest share of the benefits to the player with the highest bargaining power. This only occurs in the Nucleolus if there is a coalition with a substantial bargaining power. Based on this argument, Kaitala and Lindroos (1998) state that the Nucleolus may provide a more stable basis for regional cooperation since the least efficient countries receive nearly as much of the surplus benefits as the most efficient fishing nation, when differences in efficiency are not substantial.

This case study points out one possible weakness of the cooperative agreement—the coastal states can have clear incentives not to participate in it. If this happens, it may also represent a threat to the sustainable management of the resource, as the stock will be depleted in the long run.

This problem does not emerge in the theoretical frameworks developed by Li (1998) and Kaitala and Lindroos (1998), as each player loses by defecting from the grand coalition and adopting a noncooperative strategy. In the applied setting developed herein, some of the players gain by defecting the cooperative agreement, although it is assumed that the others react by choosing a strategy that maximizes its payoff. In fact, this is a typical problem faced by cooperative agreements in the presence of significant economic rents.

This applied work can be extended in several ways. First, expanding the calculation of the sharing rules for n players is a straightforward exercise, although one requiring the simulation of all possible coalitions. In addition, the inter-temporal consistency of the sharing rules needs to be considered. In fact, the coalition's optimal strategies may change as the stock recovers, and this can create additional sources of instability for the cooperative solution. Furthermore, in the UN Agreement there is scope for new entrants; that is, new countries that want to participate in the fishery. The analysis of the proposed solutions in the context of new entrants is, thus, a very relevant extension.

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Appendix

The Model Equations
Biological Sub-model

Population Numbers

(1) $N_{j,0,a} = \tilde{N}_{j,a}$ for $1 \leq a \leq A$

(2) $N_{j,t,0} = SRR_j(SSB_{j,t-2})$

(3) $N_{j,t,a} = N_{j,t-1,a-1} e^{-M_{j,a-1} - F_{j,t-1,a-1}}$ for $a = 1, 2, \ldots 9$; $t = 1, 2, \ldots$

(4) $N_{j,t,A} = N_{j,t-1,9} e^{-M_{j,9} - F_{j,t-1,9}} + N_{j,t-1,A} e^{-M_{j,A} - F_{j,t-1,A}}$

(5) $SSB_{j,t} = \sum_{a=1}^{A} Mat_{j,t,a} N_{j,t,a} W_{j,t,a}$

(6) $B_{j,t} = \sum_{a=1}^{A} N_{j,t,a} W_{j,t,a}$

Catch at Age by Gear

(7) $F_{j,t,a,s} = FMax_{j,t,s} \cdot Sel_{j,a,s}$

(8) $F_{j,t,a} = \sum_{s=1}^{S} FMax_{j,t,s} \cdot Sel_{j,a,s}$

(9) $CN_{j,t,a,s} = \frac{F_{j,t,a,s} \cdot N_{j,t,a}}{\sum_{s=1}^{S} (F_{j,t,a,s} + M_{j,a})} \left[1 - e^{-\sum_{s=1}^{S} (F_{j,t,a,s} + M_{j,a})} \right]$

(10) $CB_{j,t,s} = \sum_{a=1}^{A} CN_{j,t,a,s} \cdot W_{j,a}$

(11) $C_{j,t,s} = \sum_{a=1}^{A} \frac{FMax_{j,t,s} \cdot Sel_{j,a,s} \cdot N_{j,t,a} \cdot W_{j,t,a}}{\sum_{s=1}^{S} (FMax_{j,t,s} \cdot Sel_{j,a,s} \cdot M_{j,a})} \left[1 - e^{-\sum_{i=1}^{S} (FMax_{j,t,s} \cdot Sel_{j,a,si} \cdot M_{j,a})} \right]$

for $s = 1, \ldots S$

Harvest Function

(12) $C_{p,j,t,s} = q_{j,s} E_{p,j,t,s} B_{j,t}^{\alpha_s}$

(13) $C_{p,j,0,s} = sh_{p,j,0,s} * C_{j,0,s}$

(14) $E_{p,j,0,s} = sh_{p,j,0,s} * E_{j,0,s}$

Economic Sub-model

(15) $\text{Re}\, v_{p,j,t,s} = \overline{P}_{j,s} * C_{p,j,t,s}$

(16) $Cost_{p,j,t,s} = wg_{j,s} * E_{p,j,t,s} + \gamma_{j,s}(\overline{P}_{j,s} * C_{p,j,t,s})$

(17) $\prod_{p,j,t,s} = \text{Re}\, v_{p,j,t,s} - Cost_{p,j,t,s}$

(18) $TNPV_j = \sum_{p}^{m} \sum_{s=1}^{S} \sum_{t=1}^{25} \prod_{j,t,s} * \left(\frac{1}{1+r}\right)^t$

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(19) $$E_{p,j,t,s} = \begin{cases} (1-\beta_{j,s})E_{p,j,t-1,s} & if \quad \prod_{p,j,t-1,s} \leq -\prod b_{j,s} \\ E_{p,j,s,t-1} & if \quad -\prod b_{j,s} \leq \prod_{p,j,t-1,s} \leq \prod b_{j,s} \\ (1+\beta_{j,s})E_{p,j,s,t-1} & if \quad \prod_{p,j,t-1,s} \geq \prod b_{j,s} \end{cases}$$

Exit Condition

(20) $Cost_{p,j,t-1,s} > (1 + h_{j,s}) * \text{Re}\, v_{p,j,t-1,s}$

Table A1
Glossary of Symbols

Variables		Coefficients	
N	No. of fish (beginning of year)	*M*	Instantaneous natural mortality
Ñ	Estimated no. fish (beginning of 1995)	*Mat*	Maturity rate
SRR	Stock recruitment relation	*W*	Average weight
SSB	Spawning stock biomass	*q*	Production function parameter
F	Instantaneous fishing mortality	α	Catch-stock elasticity
FMax	Fishing mort. at maximum selectivity	w*g*	Costs parameter
B	Total biomass	γ	Crew share
Sel	Selectivity	*r*	Interest rate
CN	Catch numbers	β	Effort adjustment parameter
CB	Catch biomass	Π*b*	Profit bound
E	Effort	*h*	Exit condition parameter
C	Catch	*sh*	Share on the gear catch
Rev	Revenue	*m*	Number of players
Cost	Cost		
$\overline{P}$	Average price	**Indices**	
π	Profit	*p*	Player (EU, OCS, DWFN, …)
TNPV	Total net present value	*j*	Stock (*j*=East Atl., West Atl.)
		t	Time (*t*=1,…,*T*), *T*=25 (2020)
		a	Age (*a*=1,…,*A*), *A*=10+
		s	Gear (*s*=1,2,…,S)

Table A2
Economic Parameters of the Model

	East Atlantic				West Atlantic			
Gears	Prices (USD/kg)	β	wg	Unit of Effort	Prices (USD/kg)	β	wg	Unit of Effort
Longline	17	0.25	14,102	Fishing days	17	0.1	15,265	Fishing days
Purse seine	9	0.1	45,185*	Fishing days	18	0.1	20,092	Days at sea
Trap	25	0.2	15,738	Trap days	–	–	–	–
Bait boat	5	0.2	4,638	Days at sea	–	–	–	–
Rod and reel	–	–	–		18	0.1	163	Fishing hours
Remainder	17	0.01	2,408	Days at sea	20	0.1	22,417	Fishing days

* Note that for the PS, in the East Atlantic, one fishing day corresponds to more than three days at sea.

Table A3
Shares of Catches by Gear—Base Year (1995)

	East Atlantic			West Atlantic		
Gears	EU	OCS	DWFN	USA	CAN	DWFN
Longline	0.22	0.19	0.59	0.16	0.01	0.83
Purse seine	0.78	0.22	0	1.00	0	0
Trap	0.57	0.43	0	–	–	–
Bait boat	1	0	0	–	–	–
Rod and reel	–	–	–	0.81	0.19	0
Remainder	0.74	0.26	0	0.28	0.72	0