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Coalition Formation with Externalities: The Case of the Northeast Atlantic Mackerel Fishery in a Pre and Post Brexit Context

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COALITION FORMATION WITH EXTERNALITIES:
THE CASE OF THE NORTHEAST ATLANTIC MACKEREL FISHERY
IN A PRE AND POST BREXIT CONTEXT

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Abstract

In this paper we apply the so-called partition function approach to study coalition formation in the Northeast Atlantic mackerel fishery in the presence of externalities. Atlantic mackerel is mainly exploited by the European Union (EU), the United Kingdom (UK), Norway, the Faroe Islands and Iceland. Two games are considered. First, a four-player game where the UK is still a member of the EU. Second, a five-player game where the UK is no longer a member of the union. Each game is modelled in two stages. In the first stage, players form coalitions following a predefined set of rules. In the second stage, given the coalition structure that has been formed, each coalition choose the economic strategy that maximises its own net present value of the fishery given the behaviour of the other coalitions. The game is solved using backward induction to obtain the set of Nash equilibria coalition structures in pure strategies, if any. We find out that the current management regime is among the stable coalition structures in all eight scenarios of the four-player game, but in only one case of the five-player game. In addition, stability in the five-player game is sensitive to the growth function applied and the magnitude of the stock elasticity parameter.

Keywords: Mackerel dispute; straddling fish stock; brexit; games in partition function form; externalities; coalition formation; coalition structure stability.

JEL Classification: C71, C72, Q22, Q57.

1. Introduction

The 1982 United Nations Convention on the Law of the Sea (UNCLOS) recognized a 200 nautical-mile Exclusive Economic Zone (EEZ) stretching from the baseline of a coastal state (United Nations [1982]). The establishment of the EEZ has fundamentally changed the management of world marine captured fisheries by recognizing property rights. Thus, allowing coastal states to manage their stocks for their own benefit. However, such regime has inadequately addressed issues arising from internationally shared fishery resources, e.g., unregulated fishing, over-capitalization, excessive fleet size and etc. (United Nations [1995], Munro [2008]).

The Food and Agriculture Organisation of the UN (FAO) categorize international shared fish stocks as follows: (i) transboundary fish stocks – found in the neighbouring EEZs of two or more coastal states, (ii) highly migratory (consisting, primarily, of the major tuna species) and straddling fish stocks – found both within the EEZ(s) of coastal state(s) and the adjacent high seas, (iii) discrete high seas fish stocks – found exclusively in the high seas (FAO [2003]). Furthermore, Gulland [1980] presents a biological/geographical categorization of transboundary fish stocks, i.e., those that show a clear migratory pattern, e.g., seasonal migration, and those that do not. Munro *et al.* [2004] conclude that if the pattern of movement of a stock is not clear, it is possible that each coastal state can sustainably manage its segment of the stock without cooperating with the other coastal state(s) in accordance with the 1982 UNCLOS.[i] However, if the harvesting activities of one coastal state have a significant negative effect on the harvesting opportunities of the other coastal state(s), whether the migration pattern is clear or not, a coordinated plan for sustainable management from all parties is required.

This need for cooperation has led to the adoption of the 1995 United Nations Fish Stocks Agreement (UNFSA), which supplements and strengthens the 1982 UNCLOS by addressing the problems related to the conservation and management of internationally shared fishery resources (United Nations [1995]). According to UNFSA, exploitation of a shared fish stock within its spatial distribution, should be coordinated by a coalition of all interest parties through a UN sanctioned Regional Fisheries Management Organisation (RFMO), e.g., the Northeast Atlantic Fisheries Commission (NEAFC). Membership into an RFMO is open both to nations in the region, i.e., coastal states, and distant nations with interest in the fisheries concerned, as long as they agree to abide by the RFMO's conservation and management measures.

Although UNFSA has established robust international principles and standards for the conservation and management of shared fish stocks (Balton and Koehler [2006]), the fact that RFMOs lack the necessary coercive enforcement power, either to exclude non-members from harvesting or to set the terms of entry for new members, has caused doubts over the long-term viability of such regional management

[i] One example presented in Munro [1987] is the Georges Bank scallop fishery, shared by Canada and the United States.

mechanisms (McKelvey *et al.* [2002]). These two inter-related problems, namely the "interloper problem" (Bjørndal and Munro [2003]) and the "new member problem" (Kaitala and Munro [1993]), merge when a nation with no past interest in a particular shared fishery starts exploiting the resource. In this case the interests of the traditional fishing nations (incumbents) and the new entrant(s) are strongly opposed. On the one hand, incumbents face the prospect of having to give up a share of their quotas to the new entrant(s) in order to join their coalition and exploit the resource sustainably; whereas on the other hand, it might be more profitable for the new entrant(s) not to join and therefore harvest without having to abide by the coalition's conservation measures.

The aforementioned situation gives rise to the free-rider problem due to stock externalities, i.e., the effect of this period's harvest on next period's stock level (Bjørndal [1987]). Stock externalities, which occur when the cost of fishing changes as the population of fish is altered, are negative externalities (Smith [1969],Agnello and Donnelley [1976]). That is, a nation's harvesting activities lead to less fishing opportunities for another nation and therefore increases the other's nation fishing cost. As nations start cooperating, the externality is internalised and thus the external cost is reduced. The externality disappears, if all nations cooperate together. Because the reduction of the negative externality leads to higher benefits for all nations, not only the ones cooperating, some authors within the fishery literature refer to it as positive.

The intuition is as follows. Assume that a cooperative agreement, which aims to preserve a fish stock by limiting the amount of catches and thus increasing its population, is signed by a group of nations. A nation who is not part of such agreement can still enjoy the positive effects that the agreement has on fish stock level without having to reduce its fishing activities. Therefore, a free-rider (non-cooperating nation or coalition of nations[ii]) can enjoy a lower cost of fishing without having to mitigate its fishing strategy. Because of the free-rider problem cooperative agreements among all interest parties in a fishery have not always been possible to achieve.

The importance of externalities emanating from coalition formation where the economic performance of a coalition, including singletons,[iii] is affected by the structure of other distinct coalitions has been studied both within game theoretic and fisheries literature. Bloch [1996], Yi [1997] and Ray and Vohra [1999], among others, have established the theoretical framework to analyse coalition formation in the presence of externalities, also referred as endogenous coalition formation, using the partition function approach introduced by Thrall and Lucas [1963]. The advantage of those models to the ones using the traditional characteristic function approach, is that they consider all possible coalition structures and compute coalition values for every one of them, instead of fixating on some. Thus, stability of different

[ii]It is possible, although not usual, that a shared fishery is managed by more than one cooperative agreements, where the signatories of one agreement differ from the signatories of the other agreement. An example presented in Munro (2003) consists of the fourteen independent Pacific Island Nations, which where coalesced into two sub-coalitions. If this is the case, then a coalition of nations can free-ride on another coalition.

[iii]A coalition consisting of one member.

coalition structures, i.e., partial cooperation, can be tested and externalities across coalitions can be captured.

Within the fisheries literature, Pintassilgo [2003] and Pham Do and Folmer [2003] have introduced the partition function approach in fishery games. Pintassilgo [2003] applies this method to the Northern Atlantic bluefin tuna. Pham Do and Folmer [2003] study feasibility of coalitions smaller than the grand coalition. Kronbak and Lindroos [2007] apply different sharing rules to study the stability of a cooperative agreement for the Baltic cod in the presence of externalities. They state that even though the benefit from cooperation is high enough for a cooperative agreement to be reached, its stability is very sensitive to the sharing rule applied due to free-riding effects. For more comprehensive reviews on coalition games and fisheries, as well as game theory and fisheries, see Kaitala and Lindroos [2007], Lindroos *et al.* [2007], Bailey *et al.* [2010] and Hannesson [2011].

In this paper, we implement the partition function approach to study coalition formation in the Northeast Atlantic mackerel fishery. Atlantic mackerel is a highly migratory and straddling stock making extensive annual migrations in the Northeast Atlantic. The stock consist of three spawning components, namely, the southern, the western and the North Sea component, which mix together during its annual migration pattern. As a result, exploitation of mackerel in different areas cannot be separated. Thus, all three spawning components are evaluated as one stock by the International Council for the Exploration of the Sea (ICES) since 1995 (ICES [1996]).

Because of the wide geographic range that mackerel is distributed, it is exploited by several nations both in their EEZs and the high seas. Traditionally, mackerel has been cooperatively exploited by the European Union[iv] (EU), Norway and the Faroe Islands, with the latter taking only a small proportion of the overall catch until 2010 (2%[v] on average). Also, the NEAFC, of which the three nations are members, allocates a share of the mackerel quota to Russia (7% on average), which can fish mackerel in the high seas. In the last decade however, mackerel has extended its distribution and migration pattern starting to appear into the Icelandic and Greenlandic economic zones. Although the causes of such northward expansion are not fully understood, increased sea surface temperatures in the northeast Atlantic (Pavlov *et al.* [2013]) and high population size of the mackerel stock (Hannesson [2012]) are mostly referred in the literature.

Due to mackerel's distributional shifting, Iceland, which in the past had requested and been denied to be recognised as a coastal state for the management of mackerel, has begun fishing mackerel at increasingly large quantities in 2008 (approximately 18% of the total catch). In 2009, the Faroese, having observed the quantities that Iceland was harvesting, withdrew from the cooperative agreement with the EU and Norway on the grounds that their quota was very low. A bilateral agreement between

[iv]To convenient ourselves, we refer to the European Union as a nation in this context due to the fact that all of its members abide by the Common Fisheries Policy.

[v]Unless otherwise stated, all computations in this paper are based on ICES (2016a) advice report 9.3.39, tables 9.3.39.12 and 9.3.39.14.

the EU and Norway was not reached until 2010. Since then, and despite many rounds of consultations, no consensus agreement by all four nations has been reached. However, in 2014, the Faroe Islands together with Norway and the EU signed a 5-year arrangement, which is still in place, determining the total allowable catch (TAC) and the relative share for each participant.

In the past, several authors have closely examined the so-called mackerel dispute between the EU, Norway, Iceland and the Faroe Islands. Ellefsen [2013] applied the partition function approach to study the effects of Iceland's entry into the fishery. He considered two games, a three-player game between the EU, Norway and the Faroe Islands, and a four-player game where he included Iceland. His results indicated that the grand coalition is potentially stable, i.e., it is stable for some but not all sharing rules, in the three-player but not in the four-player game. Hannesson [2012], [2013] studied the outcome of cooperation on different migratory scenarios of the mackerel stock. He found out that if the migrations are stock dependent, then minor players, like Iceland and the Faroe Islands, are in a weak position to bargain. The opposite is true, if the migrations are purely random or fixed. Jensen *et al.* [2015] tried to empirically explain the outcome of the mackerel crisis after Iceland's entry into the fishery. They considered two strategies for all nations, namely, cooperation and non-cooperation. They concluded that non-cooperation is a dominant strategy for each player.

The purpose of this paper is to investigate how the UK's decision to withdraw from the EU is likely to affect the current management regime in the mackerel fishery. The UK, which has been a member of the EU since 1973, voted on 26 June 2016 to leave the Union. Nine months later, on 29 March 2017, the British government officially initiated Brexit by invoking Article 50 of the European Union's Lisbon Treaty. This will lead to the conclusion of an international agreement between the two parties by the 29th of March 2019 unless the European Council extends this period. Such agreement will define the terms of the UK's disengagement from the European legal system, internal market and other policies, including the Common Fisheries Policy (Sobrino Heredia [2017]). Being a member state of the EU, the UK has not been directly involved in the negotiations for the mackerel quota but represented by the EU, which allocates fishing opportunities to member states based on the principle of relative stability, i.e., a fixed percentage of the quota based on historical catch levels. Thus, after Brexit is concluded, the UK will have to negotiate on its behalf with the remaining coastal states regarding its share of the mackerel quota, which will most likely based on the principle of zonal attachment, i.e., each party's share of the quota should be proportional to the catchable stock found in its EEZ (Churchill and Owen [2010]).

In what follows, we focus on two games: (i) a four-player game where the UK is still part of the EU, and (ii) a five-player game where the UK is allowed to make its own decisions. The remaining players/nations considered are Norway, Iceland and the Faroe Islands. Both games are analysed using the partition function approach. That is, we investigate how players are likely to organise themselves in coalitions, which result in the formation of a coalition structure. The objective of a coalition is to maximise its own net present value of the fishery given the behaviour of the other coalitions in the coalition structure. The optimal strategies and payoffs of the games are derived as pure Nash equilibria between coalitions in a coalition structure. Finally, stability of a coalition structure is tested and the set of the Nash equilibria coalition structures is obtained.

The paper is structured as follows. In sections 2 and 3 we lay out the bioeconomic and game theoretic models employed in the paper. The empirical model specification is presented in section 4. In section 5, we report the solution of both games, evaluate the stability of the coalition structures and discuss the results. Finally, section 6 summarises our main findings and concludes the paper.

2. Bioeconomic Model

The bioeconomic model we expand on is a deterministic stock-recruitment model introduced by Clark [1973].[vi] The model is in discrete time between seasons but continuous within them. Also, it is linear in the control variable, i.e., harvest.

The spawning stock biomass of a fishery at the beginning of a period t, for $t = 0, 1, 2, \ldots$, is referred to as the recruitment R_t. The harvested biomass in a period t is denoted by H_t and must be between zero and the recruitment, $0 \leq H_t \leq R_t$. Assuming no natural mortality, the spawning stock biomass at the end of a period is the difference between the recruitment and the harvest and is called the escapement S_t, $S_t = R_t - H_t$.

The spawning stock biomass at the beginning of the next period R_{t+1} is a function of the spawning stock biomass at the end of the current period S_t, $R_{t+1} = F(S_t)$. The schema below illustrates the stock dynamics between time periods.

$$R_t \longrightarrow H_t \longrightarrow S_t \longrightarrow R_{t+1} = F(S_t) \ldots \ .$$

The function $F(S)$, which is usually referred to as the stock-recruitment relationship, is assumed to be continuous, increasing, concave and differentiable in $[0, K]$ with $F(0) = 0$ and $F(K) = K$, where $K > 0$ is the carrying capacity of the fishery.

2.1. *Cooperative management*

Suppose now that a shared fishery, like the Northeast Atlantic mackerel, is cooperatively managed by a coalition whose members are all the relevant coastal states, also referred to as grand coalition. The goal

[vi]Important contributors towards the development of stock-recruitment models have also been Reed [1974] and Jaquette [1974] who analysed stochastic stock-recruitment models in discrete time.

of the grand coalition is to maximise the net present value of the fishery over an infinite horizon subject to the biological constraint. The maximisation problem can be expressed as follows:

$$\begin{aligned} &\underset{S_t}{\text{maximise}} && \sum_{t=0}^{\infty} \gamma^t \Pi(R_t, S_t) \\ &\text{subject to} && R_{t+1} = F(S_t) \\ & && 0 \leq S_t \leq R_t, \end{aligned}$$

where $\Pi(R_t, S_t)$ is the joint profit from the fishery for each period, which is defined as the difference between gross revenue and total cost. Two assumptions are made when specifying the net revenue function. First, the demand curve is assumed to be infinitely elastic, i.e., each harvested unit of fish can be sold at a fixed price p. Thereafter, the gross revenue from the fishery is expressed as $TR(R_t, S_t) = p(R_t - S_t)$. Second, the unit cost of harvest is assumed to be density dependent, i.e., it increases as the size of the stock decreases. Thus, for a given stock size x the unit cost of harvest is equal to $c(x)$, which is a continuous and decreasing function. Consequently, the total cost of harvest within one period is defined as $TC(R_t, S_t) = \int_{S_t}^{R_t} c(x)dx$. To sum up, the joint profit in period t can be written as:

$$\Pi(R_t, S_t) = p(R_t - S_t) - \int_{S_t}^{R_t} c(x)dx.$$

Clark [1973] shows that, if the profit function is specified as above, then the optimal harvest strategy that maximises the net present value of the fishery is given by a "bang-bang" strategy with equilibrium escapement S^*

$$H_t = \begin{cases} R_0 - S^* & t = 0 \\ F(S^*) - S^* & t \geq 1, \end{cases}$$

i.e., for the initial period the stock should be depleted to the equilibrium escapement level and then harvest the difference between optimal recruitment and escapement. The optimal escapement level is independent of t and must satisfy the so-called "golden rule"

$$\pi(S^*) = \gamma F'(S^*)\pi[F(S^*)], \tag{1}$$

where $\pi(x)$ is the marginal profit defined as $\pi(x) = p - c(x)$. The interpretation of the "golden rule" is straightforward, a cooperatively managed fishery is exploited until the marginal profit of harvesting the last unit of the stock is equivalent to the marginal profit of letting that unit grow and be harvested in the next period.

2.2. *Non-cooperative management*

Although cooperative management is the desired outcome from the perspective of stock conservation, it is often the case that shared fisheries are non-cooperatively managed. In this subsection we generalise the above model in order to allow for non-cooperative behaviour among nations. First, we describe how the mackerel stock is exploited in the presence of two or more distinct coalitions. Then, we specify coalition's i maximization problem and derive the non-cooperative "golden rule".

If the mackerel fishery is non-cooperatively managed, then a number of coalitions[vii] interacting with each other must exist. Each coalition acts on its own, aiming to maximise its own net present value of the fishery, which is potentially detrimental to other coalitions. Coalitions are assumed to harvest mackerel in the EEZs of their members. Furthermore, we ignore mackerel exploitation on international waters for the following reasons. First, the size of the high seas territory where mackerel potentially exists is relatively small and remote, compared to the rest of its habitat. Second, mackerel is mainly exploited on the high seas by Russia, which receives a small proportion of the total quota and is not directly involved in the management of the stock.

Let θ_l be the share of the mackerel stock that only appears in the EEZ of nation l for a whole year. The share of the mackerel stock that a coalition i enjoys is simply the sum of its members shares, i.e., $\theta_i = \sum_{l \in i} \theta_l$. For example, if EU and NO form a coalition, then $\theta_{(EU,NO)} = \theta_{EU} + \theta_{NO}$. Parameter θ is assumed to be stationary, i.e., constant through all time periods. For details on the specification of the share parameter see section 4.

Although each coalition exploits mackerel in its own zone, the stock-recruitment relationship specified in the beginning of this section still holds for the aggregated population level, i.e., $R_{t+1} = F(S_t)$. Let m be the number of coalitions that non-cooperatively manage the mackerel fishery. The share parameter θ_i, where $i = 1, 2, \dots, m$, enables us to work out the share of recruitment R_{it} for each coalition in a time period, i.e., $R_{it} = \theta_i R_t$. After mackerel harvesting activities H_{it} are performed by all coalitions, the escapement from the zone of each coalition is $S_{it} = R_{it} - H_{it}$. The total recruitment for the next time period is determined by the total escapement of the current period through the stock-recruitment relationship on the aggregated escapement level S_t, where $S_t = \sum_{i=1}^{m} S_{it}$. The schema below illustrates such process when three coalitions exist, $m = 3$.

$$
\begin{array}{ccccccccc}
 & \nearrow & R_{1t} = \theta_1 R_t & \longrightarrow H_{1t} & \longrightarrow S_{1t} & \searrow & & & \\
R_t & \longrightarrow & R_{2t} = \theta_2 R_t & \longrightarrow H_{2t} & \longrightarrow S_{2t} & \longrightarrow & S_t = \sum_{i=1}^{3} S_{it} & \longrightarrow R_{t+1} = F(S_t) \dots & . \\
 & \searrow & R_{3t} = \theta_3 R_t & \longrightarrow H_{3t} & \longrightarrow S_{3t} & \nearrow & & &
\end{array}
$$

Based on the above setting, a coalition i maximises its own net present value of the fishery subject to

[vii]The term coalition is typically used to refer to situations that more than one players act together, however within this paper we allow for coalitions consisting of only one player, which we will sometimes refer to as singletons.

its recruitment share R_i, the escapement strategies of the other coalitions S_j and the stock-recruitment relationship. Such maximisation problem can be expressed as follows:

$$
\begin{aligned}
\underset{S_{it}}{\text{maximise}} \quad & \sum_{t=0}^{\infty} \gamma^t \Pi_i(R_{it}, S_{it}) \\
\text{subject to} \quad & R_{it} = \theta_i R_t \\
& S_t = S_{it} + \sum_{j=1}^{m-1} S_{jt} \quad i \neq j \\
& R_{t+1} = F(S_t) \\
& 0 \leq S_{it} \leq R_{it}.
\end{aligned}
\tag{2}
$$

$\Pi_i(R_{it}, S_{it})$ is the profit for coalition i for each period and is specified as in the cooperative case, i.e.,

$$
\Pi_i(R_{it}, S_{it}) = p(R_{it} - S_{it}) - \int_{S_{it}}^{R_{it}} c_i(x)dx.
$$

The optimal harvest strategy that maximises the net present value for coalition i is given by a target escapement strategy with equilibrium escapement S_i^*

$$
H_{it} = \begin{cases} R_{i0} - S_i^* = \theta_i R_0 - S_i^* & t = 0 \\ R_i - S_i^* = \theta_i F(S_i^* + \sum_{j=1}^{m-1} S_j) - S_i^* & t \geq 1, \end{cases}
$$

i.e., for the first period the initial recruitment of coalition i should be depleted to its equilibrium escapement level, and then harvest the difference between its recruitment share and its optimal escapement. The recruitment share of coalition i is determined by its share and the stock-recruitment relationship, which depends on the optimal escapement of coalition i and the escapement strategies of the other coalitions j. The optimal escapement level is independent of t and must satisfy the following "golden-rule" (see Appendix A.1 for the proof):

$$
\pi_i(S_i^*) = \gamma \theta_i F'(S) \pi_i[\theta_i(F(S)], \tag{3}
$$

where $\pi_i(x)$ is the marginal profit for coalition i defined as $\pi_i(x) = p - c_i(x)$ and S is the aggregated escapement defined as $S = S_i^* + \sum_{j=1}^{m-1} S_j$.

The underlying assumption of coalition's i maximisation problem is that the escapement strategies of all other coalitions j are known and remain unchanged in the future. However, if all coalitions determine their escapement strategies in the same manner, i.e., solving the same maximisation problem, the optimal escapement strategy of coalition i would only hold temporarily until another coalition j adjust its escapement strategy based on the new information. The "true" steady state is reached when no coalition can gain by further adjusting its escapement strategy.

Finally, the non-cooperative "golden-rule" is a generalisation of the cooperative one. To see this, assume that all nations cooperate and the grand coalition is formed. The stock share of the grand coalition is equal to one, $\theta_i = 1$, and since no other coalition exist the aggregated escapement is equivalent to the optimal escapement of the grand coalition, $S = S_i^*$. Thus, the two rules are equivalent under full cooperation.

3. Game Theoretic Model

A coalition game with externalities is modelled in two stages. In the first stage, players, i.e., nations, form coalitions following a predefined set of rules. For our fishery game we adopt the simultaneous-move "Open Membership" game described in Yi and Shin [1995]. According to this rule, players can freely form coalitions as long as no player is excluded from joining a coalition. This type of coalition game is inline with how membership is established within an RFMO according to Article 8(3) of the UNFSA. Also, it is the de facto framework used so far to analyse coalition games in fisheries.

Let $N = \{1, 2, \ldots, n\}$ be the set of players. A coalition C is a subset of N, i.e., $C \subseteq N$, with 2^n being the number of coalitions that can be formed, including the empty set. The coalition(s) formed in the first stage lead to a coalition structure $CS = \{C_1, C_2, \ldots, C_m\}$, where $1 \leq m \leq n$. A coalition structure has at least one coalition, i.e., full cooperation, and at most n coalitions, i.e., full non-cooperation. The formal definition of a coalition structure as provided in Yi [1997] states that a coalition structure is a partition of the players N into disjoint, non-empty and exhaustive coalitions, i.e., $C_i \cap C_j = \varnothing$ for all $i, j = 1, 2, \ldots, m$ and $i \neq j$, and $\bigcup_{i=1}^{m} C_i = N$. This means that within a coalition structure each player belongs only to one coalition and some players may be alone in their coalitions.

Given the coalition structure that has been formed in the first stage, in the second stage, each coalition chooses the economic strategy that maximises its own net present value of the fishery given the behaviour of the other coalitions. If the grand coalition is formed then the total net present value of the fishery is maximised. The economic strategies in the second stage game as well as the respective payoffs are pure strategy Nash equilibria[viii]. Given the optimal strategies in the second stage of the game, the Nash equilibria coalition structures in pure strategies are the ones that satisfy the stability criteria.

The game is solved using backward induction to obtain the set of stable coalition structures, if any. First, we fix all coalition structures. Then, we compute optimal strategies and payoffs for all coalitions in every coalition structure. Finally, we check which coalition structures satisfy the stability criteria.

[viii] No mixed strategies are considered when solving this game.

3.1. *Second stage of coalition formation*

Let $K = \{CS_1, CS_2, \ldots, CS_\kappa\}$ be the set of coalition structures and κ the number of coalition structures that can be formed.[ix] From the κ coalition structures, the $\kappa - 1$ consist of two or more coalitions, which non-cooperatively manage the fishing resource. The κ-th coalition structure contain only one coalition the grand coalition that cooperatively manages the stock.

For a given coalition structure $CS_k = \{C_1, C_2, \ldots, C_m\}$, where $k = 1, 2, \ldots, \kappa$, we denote the payoff of coalition C_i, where $i = 1, 2, \ldots, m$, as $v_i(S_i, S)$. The coalitional payoff depends on the escapement strategy of the coalition, S_i, and the overall escapement strategy profile of the coalition structure, $S = S_i + \sum_{j=1}^{m-1} S_j$.[x] Also, the set of feasible escapement strategies for any coalition i is between zero, i.e., harvest everything, and its recruitment, i.e., harvest nothing, $S_i \in [0, R_i]$.

The equilibrium escapement strategies S_i^* for all coalitions C_i in a coalition structure CS_k are derived as a Nash equilibrium between coalition C_i and coalitions C_j, , where $j = 1, 2 \ldots, m-1$, $i \neq j$ and $C_i \cup C_j = CS_k$, and must satisfy the following m inequalities:

$$v_i(S_i^*, S_i^* + \sum_{j=1}^{m-1} S_j^*) \geq v_i(S_i, S_i + \sum_{j=1}^{m-1} S_j^*),$$
$$\forall\; C_i \in CS_k;\; S_i, S_i^* \in [0, R_i];\; S_j^* \in [0, R_j];\; i, j = 1, 2, \ldots, m;\; i \neq j,$$

i.e., for every coalition C_i the optimal escapement strategy S_i^* must maximise the coalitional payoff given the optimal escapement strategies of the other coalitions S_j^*. In other words, the equilibrium escapement strategy profile of a coalition structure requires that no coalition can get better-off by deviating from its escapement strategy, i.e., optimal escapement strategies are best responses. If the grand coalition is formed the above decision rule reduces to a single inequality:

$$v(S^*) \geq v(S) \qquad S, S^* \in [0, R],$$

i.e., the optimal escapement level must maximise the grand coalition's payoff.

In order to determine the equilibrium escapement strategy profile of a coalition structure CS_k the maximisation problem (2) as specified in subsection 2.2 must be repeatedly solved for every coalition C_i within a coalition structure CS_k until no coalition can further increase its net present value by adjusting its escapement strategy given the escapement strategies of the other coalitions. However, as described in the same subsection, such maximisation problem boils down to a single expression, the "golden-rule",

[ix] The number of coalition structures κ depends on the number of players and is referred to as the Bell number within combinatorial mathematics.

[x] Games where a player's or a coalition's payoff depend only upon its own strategy (S_i in our setting), and a linear aggregate of the full strategy profile (S in our setting) are also called aggregate games, see Martimort and Stole [2012] for additional details and applications.

specified in (3). Therefore, in order to determine the equilibrium escapement strategy profile of a coalition structure, we solve the following system of m equations:

$$
\begin{aligned}
&\pi_i(S_i) = \gamma\theta_i F'(S)\pi_i[\theta_i(F(S)] \quad \forall C_i \in CS_k;\ i = 1, 2, \ldots, m, \\
&\text{where } S = \sum_{i=1}^{m} S_i \quad i = 1, 2, \ldots, m.
\end{aligned}
\tag{4}
$$

These equations refer to the “golden-rules” that coalitions within a coalition structure apply in order to determine their escapement strategies. The overall escapement, S, is a linear aggregate of the full strategy profile and captures how coalitions interact with each other through their escapement strategies. Note that in the case of the grand coalition the above system of equations consist of only one equation, which is equivalent to the cooperative “golden-rule” (1).

It should be obvious by now that the equilibrium escapement strategies depend on the coalition structure that is formed and on the parameters of the model. The coalitions formed are assumed to by asymmetric. They are differentiated by parameter θ_i, the share of mackerel stock that occurs in the EEZ(s) of a coalition, and their marginal cost of harvest, $c_i(x)$. Some coalitions may have equivalent shares, if their members are of the same type, see section 4 for additional details. These asymmetries ensure that escapement strategies across coalitions are different and depend upon the form of the coalition structure. Thus, a unique payoff, which depends on the coalition structure, can be computed for every coalition in a coalition structure.

The coalitional payoff, which is equivalent to the net present value of the fishery over an infinite time horizon and depends on the escapement strategy profile of the coalition structure formed, can be written as follows:

$$
v_i(S_i^*, S^*) = \sum_{t=0}^{\infty} \gamma^t \Pi_i(R_{it}, S_{it}) = \Pi_i(\theta_i R_0, S_i^*) + \frac{\gamma}{1-\gamma}\Pi_i[\theta_i F(S^*), S_i^*], \tag{5}
$$

where R_0 is the initial recruitment and $S^* = S_i^* + \sum_{j=1}^{m-1} S_j^*$ is the optimal escapement strategy profile of a coalition structure. While specifying the coalitional payoff, it is important to remember that two things are assumed. First, the initial recruitment is high enough to allow for the prescribed harvest strategy in the first period, i.e., $S_i^* \leq \theta_i R_0\ \forall C_i \in CS_k$. If this is not the case, the stock should not be harvested but allowed to grow until recruitment exceeds escapement. For our mackerel case, the initial recruitment is high enough to sustain all escapement strategies as feasible. Second, the fishing fleet capacity required to implement such harvest strategies (initial depletion and steady state harvest) exists. If the necessary capacity does not exist, the following situations arise: (i) there exist sufficient capacity to harvest the steady state quantity but not to deplete the stock to the steady state in one period, and (ii) no sufficient capacity exists to harvest the steady state quantity.[xi,xii] If case (i) occurs then the initial depletion of the stock to the steady state escapement level would take a couple of periods depending on the capacity of the current fishing fleet. On the other hand, if case (ii) occurs, we will never reach the "true" steady state prescribed by the optimal escapement strategy. In the long run however, a nation would increase its fishing fleet capacity to meet the optimal escapement strategy, either by investing in more fishing vessels or by shifting vessels that operate in less profitable stocks. Since mackerel is one of the most valuable stocks in the Northeast Atlantic region and in order not to complicate things by endogenously determining the fishing fleet capacity, we assume that the necessary capacity for implementing the prescribed strategies exists for all nations.

3.2. *First stage of coalition formation*

Our analysis is inline with the internal and external stability concepts of d'Aspremont *et al.* [1983] and what is defined as potential internal stability by Eyckmans and Finus [2004]. These concepts have been used to test a coalition's stability in both characteristic and partition function games.[xiii]

We start by introducing the notion of an embedded coalition, which is extensively used throughout this subsection. An embedded coalition is a pair (C_i, CS_k) consisting of a coalition and a coalition structure which contains that coalition, $C_i \in CS_k$. Let $V(C_i, CS_k)$ denote the payoff of an embedded coalition[xiv] and $V_x(C_i, CS_k)$ denote the payoff received by subcoalition x of the embedded coalition (C_i, CS_k), $x \subset C_i$. The subscript x may refer to an individual player (see internal stability condition below) or a coalition of players (see external stability condition below). The following relationship holds: $\sum_{x \in C_i} V_x(C_i, CS_k) = V(C_i, CS_k)$.

An embedded coalition (C_i, CS_k) is internal stable if none of its members l, $l \in C_i$, has incentives to leave and form a singleton coalition C^l, where $C^l = \{l\}$. Such condition can be written as follows:

$$V_l(C_i, CS_k) \geq V(C^l, CS_k^l) \qquad \forall l \in C_i, \tag{6}$$

where $CS_k^l = \{(CS_k \backslash C_i), (C_i \backslash l), (C^l)\}$ stands for a coalition structure formed from the original coalition structure CS_k in which coalition C_i is split into two coalitions: $(C_i \backslash l)$ and (C^l). In other words, given an

[xi] For a formal analysis of these two cases see Clark [1972].

[xii] If a capacity constraint is to be included, then instead of harvesting $\max(R - S, 0)$ our sequence of harvest strategies should satisfy the following: $\max\big[\min(R - S, Cap), 0\big]$, i.e., if $S < R$ then harvest their difference if it is below the fishing fleet capacity Cap or harvest the capacity, otherwise do not harvest and let the stock grow.

[xiii] See, among others, Pintassilgo *et al.* [2010] and Liu *et al.* [2016] for applications of these concepts on fishery games in partition function form.

[xiv] Note that the payoff of an embedded coalition is equivalent to the coalitional payoff specified in subsection 3.2 given that the coalition structure in which the coalitional payoff refers to is the same, i.e., $V(C_i, CS_k) \equiv v_i(S_i^*, S^*)$ if the coalition structure that v_i refers to is equivalent to CS_k.

embedded coalition (C_i, CS_k), the payoff a member l receives as a member of coalition C_i must be higher or equal to the payoff that l can receive if it leaves the coalition in order to form a singleton coalition. If this is true for all the members, then the embedded coalition (C_i, CS_k) is internal stable. Notice that the remaining form of the coalition structure is assumed to be unaffected by l's deviation, i.e., the remaining members of the said coalition do not leave after l leaves and the remaining coalitions in the coalition structure, if any, do not merge or split. This assumption is equivalent to the ceteris paribus assumption. By definition all embedded coalitions which are singletons are always internal stable.

In an open membership game, where membership into a coalition is free for all players, a second condition ensuring that outsiders do not have incentives to join a coalition is needed. Such condition is referred to as external stability. An embedded coalition (C_i, CS_k) is external stable if no other embedded coalition (C_j, CS_k), singleton or not, in the coalition structure CS_k has incentives to join coalition (C_i, CS_k). Such condition can be written as follows:

$$V(C_j, CS_k) \geq V_j(C_j^i, CS_k^j) \qquad \forall C_j \in CS_k; C_j \neq C_i, \tag{7}$$

where $C_j^i = C_j \cup C_i$ stands for a coalition formed if coalitions C_i and C_j merge, and $CS_k^j = \{(CS_k \backslash (C_j, C_i)), (C_j^i)\}$ stands for a coalition structure formed from the original coalition structure CS_k in which coalitions C_i and C_j are merged into one coalition: (C_i^j). That is to say, given a coalition structure CS_k, the payoff an embedded coalition (C_j, CS_k) receives must be higher or equal to the payoff C_j can receive if it joins coalition C_i and form a larger coalition. If this is true for all coalitions other than C_i within coalition structure CS_k, then the embedded coalition (C_i, CS_k) is external stable. Again, the remaining form of the coalition structure is assumed to be unaffected by the mergence. By definition the grand coalition is always external stable.

So far our analysis has been within the context of d'Aspremont *et al.* [1983] applied for embedded coalitions. Testing stability within this context requires the division of the coalitional payoff among coalition members. For instance, it is impossible to test for internal stability without knowledge of the individual payoff a coalition member receives (LHS of (6)). Likewise, external stability requires information regarding the payoff the merging coalition will receive after the merger takes place (RHS of (7)). Hence, a sharing rule is needed in order to split the coalitional payoff. Consequently, the stability of a coalition is going to depend upon such sharing rule.

The existing literature on sharing rules that can be applied to partition function games is not so extensive compared to the one for characteristic function games.[xv] Specifying a sharing rule for games in partition form is not an easy undertaking because of the complexity of the partition function. A common issue is that for a given coalition the coalitional payoff is not unique since the same coalition can belong

[xv]The coalitional payoff of a game in characteristic form is indepedent of the coalition structure.

to more than one coalition structures.[xvi] Some authors have proposed different weighted rules in order to determine a unique coalitional payoff.[xvii] However, these approaches do not provide a unique solution unless the weight parameters are fully specified.

In order to avoid these issues and since the main objective of this paper is to determine the set of stable coalition structures and not to distribute the gains of cooperation among cooperating nations, we adopt Eyckmans and Finus [2004] concept of potential internal stability. An embedded coalition (C_i, CS_k) is potentially internal stable if the sum of the free-riding payoffs of its members l, $l \in C_i$, does not exceed its coalitional payoff, i.e.,

$$V(C_i, CS_k) \geq \sum_{l \in C_i} V(C^l, CS_k^l), \tag{8}$$

where $C^l = \{l\}$ is a singleton coalition and $CS_k^l = \{(CS_k \backslash C_i), (C_i \backslash l), (C^l)\}$ stands for a coalition structure formed from the original coalition structure CS_k in which coalition C_i is split into two coalitions: $(C_i \backslash l)$ and (C^l). $V(C^l, CS_k^l)$ is the free-riding payoff that a coalition member l can receive if it leaves coalition C_i and form the singleton coalition C^l, ceteris paribus. By definition a singleton embedded coalition is always potential internal stable.

A clear advantage of condition (8) over (6) is that it can test for internal stability in the absence of a sharing rule. If an embedded coalition is potentially internal stable, then there exist some allocation schemes which can ensure internal stability. On the other hand, if potential internal stability does not hold, then no sharing rule can make an embedded coalition internal stable (Pintassilgo *et al.* [2010]).

Clearly, potential internal stability is a necessary condition for internal stability. By the same token, a necessary condition for external stability is needed in order to be able to determine stability in the absence of a sharing rule. An embedded coalition (C_i, CS_k) is potentially external stable if for all other embedded coalitions (C_j, CS_k) the following inequality holds:

$$V(C_j, CS_k) \geq V(C_j^i, CS_k^j) - \sum_{l \in C_i} V(C^l, CS_k^{jl}) \qquad \forall C_j \in CS_k; C_j \neq C_i, \tag{9}$$

where $C_j^i = C_j \cup C_i$ stands for a coalition formed if coalitions C_i and C_j merge, and $CS_k^j = \{(CS_k \backslash (C_j, C_i)), (C_j^i)\}$ stands for a coalition structure formed from the original coalition structure CS_k in which coalitions C_i and C_j are merged into one coalition: (C_i^j). In addition, $C^l = \{l\}$ is a singleton coalition and $CS_k^{jl} = \{(CS_k^j \backslash C_j^i), (C_j^i \backslash l), (C^l)\}$ stands for a coalition structure formed from coalition structure CS_k^j in which coalition C_j^i is split into two coalitions: $(C_j^i \backslash l)$ and (C^l). $V(C_j^i, CS_k^j)$ is the payoff coalition C_j^i receives after the merger occurs, ceteris paribus (hereinafter the merging payoff).

[xvi] To see this point consider a four player game and the following two coalition structures: $CS_1 = \{12, 3, 4\}$ and $CS_2 = \{12, 34\}$. In both coalition structures players 1 and 2 form a coalition. Players 3 and 4 act as singletons in CS_1 and also form a coalition in CS_2. The payoff of coalition (12) depends on the coalition structure that it belongs, and the coalition structure that contains coalition (12) is not unique.

[xvii] See Macho-Stadler *et al.* [2007], Pham Do and Norde [2007] and De Clippel and Serrano [2008] for examples.

And, $V(C^l, CS_k^{jl})$ is the free-riding payoff that a member l of coalition C_i receives if it leaves coalition C_j^i, ceteris paribus. Thus, given a coalition structure CS_k, an embedded coalition (C_i, CS_k) is potentially external stable if and only if the payoff of all other embedded coalitions C_j in CS_k is greater than the merging payoff minus the sum of the free-riding payoffs of coalition's C_i members. In other words, in order for coalition C_j not to be willing to merge with coalition C_i, its potential share of the merging payoff must be lower than its current payoff. The potential share of the merging payoff that coalition C_j is entitled to is the remainder of the merging payoff after all members of coalition C_i have received their free-riding payoffs. By definition the grand coalition is always potentially external stable.

Having defined the necessary conditions for an embedded coalition to be internal and external stable in the absence of a sharing rule we can now proceed in defining the necessary conditions for a coalition structure to be stable. As in the case of a coalition, stability of a coalition structure in an open membership game requires that the coalition structure is both internal and external stable.

Before we start analysing the two conditions, let us take a step back and visualise what internal and external stability of a coalition structure is. Figure 1 depicts the coalition structures for a four-player game. The nodes represent coalition structures. The arcs represent mergers of two coalitions when followed upward and splits of a coalition into two subcoalitions when followed downward. In a four-player game there exist four levels in total. A coalition structure level is a subset of the coalition structure set that consists of coalition structures with equal number of coalitions. In our example, the third level subset is composed of coalition structures that have only two coalitions. A stable coalition structure should not move upwards or downwards in the graph but remain in its position. This occurs if all embedded coalitions in a coalition structure do not have incentives to merge or split.

The split part is the easiest to test as it merely requires all embedded coalitions of a coalition structure to be internal stable. If this is true, then the coalition structure cannot be downgraded, i.e., move downwards in the graph. Using the notion of potential internal stability such condition can be written as follows:

$$V(C_i, CS_k) \geq \sum_{l \in C_i} V(C^l, CS_k^l) \qquad \forall C_i \in CS_k. \tag{10}$$

Therefore, if all embedded coalitions of a coalition structure are potentially internal stable, then the coalition structure is potentially internal stable, which is a necessary condition for internal stability to hold.

On the other hand, the merge part of our argument is not so straightforward to test. This is because it is not equivalent as saying that all embedded coalitions of a coalition structure should be external stable. If we say so, then some externally stable coalition structures will fail to pass the test and considered as externally unstable. To see this point, suppose that external stability of a coalition structure requires all of its embedded coalitions to be external stable. Consider the following coalition structure: $CS_{11} = \{123, 4\}$.

According to the aforementioned definition, CS_{11} is external stable if coalitions (123) and (4) are external stable. That is to say that coalition (123) does not want to merge with (4) and coalition (4) does not want to merge with (123). This sounds like a valid definition for a coalition structure to be external stable, and as a matter of fact it is. If all embedded coalitions of a coalition structure are external stable, then the coalition structure cannot be upgraded, i.e., move upwards in the graph.

Suppose now that one of the two embedded coalitions of CS_{11} is not external stable. Is this assumption going to upgrade CS_{11} permanently and therefore making it "truly" external unstable? Let coalition (123) be the only external stable coalition. In other words, (4) does not want to merge with (123) but (123) wants to merge with (4). Since not all embedded coalitions are external stable, by definition coalition structure CS_{11} is not external stable. Therefore, upgrade into coalition structure $CS_{15} = \{1234\}$ occurs. But we know that only coalition (123) is better off under the new coalition structure since by assumption it is the only coalition that wants to merge. Thus, coalition (4) deviates and coalition structure $CS_{11} = \{123, 4\}$ forms again.

The question now becomes: is it possible, given a pair of embedded coalitions, that only one has incentives to join the other? The short answer is yes. Typically, games with positive externalities are superadditive, i.e., $V(C_i \cup C_j, CS_k) \geq V(C_i, CS_k^i) + V(C_j, CS_k^j)$, where $CS_k^i = CS_k^j = \{(CS_k \backslash (C_i \cup C_j)), ((C_i \cup C_j) \backslash C_i)\}$. Superadditivity means that a merger between two embedded coalitions generates a payoff at least equal to the sum of the individual payoffs. The superadditivity property may or may not hold across the entire game but it holds for at least some embedded coalitions, at least it does in the game analysed in this paper.

Back to our question. Suppose that the superadditive property holds between the embedded coalitions of CS_{11} and CS_{15}, i.e., $V(1234, \{1234\}) \geq V(123, \{123, 4\}) + V(4, \{123, 4\})$. If this is true, then coalition (123) is better off under the mergence (strict inequality) or indifferent (equality). This is because the individual payoff of coalition (4) under CS_{11} is also its free-riding payoff. That is, after the mergence occurs, if coalition (4) deviates, it cannot receive a payoff greater than the payoff it already receives. Therefore, after mergence, coalition (123) receives at least its individual payoff. However, after mergence, coalition (4) may not necessarily receive its individual payoff. This is because, coalition (123) must receive a payoff which is at least as high as the sum of the free-riding payoffs of its members, i.e., $V_{123}(1234, \{1234\}) \geq \sum_{l \in (123)} V(l, \{(1234 \backslash l), (l)\})$. Therefore the potential payoff that coalition (4) can receive cannot exceed the difference between the merging payoff and the sum of the free-riding payoffs of coalition (123), i.e., $V_4(1234, \{1234\}) \leq V(1234, \{1234\}) - \sum_{l \in (123)} V(l, \{(1234 \backslash l), (l)\})$. If $V_4(1234, \{1234\})$ is greater than $V(4, \{123, 4\})$ then coalition (4) has incentives to merge otherwise it does not. It should be clear by now, that given a pair of coalitions, (C_1, C_2), the fact that C_1 wants to merge with C_2 does not imply that C_2 also wants to merge with C_1. In order for C_2 to be willing to merge, its payoff under the mergence should be greater than its individual payoff and this depends on the magnitude of the free-riding payoffs of C_1 members.

Even if the entire game is superadditive, i.e., at least some coalitions want to merge, the free-riding effects of these coalitions may be so strong they make it impossible for mergence to occur. And, it is because of strong free-riding effects that superadditive games with externalities cannot necessarily sustain the grand coalition as a stable outcome.

So far we have argued that requiring all embedded coalitions of a coalition structure to be external stable does not necessarily provide us with the set of all external stable coalition structures. So, is there a rule that when applied can give us the set of all external stable coalition structures? The answer is yes. Such condition requires that, given a coalition structure CS_k, all possible embedded coalitions pairs $\big[(C_i, CS_k), (C_j, CS_k)\big]$, $\forall C_i, C_j \in CS_k$ and $C_i \neq C_j$, are not willing to merge. An embedded coalition pair is not willing to merge if at least one of its embedded coalitions do not want to merge. Such conditions can be written as follows:

$$\text{A:} \quad V(C_i, CS_k) \geq V(C_i^j, CS_k^i) - \sum_{l \in C_j} V(C^l, CS_k^{il}) \qquad C_i \neq C_j; C_i, C_j \in CS_k \tag{11}$$

$$\text{B:} \quad V(C_j, CS_k) \geq V(C_j^i, CS_k^j) - \sum_{l \in C_i} V(C^l, CS_k^{jl}) \qquad C_j \neq C_i; C_j, C_i \in CS_k. \tag{12}$$

Condition A (B) is equivalent to the potential external stability condition (9) but only with respect to coalition C_i (C_j). That is, if A is true, then C_i does not want to merge with C_j, i.e., C_j is potentially external stable with respect to C_i. Similarly if B is true, then C_j does not want to merge with C_i, i.e., C_i is potentially external stable with respect to C_j. If one of the two conditions holds, i.e., A $\vee$ B, then the pair $\big[(C_i, CS_k), (C_j, CS_k)\big]$ will not merge and therefore is considered external stable. If this is true for all possible pairs within a coalition structure, i.e.,

$$\text{A} \ \vee \ \text{B} \qquad \forall C_i, C_j \in CS_k; C_i \neq C_j, \tag{13}$$

then the coalition structure is potentially external stable, which is a necessary condition for external stability to hold. A coalition structure is stable if it is both internal and external stable, i.e., stability of a coalition structure requires conditions (10) and (13) to hold simultaneously. An illustration of the stability concepts applied in this paper is provided through a small numerical example in Appendix A.2.

4. Empirical Model

Before proceeding with the specification of functional forms and parameters we first identify the different coalition structures in the four- and five-player games. The four-player game consists of the following nations: the EU, Norway, the Faroe Islands and Iceland. The total number of coalitions and coalition structures that are likely to occur in a four-player game are 15 and are depicted in Tables 1 and 2. The five-player game consists of the following nations: the EU, the UK, Norway, the Faroe Islands and Iceland. The total number of coalitions and coalition structures that are likely to occur in this game are 31 and 52 and are shown in Tables 3 and 4.

The singleton coalition of EU in the four-player game is treated to be equivalent to the coalition of EU and UK in the five-player game. As a consequence, all of the coalition structures that are likely to occur in the four-player game are also likely to reoccur in the five-player game. For example, CS_1 in the four-player game is equivalent to CS_2 in the five-player game and etc. However, the set of stable coalition structures is not necessarily equivalent between the two games. This is due to the fact that in the five-player game we allow for UK to make its own decisions and these decisions may not necessarily be aligned to the ones EU and UK as cooperators may implement. For the remaining of the paper and unless explicitly stated all figures related to EU refer to the five player game and do not take into consideration UK. Table 5 provides a concrete list of all the symbols we use in this paper.

4.1. *Stock-recruitment relationship*

In order to capture the relationship between a period's escapement S_t and next period's recruitment R_{t+1} a function $F(S)$ is needed where $R_{t+1} = F(S_t)$. One functional form, introduced by Ricker [1954] is: $F(S) = aSe^{-bS}$. This function has the property of overcompensation, i.e., it reaches a peak and then descends asymptotically towards $R = 0$, $\lim_{S\to\infty} F(S) = 0$. Another functional form, proposed by Beverton and Holt [1957] is: $F(S) = \frac{aS}{b+S}$. This one does not decrease but instead increases asymptotically towards $R = a$, $\lim_{S\to\infty} F(S) = a$. Both functions are well known among the models that have been developed to fit stock-recruitment curves to data sets.[xviii] We estimate and make use of both when running our model. By doing so, we are able to test how sensitive the set of stable coalition structures is to the biological constraint of our model.

Both functions are non-linear, thus before proceeding with the regressions we linearise them. The Ricker stock-recruitment relationship becomes:

$$R_t = aS_{t-1}e^{-bS_{t-1}} \Leftrightarrow ln(R_t) = ln(a) + ln(S_{t-1}) - bS_{t-1} \Leftrightarrow ln\left(\frac{R_t}{S_{t-1}}\right) = ln(a) - bS_{t-1}. \tag{14}$$

[xviii] See Iles [1994] for a review.

Similarly, the Beverton-Holt function becomes:

$$R_t = \frac{aS_{t-1}}{b + S_{t-1}} \Leftrightarrow \frac{1}{R_t} = \frac{1}{a} + \frac{b}{a}\frac{1}{S_{t-1}}. \tag{15}$$

We fit Eq. (14) and (15) using Ordinary Least Squares on recruitment and escapement data. The data used are obtained from ICES [2016a] advice report 9.3.39 Table 9.3.39.14. In particular, the following columns covering the period between 1980 and 2015 are used: (i) SSB (Spawning time), and (ii) Landings. According to ICES [2014], SSB means the estimate of the spawning stock biomass at spawning time in the year in which the TAC applies, taking into account of the expected catch (Annex 9.3.17.1 Management plan harvest control rule). In the beginning of section 2 of this paper, we define the recruitment of a fishery as the unexploited spawning stock biomass at the beginning of a period. If we identify that the beginning of a period occurs when spawning takes place, then the terms recruitment and SSB are equivalent. Moreover, landings refers to the mackerel biomass landed in all ports in the Northeast Atlantic area in a respective year, which is equivalent to the total harvested biomass. Therefore, the difference between SSB and landings represents the escapement of the stock in a particular period/year.

The parameters a and b in Eq. (14) and (15) are estimated after the time lag as well as transformation for variables R and S have been taken into account. The results of the regression are shown in Table 6. Figure 2 shows the actual development of the mackerel stock and the fitted curves for both stock-recruitment functions on the escapement data. Both functions can trace the actual mackerel stock reasonably well.

4.2. *Share of mackerel stock*

As we already mention in subsection 2.2, θ_l denotes the share of the mackerel stock that only appears in the EEZ of nation l during the whole year. We believe that the share parameters consists of two dimensions, namely, time and space. Time refers to the percentage of months in a year that mackerel appears in the EEZ of a nation. And, space refers to the percentage of the mackerel stock that appears in the EEZ of a nation. Multiplication of the two percentages for nation l yields parameter θ_l.

For the dimension of time, we base our analysis on the annual migration pattern of the mackerel stock and the time it spends on the respective EEZs of the nations concerned in this paper. The migration pattern of mackerel is divided into two elements, namely, a pre-spawning migration and a post-spawning one (ICES [2016b]). From late summer to autumn, the pre-spawning migration starts from the feeding grounds in the North and Nordic seas. This migration phase includes shorter or longer halts in deep waters along the edge of the continental shelf where mackerel shoals overwinter until they reach the spawning grounds south down the west coast of Scotland and Ireland, and along the shelf break waters between Spain and Portugal. The stock is targeted by Norwegian, British and European vessels when it overwinters (fourth quarter) and by European and British vessels afterwards (first quarter). After spawning occurs, the post-spawning migration towards the feeding grounds begins. No significant catches occur during this migration, which takes place in spring (second quarter). During summer the stock is more spread as it feeds in Northern waters. At this time Norwegian, Icelandic and Faroese vessels are active (third quarter).

According to the mackerel migration pattern, we conclude that the stock occurs 50% of the time in the Norwegian EEZ (third and fourth quarters), 50% of the time in the European and British EEZs (fourth and first quarters), and 25% of the time in the Icelandic and Faroese EEZs (third quarter).

For the spatial distribution, unfortunately, no data exist that measures the amount of mackerel that appears in a specific geographical area within the Northeast Atlantic. Therefore, we make the simplifying assumption that approximately half of the stock appears in the EEZ of a nation during mackerel's annual migration pattern. That is, the space percentage that appears in the EEZ of a nation is constant and equal to 50% for all nations. Table 7 shows the share of the mackerel stock that appears in the EEZ of the nations we consider in this paper, calculated as the product of the two dimensions analysed here. As already mentioned in subsection 2.2, the share of the mackerel stock of coalition i is computed as the sum of the individual shares of its members.

4.3. *Unit cost of harvest*

As we discuss in section 2, the coalitional unit cost of harvest $c_i(x)$ is a continuous and decreasing function with respect to stock size and the total cost within one period is specified as $TC_i(R_{it}, S_{it}) = \int_{S_{it}}^{R_{it}} c_i(x)dx$. Total costs can be also expressed to be proportionate with fishing effort E_i, that is $TC_i(E_i) = c_iE_i$, where c_i is a cost parameter. Furthermore, we define the harvest production function of a coalition to be $H_i = E_ix^{\beta}$, where β is the stock elasticity and is assumed to be the same for all coalitions. Solving the harvest production function with respect to fishing effort and substituting in the total cost function yields: $TC_i(H_i, x) = c_iH_ix^{-\beta}$. Dividing with harvest, the unit cost of harvest can be expressed as $c_i(x) = c_ix^{-\beta}$. Substituting for the unit cost of harvest in the initial total cost expression and solving the integral provides us with an analytic expression for the total cost of harvest of coalition i. Notice that for values of $\beta = 1$ and $\beta \in (0,1)$ the integral yields different solutions.[xix] Thus,

$$TC_i(R_{it}, S_{it}) = \begin{cases} c_i ln\left(\dfrac{R_{it}}{S_{it}}\right) & \beta = 1 \\ c_i \dfrac{1}{1-\beta}(R_{it}^{1-\beta} - S_{it}^{1-\beta}) & 0 < \beta < 1 \ . \end{cases} \tag{16}$$

Due to lack of uniformly reported cost data across the nations considered in this paper as well as the short-length of some of these series, the cost parameters cannot be estimated through statistical procedures. Instead, the cost coefficients c_i for all coalitions are calibrated at the level which ensures that for base year harvest, $\bar{H}_i = \sum_{l \in C_i} \bar{H}_l$, and base year recruitment, $\bar{R}_i = \theta_i \bar{R}$, total cost is the estimated base year proportion of total revenue ψ, i.e.,

$$c_i = \begin{cases} \psi p \bar{H}_i ln\left(\dfrac{\bar{R}_i}{\bar{R}_i - \bar{H}_i}\right)^{-1} & \beta = 1 \\ \psi p \bar{H}_i (1-\beta)\big[\bar{R}_i^{\,1-\beta} - (\bar{R}_i - \bar{H}_i)^{1-\beta}\big]^{-1} & 0 < \beta < 1 \ . \end{cases} \tag{17}$$

The cost-revenue ratio ψ is equal to 0.78 and is assumed to be equal for all nations. Its computation is based on operating expenses and operating revenues of licensed Norwegian purse seiners for the year 2015 obtained from the report: Profitability survey on the Norwegian fishing fleet, Table G 20 (Norwegian Directorate of Fisheries [2015]).

Base year harvest for all nations, $\bar{H}_l$, and base year recruitment for the entire mackerel fishery, $\bar{R}$, are obtained from ICES [2016a] advice report 9.3.39. Recruitment for year 2015 is provided from Table 9.3.39.14 of the report and is equivalent to 4,887 thousand tonnes for the entire mackerel fishery. Individual harvest levels for year 2015 are provided from Table 9.3.39.12 of the ICES report and are depicted in Table 8 of this paper. Base year harvest for coalition i, $\bar{H}_i$, is defined as the sum of the base year quantities of its members l, i.e., $\bar{H}_i = \sum_{l \in C_i} \bar{H}_l$. Base year recruitment for coalition i, $\bar{R}_i$, is defined as the product of the coalition's share of mackerel stock θ_i and overall base year recruitment, i.e., $\bar{R}_i = \theta_i \bar{R}$.

The price p is equivalent to 10 NOK/kg. The stock elasticity β is not estimated empirically and is therefore varied when running our model in order to capture a range of possibilities. We set β equal to 1, 0.6, 0.3 and 0.1.[xx] Tables 9 and 10 in the Appendix show the cost parameters for all coalitions in both the four and five player games for all realisations of the stock elasticity.

[xix] For $\beta = 0$ total cost becomes proportional to harvest and the unit cost of harvest is no longer stock dependent. Constant stock density ($\beta = 0$) implies that the equilibrium escapement strategy profile of a coalition structure as specified in subsection 3.2 (system of equations (4)) cannot be obtained. This is because marginal profit at the beginning and the end of a harvesting period is no longer different and the non-cooperative golden rule becomes $1 = \gamma \theta_i F'(S)$.

[xx] For models which empirically estimate the stock elasticity see Nøstbakken [2006] and Ekerhovd and Steinshamn [2016].

5. Numerical Results and Discussion

Having defined all parameters and functional forms, the solution process of the game is as follows. First, optimal escapement strategies for all coalitions in a coalition structure are computed by solving the system of equations presented in (4). The sum of the optimal escapement strategies determine the optimal recruitment through the Ricker (Eq. (14)) or the Beverton-Holt (Eq. (15)) stock-recruitment function. Then, recruitment and harvest levels for all coalitions in a coalition structure are calculated following the framework described in the beginning of subsection 2.2. The coalitional payoff of all coalitions in a coalition structure is determined through Eq. (5). This process is repeated for all coalition structures in both games. Finally, internal and external stability of a coalition structure is tested using conditions (10) and (13). Both games are solved eight times in total, two times for each stock-recruitment function (Ricker and Beverton-Holt) and four times for all the different variations of the stock elasticity parameter. Due to limited reporting space, all result tables are placed in a supplementary report, which can be obtained from the authors by request.

Before proceeding with the discussion of stable coalition structures, we point out three facts regarding the overall results of these games. First and foremost, our results indicate that positive externalities occur in the mackerel fishery, since when coalitions merge to form a larger coalition, outside coalitions not affected by the merger are better off. According to Yi [1997] this result is the defining feature of coalition games with positive externalities. The members of merging coalitions increase the stock level and hence reduce their cost of fishing in order to internalise the positive externality which affects them. Non-cooperating coalitions benefit from the merger by free-riding on the merging coalitions stock increase.

Second, because of this internalisation, aggregate escapement and recruitment increase as the degree of cooperation between coalition structures increases. Figures 3, 4, 8 and 9 show the escapement and recruitment development across coalition structures in the four- and five-player games for both stock-recruitment functions and all realisations of the stock elasticity. Escapement and recruitment levels are almost the same for both stock-recruitment functions. For stock elasticities equal to 0.3, 0.6 and 1.0 the Ricker function gives slightly higher levels of escapement and recruitment. The opposite is true when stock elasticity is equal to 0.1 for most coalition structures. Furthermore, the lower the stock elasticity the higher the depletion of the stock and thus its growth. This effect is mitigated as the number of coalitions within a coalition structure decreases.

Harvest, which is defined as the difference between recruitment and escapement, is depicted in Figures 5 and 10. It is not clear whether it increases or not as we move to more cooperative behaviours. For stock elasticities equal to 0.6 and 1.0 it decreases and for stock elasticities equal to 0.1 and 0.3 it increases. This is due to the fact that in stock-recruitment models, as escapement increases, harvest increases from zero to a maximum, i.e., the maximum sustainable yield (MSY) point, and afterwards decreases back to zero, i.e., the carrying capacity point. The MSY points in our model occur at approximately 2,482 and 2,162 thousand tonnes for the Ricker and the Beverton-Holt functions respectively. Thus, all escapement levels before (after) these points lead to an increased (decreased) growth rate and therefore harvest, which explains the change in harvest.

Third, the aggregated value of a coalition structure increases as the number of coalitions within decrease. Figures 6, 7, 11 and 12 show this increase for both stock-recruitment functions and all realisations of the stock elasticity for both the four- and five-player games. The fact that cooperative behaviours generate more value indicates that incentives for cooperation among nations exist. However, these incentives must exceed the free-riding benefits in order for cooperation to succeed.

In the four-player game the grand coalition structure is not a stable outcome in all eight cases. That is, the sum of the free-riding payoffs of the players exceeds the payoff of the grand coalition, thus, making it impossible for any sharing rule to stabilise it. Table 11 shows the set of stable coalition structures in the four-player game for all eight cases. The set of stable coalition structures, which is the same for all cases but the Beverton-Holt with $\beta = 1$, consists of all coalition structures that consist of two coalitions, where one of them is a singleton. In addition, the coalition structure representing the current management regime, i.e., CS_{11}={(EU,NO,FO),(IS)}, is among the stable ones. Recall, that by stability we mean that in the presence of some but not all sharing rules the coalitions within a coalition structure do not have incentives to merge or split.

In the five-player game, again, the grand coalition structure cannot be sustained as an optimal outcome. The set of stable coalition structures is depicted in Table 12 for all eight cases. For both stock-recruitment functions and for stock elasticity levels equal to 0.6 and 0.3, all coalition structures consisting of two coalitions, where none of them is a singleton, are stable, namely, CS_{37} to CS_{46}.

For the two extreme stock elasticities, the set of stable coalition structures differs across the stock-recruitment functions as well as between the middle elasticities. For $\beta = 1$, CS_{37}={(EU,UK,NO),(FO,IS)} is no longer stable for both stock-recruitment functions, but CS_{27}={(EU,UK,NO),(FO),(IS)} becomes stable. Thus, according to our results, if the mackerel fishery is uniformly distributed, then Iceland and the Faroe Islands do not have incentives to cooperate with each other any more, given that the remaining nations cooperate. In addition to CS_{37}, coalition structures 42, 45 and 46 are no longer stable when $\beta = 1$ for the Beverton-Holt case. These coalition structures consist of two coalitions where in one coalition a major player (EU, UK or NO) cooperate with the two minors (FO and IS) and in the other the remaining major players cooperate together.

For $\beta = 0.1$, coalitions structures 47 to 51 also become stable for the Ricker case, but only coalition structures 49, 50 and 51 for the Beverton-Holt case. These coalition structures consist of two coalitions, where one of them is a singleton.

Compared to the four-player game, where the set of stable coalition structures remains the same in almost all the cases, in the five-player game stability of some coalition structures is sensitive to the stock-recruitment function and the stock elasticity parameter. Interesting enough, the stable coalition structures in the four-player game are no longer stable for most of the cases in the five-player game. Recall that the singleton coalition of (EU) in the four-player game is equivalent to the coalition of (EU,UK) in the five-player game. The five player game coalition structures, which are equivalent to the stables ones in the four-player game are: $CS_{11} \equiv CS_{47}$, $CS_{12} \equiv CS_{48}$, $CS_{13} \equiv CS_{49}$ and $CS_{14} \equiv CS_{46}$.

The current management regime, i.e. CS_{11} and CS_{47} in the four- and five-player games respectively, is stable only in one case in the five-player game (Ricker; $\beta = 0.1$), in contrast to the four-player game, where it is stable in all eight cases. This is also true for CS_{12} or CS_{48}={(EU,UK,NO,IS),(FO)}. Coalition structure 13, i.e., CS_{49}={(EU,UK,FO,IS),(NO)} in the five-player game, occurs only when $\beta = 0.1$ irrespective of the stock-recruitment function. The only four-player game coalition structure that remains stable in all but one (Beverton-Holt; $\beta = 1$) of the five-player game cases is CS_{14}, i.e., CS_{46}={(NO,FO,IS),(EU,UK)}.

On the other hand, some stable coalition structures in the five-player game are not stable in the four-player game, namely, CS_{27}, CS_{37}, CS_{38} and CS_{39}. The common property of these coalition structures is that the EU and the UK belong in the same coalition. This change in stability between the two games is due to the relative magnitude of the free-riding payoff of the EU in the four-player game and the sum of the free-riding payoffs of the EU and the UK together in the five-player game. In general, the smaller the free-riding payoff, the higher the chance that the external stability condition will not be satisfied, i.e., a coalition will have incentives to merge with another coalition. In the four-player game, the free-riding payoff of the EU is low enough to make it profitable for other coalitions to want to merge with the coalition that it belongs, thus the external stability condition does not hold and therefore the respective coalition structures in the four-player game, i.e., CS_2, CS_8, CS_9 and CS_{10}, are not stable. In the five-player game, however, the free-riding payoffs of the EU and the UK together are high enough that is no longer profitable for other coalitions to merge with the coalition that they belong, and therefore making these coalition structures stable.

Having determined the set of stable coalition structures, we now ask ourselves how likely are to form in reality. From the four stable coalition structures of the four-player game, we know that only CS_{12} has been formed in the mackerel fishery. So, from the stable coalition structures of the five-player game, which ones are likely to occur in reality? Or, to put it another way, which ones are unlikely to occur? In what follows, we discuss which coalitions we believe are likely or not to occur post-Brexit based on our intuition of the relations between all five parties.

First, is the cooperation between the EU, the UK, Norway and the Faroe Islands as defined by the current 5-year management plan, likely to continue after the conclusion of the Brexit's negotiations?

The agreement itself will cease to exist, since the UK will no longer be represented by the EU and therefore must sign its own agreements. In general, after Brexit, the UK will have to negotiate fisheries agreements with other coastal states as well as with the EU. Regarding, straddling and highly migratory fish stocks, such as mackerel, international law requires that all interest parties must cooperate, directly or through RFMOs, that is, the NEAFC in case of Atlantic mackerel. Thus, it is possible that post-Brexit relationships in the mackerel fishery will be similar or close to existing ones. Of course, the relative TAC shares of the EU and the UK as well as the other parties may change depending on the outcome of the negotiations.

After the conclusion of Brexit, the UK will have sovereign control over the resources in its EEZ, and therefore, the principle of equal access[xxi] will cease to apply in British waters and access will now be determined by the criteria set out in UNCLOS. In other words, access into British fisheries will no longer be regulated by European law but by international law. At the moment, EU vessels harvesting in UK's EEZ catch more fish inside British waters than UK vessels catch in the Union's EEZ. Particularly, in 2015, EU vessels caught 683,000 tonnes, i.e., 484 million GBP in revenue, in UK waters, whereas UK vessels caught 111,000 tonnes, i.e., 114 million GBP in revenue, in European waters (Brexit White Paper [2017]).[xxii] Regarding mackerel, the vast majority of catches taken by the EU occurs within the UK EEZ (Doering *et al.* [2017]). According to a recent study by Le Gallic *et al.* [2017], if the UK prohibits the EU fleet from accessing fishing stocks within its EEZ, it will cause great loss of revenues for these vessels. Even if the EU redistributes quotas inside its EEZ, it is unlikely that it will compensate for the loss of such important fishing grounds.

From the above, it seems like the UK has all the bargaining power when it comes to negotiating a post-Brexit agreement with the EU. However, this is not true. The UK depends primarily on the EU market for its fishery exports. For the period 2001-2016, 68% on average of the total value generated by fishery exports came from the EU, i.e., 1,204 million EUR. As far as mackerel is concerned, since 2010, on average, more than 60% of UK's annual mackerel exports goes to the EU market, generating on average 70 million EUR.[xxiii] Thus, the EU, which is an important trading partner of the UK when it comes to fishery products, might introduce trade barriers, if its access to British waters is limited or denied.

Furthermore, is it possible that cooperation between the EU and Norway will fall apart post-Brexit? Europe and Norway have a long tradition of positive relations, not only in fisheries but across many sectors, and it is doubtful that Norway will act unilaterally, especially if EU and UK agree to cooperate after UK's withdrawal. The bilateral agreement between the EU and Norway covering the North Sea

[xxi] Fishing vessels registered in the EU fishing fleet register have equal access to all European waters and resources that are managed under the CFP.

[xxii] Provisional Statistics – UK Fleet Landings from other EU Member States waters: 2015, Marine Management Organisation, February 2017. These figures do not include fish caught by third country vessels, for example Norway, in UK waters, or fish caught by UK fisherman in third country waters.

[xxiii] Tha data is obtained from the European Market Observatory for Fisheries and Aquaculture Products (EUMOFA).

and the Atlantic is the Union's most important international fisheries agreement in terms of both the exchange of fishing opportunities and joint fisheries management measures (Doering *et al.* [2017]).[xxiv] Although this agreement is not related to the management of the mackerel stock,[xxv] a possible conflict between the EU and Norway regarding the management of mackerel could undermine it. In addition, access of Norwegian fishery products to EU's internal market may also be undermined. As far as Norway is concerned, Brexit is going to make fishery resources in EU waters less attractive, given that when it comes to quota exchanges, stocks in UK waters are more important for Norway than those in EU waters (Sobrino Heredia [2017]). Still, the fact that the EU is a very important trading partner for Norway gives both players more or less equal bargaining power when it comes to negotiating their post-Brexit relationship. The value of Norwegian mackerel exports to the EU excluding the UK were on average 475 million NOK for the period 2007-2016, whereas to the UK for the same period were valued at 62 million NOK on average.[xxvi,xxvii] Thus, making the EU a more significant trading partner for Norway regarding mackerel.

Finally, how are Iceland and the Faroe Islands likely to behave post-Brexit? There has been no indication so far that Iceland is willing to cooperate with the remaining states to jointly determine the mackerel quota. Given its history of disputes, it is highly unlikely that it will cooperate unless it is allowed to maintain its quota or offered something else in exchange for reducing it. However, Iceland may be interested to strengthen its relations with an independent UK and perhaps willing to compromise in the prospect of a future agreement with the UK. As far as the Faroe Islands are concerned, they will most probably keep cooperating with the EU and Norway given that their post-Brexit quota is close to the current one. Like Iceland, they may also be interested to strengthen their relations with the UK. In general, the UK will have to work closely with Norway, Iceland and the Faroe Islands in order to ensure access in one another's waters.

6. Conclusion

In this paper, we analyse how cooperation is likely to occur in the Northeast Atlantic mackerel fishery after the Brexit negotiations are concluded. To do so, we have considered two games: a four-player game, which treats the EU and the UK as one coalition acting together, and a five-player game where the UK is a distinct player acting on its behalf. For our bioeconomic model of the mackerel fishery, we assume

[xxiv]The agreement was first enforced on 16 June 1981 for a 10-year period, after that has been tacitly renewed for successive 6-year periods. The last renewal tool place in 2015.

[xxv]The stocks that this agreements refers to are: cod, plaice and haddock.

[xxvi]The data is obtained from Statistics Norway, Table: 09283: Exports of fish, by country/trade region/continent.

[xxvii]Value of Norwegian fish, crustaceous animals and mollusc exported to the EU excluding the UK were on average 34,637 million NOK. That is, 90% higher compared to the respective exports in the UK, which were amounted to 3,073 million NOK on average.

a density-dependent stock-recruitment relationship. Both games are solved multiple times for different stock-recruitment functions and levels of the stock elasticity.

We find that positive stock externalities are indeed present in both games since outsiders are better off when a merger between coalitions occurs. The members of a coalition are able to reduce their fishing cost by internalising the positive externality, thus increasing the stock level. This allows outsiders to free-ride on them by benefiting from the increase in the stock. As expected, escapement and recruitment as well as the aggregated value a coalition structure generates increase as the number of coalitions within a coalition structure decreases. That is, cooperation leads to higher profits as well as higher stock preservation. However, in order for cooperation to be achieved the free-riding payoffs of the cooperating nations must not exceed their aggregate coalitional payoff.

In both games, the grand coalition cannot be sustained as an optimal outcome for all scenarios evaluated. The current management regime, however, is found to be stable outcome in all eight cases of the four-player game, but only in one case of the five-player game. This is also true for all the remaining, but one, stable coalition structures of the four-player game. In addition, some non-stable coalition structures in the four-player game become stable in the five-player game. This occurs because the free-riding payoff of the EU in the four-player game is less than the sum of the free-riding payoffs of the EU and the UK in the five-player game, and therefore making the external stability condition for those coalition structures to only hold in the five-player game. Moreover, in the four-player game, the set of stable coalition structures remains the same in almost all cases, whereas in the five-player game stability depends on the stock-recruitment function as well as the magnitude of the stock elasticity.

As far as the future of the mackerel fishery is concerned, we believe that the EU and Norway will keep cooperating post-Brexit. In the event that the UK restricts access to the EU's fleet within its waters, then perhaps Norway will have to give a percentage of its quota to the EU in order to maintain access to the European market. In case of a "hard" Brexit, i.e., no compromises between the EU and the UK during the negotiations, the UK will most likely set its mackerel quota unilaterally. It goes without saying that if this happens, then the pressure on the mackerel stock will increase even more, especially if Iceland continues not to cooperate. However, both the EU and Norway could respond harshly by introducing trade sanctions, as they have already done to Icelandic and Faroese catches in 2013. If a "soft" Brexit occurs, then relationships in the mackerel fishery may be similar or close to existing ones, but the relative shares of the TAC may change depending on the outcome of the negotiations.

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A. Appendix

A.1. *Proof of non-cooperative "golden-rule".*

The logic of the proof is similar to the one presented by Clark [2010, p. 91]. The profit of coalition i in period t is:

$$\Pi_i(R_{it}, S_{it}) = p(R_{it} - S_{it}) - \int_{S_{it}}^{R_{it}} c_i(x)dx = \int_{S_{it}}^{R_{it}} [p - c_i(x)]dx,$$

where $\pi_i(x) = p - c_i(x)$ is the marginal profit of coalition i. Let $\phi_i(x)$ be the antiderivative of $\pi_i(x)$, then we can express the profit of coalition i as:

$$\Pi_i(R_{it}, S_{it}) = \phi_i(R_{it}) - \phi_i(S_{it}).$$

Therefore, the net present value of coalition i becomes:

$$V_i = \sum_{t=0}^{\infty} \gamma^t [\phi_i(R_{it}) - \phi_i(S_{it})].$$

Substituting for the recruitment share of coalition i, $R_{it} = \theta_i R_t$, and for the stock-recruitment relationship, $R_t = F(S_{t-1})$ for $t \geq 1$, the first term of the net present value expression yields:

$$\begin{aligned}\sum_{t=0}^{\infty} \gamma^t \phi_i(R_{it}) &= \phi_i(R_{i0}) + \sum_{t=1}^{\infty} \gamma^t \phi_i[\theta_i F(S_{t-1})] \\ &= \phi_i(R_{i0}) + \sum_{t=0}^{\infty} \gamma^{t+1} \phi_i[\theta_i F(S_t)].\end{aligned}$$

Finally, substituting the above term in the net present value of coalition i, we obtain:

$$\begin{aligned}V_i &= \phi_i(R_{i0}) + \sum_{t=0}^{\infty} \gamma^{t+1} \phi_i[\theta_i F(S_t)] - \sum_{t=0}^{\infty} \gamma^t \phi_i(S_{it}) \\ &= \phi_i(R_{i0}) + \sum_{t=0}^{\infty} \gamma^t \left[\gamma \phi_i[\theta_i F(S_t)] - \phi_i(S_{it})\right].\end{aligned}$$

Now coalition i is enabled to set out the optimal escapement strategy given the escapement strategies of the other coalitions, namely, coalition i to choose the escapement level S_{it} for each time period $t = 0, 1, 2, \ldots$ by solving the following maximisation problem:

$$\begin{aligned} \underset{S_{it}}{\text{maximise}} \quad & \gamma\phi_i[\theta_i F(S_t)] - \phi_i(S_{it}) \\ \text{subject to} \quad & S_t = S_{it} + \sum_{j=1}^{m-1} S_{jt} \qquad i \neq j. \end{aligned}$$

Substituting for S_t in the objective function and taking the first order condition we get:

$$\begin{aligned} \left[\gamma\phi_i[\theta_i F(S_{it} + \sum_{j=1}^{m-1} S_{jt})] - \phi_i(S_{it})\right]' &= \gamma\phi_i'[\theta_i F(S_{it} + \sum_{j=1}^{m-1} S_{jt})]\theta_i \frac{dF(S_{it} + \sum_{j=1}^{m-1} S_{jt})}{dS_{it}} - \phi_i'(S_{it}) \\ &= \gamma\pi_i[\theta_i F(S_{it} + \sum_{j=1}^{m-1} S_{jt})]\theta_i \frac{dF(S_{it} + \sum_{j=1}^{m-1} S_{jt})}{dS_{it}} - \pi_i(S_{it}) = 0. \end{aligned} \tag{1}$$

It can be shown that the derivative of the stock-recruitment function $F(S)$ with respect to coalition's i escapement S_i is equivalent to the derivative of $F(S)$ with respect to the aggregate escapement S. The proof makes use of the chain rule and the fact that the derivative of the aggregate escapement with respect to coalition's i escapement is one, i.e.,

$$\frac{dS}{dS_i} = \frac{d(S_i + \sum_{j=1}^{m-1} S_j)}{dS_i} = 1.$$

Thus,

$$\frac{dF(S_i + \sum_{j=1}^{m-1} S_j)}{dS_i} = \frac{dF(S_i + \sum_{j=1}^{m-1} S_j)}{d(S_i + \sum_{j=1}^{m-1} S_j)} \frac{d(S_i + \sum_{j=1}^{m-1} S_j)}{dS_i} = \frac{dF(S)}{dS} = F'(S).$$

Let $S_{it} = S_i^*$ solve (1), then we can re-write it as follows:

$$\pi_i(S_i^*) = \gamma\theta_i F'(S)\pi_i[\theta_i F(S)],$$

where $S = S_i^* + \sum_{j=1}^{m-1} S_j$ is the aggregate escapement and it depends on the optimal escapement strategy of coalition i and the escapement strategies of the other coalitions j. ■

A.2. *Illustration of coalition structure stability concepts*

Consider a three player coalition formation game of the class studied in this paper. Let $N = \{a, b, c\}$ be the set of players. Table A1 depicts the payoffs of all embedded coalitions in this game. The property of superadditivity holds for the entire game, i.e., the merging payoff of two embedded coalitions belonging in the same coalition structure is at least as high as their individual payoffs.

Table A1. Embedded coalition payoffs

CS_k	$V(C_1, CS_k)$	$V(C_2, CS_k)$	$V(C_3, CS_k)$
$\{a, b, c\}$	2	4	1
$\{ab, c\}$	7	2	
$\{ac, b\}$	4	5	
$\{bc, a\}$	6	4	
$\{abc\}$	10		

Suppose we want to test if coalition structure $\{ab, c\}$ is stable. According to subsection 3.2 a coalition structure is stable if all of its embedded coalitions are potentially internal and external stable. The tested coalition structure consist of two coalitions: (ab) and (c).

Let us test for potential internal stability first. Coalition (c) is a singleton and therefore is always internal stable. In order for coalition (ab) to be potentially internal stable the payoff of (ab) given coalition structure $\{ab, c\}$ must be greater or equal to the free-riding payoffs of its members, ceteris paribus. The free-riding payoffs are determined as follows. Consider player a first, if player a leaves coalition (ab) then the new coalition structure, ceteris paribus, is $\{a, b, c\}$. Similarly, if player b leaves coalition (ab), then the new coalition structure, ceteris paribus, is $\{a, b, c\}$. Notice that the new coalition structures are the same in both deviations; this is not always the case as we will see in the next case. Having determined the new coalition structures, we can now compare the payoffs and test if coalition (ab) is potentially internal stable.

$$V(ab, \{ab, c\}) \geq V(a, \{a, b, c\}) + V(b, \{a, b, c\}) \Rightarrow 7 \geq 2 + 4 = 6.$$

Since the above inequality holds we can conclude that coalition (ab) is potentially internal stable. Seeing that both coalitions (ab) and (c) are potentially internal stable we can conclude that coalition structure $\{ab, c\}$ is potentially internal stable. We move on to test for potential internal stability.

Coalition structure $\{ab, c\}$ consist of only one pair of embedded coalitions, i.e, $\big[(ab, \{ab, c\}), (c, \{ab, c\})\big]$. In order for $\{ab, c\}$ to be external stable at least one of the two embedded coalitions should not have incentives to merge. Let us start with (ab), if (ab) merges with (c) then the new coalition structure, ceteris paribus, will be $\{abc\}$ but player c must receive at least her free-riding payoff which occurs if she deviates from the new coalition (abc). If player c leaves (abc) the new coalition structure, ceteris paribus, will be $\{ab, c\}$. Thus, the potential external stability condition for coalition (ab) with respect to coalition (c) requires the following:

$$V(ab, \{ab, c\}) \geq V(abc, \{abc\}) - V(c, \{ab, c\}) \Rightarrow 7 \geq 10 - 2 = 8.$$

Since the above inequality does not hold we can conclude that coalition (ab) does have incentives to merge with coalition (c) and therefore (c) is not potentially external stable with respect to (ab). However, coalition structure $\{ab, c\}$ may still be external stable as long as coalition (c) is better off without the mergence. If (c) merges with (ab) then the new coalition structure, ceteris paribus, will be $\{abc\}$ but players a and b must receive at least their free-riding payoffs. If player a leaves (abc) the new coalition structure, ceteris paribus, will be $\{bc, a\}$. Similarly, if player b leaves (abc) the new coalition structure, ceteris paribus, will be $\{ac, b\}$. Thus, the potential external stability condition for coalition (c) with respect to coalition (ab) requires the following:

$$V(c, \{ab, c\}) \geq V(abc, \{abc\}) - V(a, \{bc, a\}) - V(b, \{ac, b\}) \Rightarrow 2 \geq 10 - 4 - 5 = 1.$$

Since the above inequaility holds, coalition (c) does not have incentives to merge with coalition (ab) and therefore (ab) is potentially external stable with respect to coalition (c). Since $\big[(ab, \{ab, c\}), (c, \{ab, c\})\big]$ is the only embedded coalition pair of coalition structure $\{ab, c\}$ and $(c, \{ab, c\})$ is not willing to merge, we can conclude that coalition structure $\{ab, c\}$ is potentially external stable. Because coalition structure $\{ab, c\}$ is both potentially internal and external stable we can conclude that $\{ab, c\}$ is a stable coalition structure.

Following the same procedure, it can be showed that coalition structures $\{ac, b\}$ and $\{bc, a\}$ are also stable. The singleton coalition structure $\{a, b, c\}$ is not potentially external stable since all the players have incentives to form a coalition with at least one more player. The grand coalition structure $\{abc\}$ is not potentially internal stable since the sum of the free-riding payoffs of its members exceeds the payoff of the grand coalition, i.e.,

$$V(abc, \{abc\}) \geq V(a, \{bc, a\}) + V(b, \{ac, b\}) + V(c, \{ab, c\}) \Rightarrow 10 \geq 4 + 5 + 2 = 11.$$

This also verifies the fact that superadditive games with externalities cannot necessarily sustain the grand coalition as a stable outcome.

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Table 1. List of all coalitions for the four player game.

No.	Coalition	No.	Coalition	No.	Coalition
1	(EU)	6	(EU,FO)	11	(EU,NO,FO)
2	(NO)	7	(EU,IS)	12	(EU,NO,IS)
3	(FO)	8	(NO,FO)	13	(EU,FO,IS)
4	(IS)	9	(NO,IS)	14	(NO,FO,IS)
5	(EU,NO)	10	(FO,IS)	15	(EU,NO,FO,IS)

Table 2. List of all possible coalition structures for the four player game.

No.	Coalition structure	No.	Coalition structure	No.	Coalition structure
1	(EU),(NO),(FO),(IS)	6	(NO,IS),(EU),(FO)	11	(EU,NO,FO),(IS)
2	(EU,NO),(FO),(IS)	7	(FO,IS),(EU),(NO)	12	(EU,NO,IS),(FO)
3	(EU,FO),(NO),(IS)	8	(EU,NO),(FO,IS)	13	(EU,FO,IS),(NO)
4	(EU,IS),(NO),(FO)	9	(EU,FO),(NO,IS)	14	(NO,FO,IS),(EU)
5	(NO,FO),(EU),(IS)	10	(EU,IS),(NO,FO)	15	(EU,NO,FO,IS)

Table 3. List of all coalitions for the five player game.

No.	Coalition	No.	Coalition	No.	Coalition	No.	Coalition
1	(EU)	9	(EU,IS)	17	(EU,UK,FO)	25	(NO,FO,IS)
2	(UK)	10	(UK,NO)	18	(EU,UK,IS)	26	(EU,UK,NO,FO)
3	(NO)	11	(UK,FO)	19	(EU,NO,FO)	27	(EU,UK,NO,IS)
4	(FO)	12	(UK,IS)	20	(EU,NO,IS)	28	(EU,UK,FO,IS)
5	(IS)	13	(NO,IS)	21	(EU,FO,IS)	29	(EU,NO,FO,IS)
6	(EU,UK)	14	(NO,FO)	22	(UK,NO,FO)	30	(UK,NO,FO,IS)
7	(EU,NO)	15	(FO,IS)	23	(UK,NO,IS)	31	(EU,UK,NO,FO,IS)
8	(EU,FO)	16	(EU,UK,NO)	24	(UK,FO,IS)		

Table 4. List of all possible coalition structures for the five player game

No.	Coalition structure	No.	Coalition structure	No.	Coalition structure	No.	Coalition structure
1	(EU),(UK),(NO),(FO),(IS)	14	(EU,FO),(UK,NO),(IS)	27	(EU,UK,NO),(FO),(IS)	40	(EU,NO,FO),(UK,IS)
2	(EU,UK),(NO),(FO),(IS)	15	(EU,UK),(NO,IS),(FO)	28	(EU,UK,FO),(NO),(IS)	41	(EU,NO,IS),(UK,FO)
3	(EU,NO),(UK),(FO),(IS)	16	(EU,NO),(UK,IS),(FO)	29	(EU,UK,IS),(NO),(FO)	42	(EU,FO,IS),(UK,NO)
4	(EU,FO),(UK),(NO),(IS)	17	(EU,IS),(UK,NO),(FO)	30	(EU,NO,FO),(UK),(IS)	43	(UK,NO,FO),(EU,IS)
5	(EU,IS),(UK),(NO),(FO)	18	(EU,UK),(FO,IS),(NO)	31	(EU,NO,IS),(UK),(FO)	44	(UK,NO,IS),(EU,FO)
6	(UK,NO),(EU),(FO),(IS)	19	(EU,FO),(UK,IS),(NO)	32	(EU,FO,IS),(UK),(NO)	45	(UK,FO,IS),(EU,NO)
7	(UK,FO),(EU),(NO),(IS)	20	(EU,IS),(UK,FO),(NO)	33	(UK,NO,FO),(EU),(IS)	46	(NO,FO,IS),(EU,UK)
8	(UK,IS),(EU),(NO),(FO)	21	(EU,NO),(FO,IS),(UK)	34	(UK,NO,IS),(EU),(FO)	47	(EU,UK,NO,FO),(IS)
9	(NO,IS),(EU),(UK),(FO)	22	(EU,FO),(NO,IS),(UK)	35	(UK,FO,IS),(EU),(NO)	48	(EU,UK,NO,IS),(FO)
10	(NO,FO),(EU),(UK),(IS)	23	(EU,IS),(NO,FO),(UK)	36	(NO,FO,IS),(EU),(UK)	49	(EU,UK,FO,IS),(NO)
11	(FO,IS),(EU),(UK),(NO)	24	(UK,NO),(FO,IS),(EU)	37	(EU,UK,NO),(FO,IS)	50	(EU,NO,FO,IS),(UK)
12	(EU,UK),(NO,FO),(IS)	25	(UK,FO),(NO,IS),(EU)	38	(EU,UK,FO),(NO,IS)	51	(UK,NO,FO,IS),(EU)
13	(EU,NO),(UK,FO),(IS)	26	(UK,IS),(NO,FO),(EU)	39	(EU,UK,IS),(NO,FO)	52	(EU,UK,NO,FO,IS)

Table 5. List of symbols and abbreviations.

Symbol	Description	Value	Unit
Sets			
N	Players		
K	Coalition structures		
Subscripts			
n	Number of players	$4, 5$	
m	Number of coalitions in a CS	$1, 2, \ldots, n$	
κ	Number of CSs	$15, 52$	
t	Time index	$0, 1, 2, \ldots$	
l	Player index	$1, 2, \ldots, n$	
i, j	Coalition index	$1, 2, \ldots, m$	
k	CS index	$1, 2, \ldots, \kappa$	
Variables			
S_i	Escapement of coalition i in a CS		Thousand tonnes
S	Total escapement		Thousand tonnes
R	Total recruitment		Thousand tonnes
H	Total harvest		Thousand tonnes
V_i	NPV of coalition i in a CS (embedded coalition)[a]		Million NOK
V_{CS}	Total NPV of a CS[b]		Million NOK
Parameters			
p	Price	10	NOK/kg
r	Discount rate	5%	
θ_l	Share of mackerel stock in player's l EEZ	cf. Table 7	
a	Stock – Recruitment parameter	cf. Table 6	
b	Stock – Recruitment parameter	cf. Table 6	
c_i	Cost parameter of coalition i	cf. Tables 9-10	
β	Stock elasticity parameter	1.0, 0.6, 0.3	
$\bar{R}$	Base year recruitment	4887	Thousand tonnes
$\bar{H}_l$	Base year harvest of player l	cf. Table 8	
ψ	Cost – Revenue ratio	0.78	
Abbreviations			
CS	Coalition structure		
EU	European Union		
UK	United Kingdom		
NO	Norway		
FO	Faroe Islands		
IS	Iceland		
NPV	Net present value		

[a] V_i is equivalent to $V(C_i, CS_k)$ and should not be confused with $V_x(C_i, CS_k)$. We make use of compact notation in order to convenience ourselves in the presentation of the results.
[b] $V_{CS} = \sum_{i \in CS_k} V(C_i, CS_k)$.

Table 6. Results from fitting recruitment and escapement data on the Ricker and Beverton-Holt functions.

Functional form	Parameters a	Parameters b	Adjusted R^2
Ricker	1.6784 (0.000)	9.73×10^{-5} (0.000)	0.35
Beverton-Holt	10,977 (0.000)	5,965 (0.000)	0.88

Note: p-values of the transformed regression in parentheses.

Table 7. Shares of mackerel stock in player's l EEZ

	EU[a]	UK	NO	FO	IS
Mackerel share in %, θ_l	25.0	25.0	25.0	12.5	12.5

Note: See Table 5 for abbreviations.
[a] Mackerel share for EU refers to the five player game, which does not include UK. Mackerel share for EU in the four player game is equivalent to the sum of EU and UK mackerel shares, i.e., 50%.

Table 8. Base year (2015) harvest for European Union, United Kingdom, Norway, Faroe Islands and Iceland. Units: Thousand tonnes.

	EU[a]	UK	NO	FO	IS
Base year harvest, $\bar{H}_l$	269.929	247.986	242.231	108.412	169.333

Note: See Table 5 for abbreviations.
[a] Base year harvest for EU refers to the five player game, which does not include UK. Base year harvest for EU in the four player game is equivalent to the sum of EU and UK base year harvests, i.e., 517.915 thousand tonnes.

Table 9. Cost parameters for coalitions i in the four player game for different stock elasticity levels.

	Cost parameter, c_i			
Coalition, C_i	$\beta = 1$	$\beta = 0.6$	$\beta = 0.3$	$\beta = 0.1$
(EU)	17,032.48	788.13	78.59	16.90
(NO)	8,587.07	522.52	63.99	15.78
(FO)	4,346.93	347.26	52.16	14.74
(IS)	4,086.31	334.84	51.24	14.65
(EU,NO)	25,619.69	1,006.85	88.83	17.60
(EU,FO)	21,379.94	903.27	84.14	17.28
(EU,IS)	21,120.84	896.80	83.84	17.26
(NO,FO)	12,934.16	668.07	72.35	16.44
(NO,IS)	12,675.85	660.17	71.93	16.40
(FO,IS)	8,436.17	517.08	63.66	15.75
(EU,NO,FO)	29,967.05	1,106.10	93.10	17.88
(EU,NO,IS)	29,708.49	1,100.46	92.87	17.86
(EU,FO,IS)	25,468.83	1,003.35	88.68	17.59
(NO,FO,IS)	17,023.72	787.89	78.58	16.90
(EU,NO,FO,IS)	34,056.20	1,194.40	96.75	18.11

Note: See Table 5 for abbreviations.

Table 10. Cost parameters for coalitions i in the five player game for different stock elasticity levels.

	Cost parameter, c_i			
Coalition, C_i	$\beta = 1$	$\beta = 0.6$	$\beta = 0.3$	$\beta = 0.1$
(EU)	8,469.55	518.29	63.73	15.76
(UK)	8,562.75	521.65	63.94	15.77
(NO)	8,587.07	522.52	63.99	15.78
(FO)	4,346.93	347.26	52.16	14.74
(IS)	4,086.31	334.84	51.24	14.65
(EU,UK)	17,032.48	788.13	78.59	16.90
(EU,NO)	17,056.91	788.80	78.62	16.90
(EU,FO)	12,817.18	664.50	72.16	16.42
(EU,IS)	12,557.15	656.52	71.73	16.39
(UK,NO)	17,149.83	791.33	78.75	16.91
(UK,FO)	12,909.92	667.33	72.32	16.43
(UK,IS)	12,651.26	659.41	71.89	16.40
(NO,IS)	12,934.16	668.07	72.35	16.44
(NO,FO)	12,675.85	660.17	71.93	16.40
(FO,IS)	8,436.17	517.08	63.66	15.75
(EU,UK,NO)	25,619.69	1,006.85	88.83	17.60
(EU,UK,FO)	21,379.94	903.27	84.14	17.28
(EU,UK,IS)	21,120.84	896.80	83.84	17.26
(EU,NO,FO)	21,404.30	903.88	84.16	17.29
(EU,NO,IS)	21,145.41	897.41	83.87	17.27
(EU,FO,IS)	16,905.74	784.67	78.42	16.88
(UK,NO,FO)	21,497.00	906.19	84.27	17.29
(UK,NO,IS)	21,238.92	899.75	83.97	17.27
(UK,FO,IS)	16,999.26	787.22	78.55	16.89
(NO,FO,IS)	17,023.72	787.89	78.58	16.90
(EU,UK,NO,FO)	29,967.05	1,106.10	93.10	17.88
(EU,UK,NO,IS)	29,708.49	1,100.46	92.87	17.86
(EU,UK,FO,IS)	25,468.83	1,003.35	88.68	17.59
(EU,NO,FO,IS)	25,493.32	1,003.92	88.70	17.59
(UK,NO,FO,IS)	25,586.54	1,006.08	88.79	17.60
(EU,UK,NO,FO,IS)	34,056.20	1,194.40	96.75	18.11

Note: See Table 5 for abbreviations.

Table 11. Nash equilibria coalition structures for the four player game for the Ricker and Beverton-Holt stock-recruitment relationships, and different realisations of stock elasticity.

Ricker				Beverton-Holt			
$\beta = 1$	$\beta = 0.6$	$\beta = 0.3$	$\beta = 0.1$	$\beta = 1$	$\beta = 0.6$	$\beta = 0.3$	$\beta = 0.1$
11	11	11	11	11	11	11	11
12	12	12	12	12	12	12	12
13	13	13	13	13	13	13	13
14	14	14	14		14	14	14

Note: See Table 2 for which coalition structures the indices refer to.

Table 12. Nash equilibria coalition structures for the five player game for the Ricker and Beverton-Holt stock-recruitment relationships, and different realisations of stock elasticity.

Ricker				Beverton Holt			
$\beta = 1$	$\beta = 0.6$	$\beta = 0.3$	$\beta = 0.1$	$\beta = 1$	$\beta = 0.6$	$\beta = 0.3$	$\beta = 0.1$
27	37	37	37	27	37	37	37
38	38	38	38	38	38	38	38
39	39	39	39	39	39	39	39
40	40	40	40	40	40	40	40
41	41	41	41	41	41	41	41
42	42	42	42	43	42	42	42
43	43	43	43	44	43	43	43
44	44	44	44		44	44	44
45	45	45	45		45	45	45
46	46	46	46		46	46	46
			47				49
			48				50
			49				51
			50				
			51				

Note: See Table 4 for which coalition structures the indices refer to.

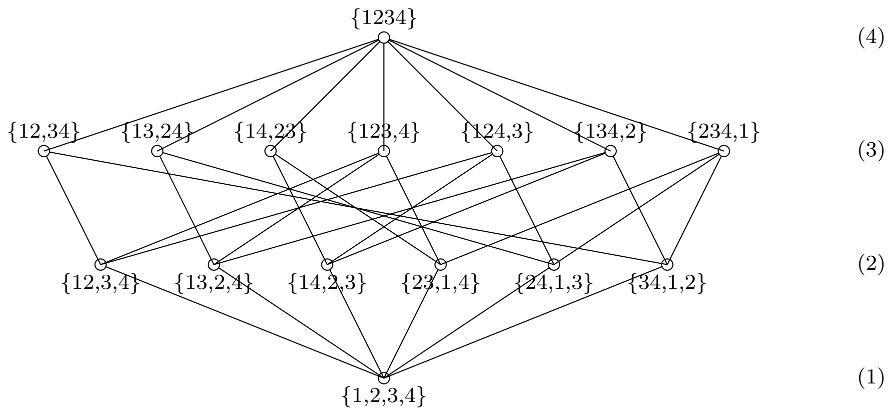

Fig. 1. Coalition structure graph for a four player game.

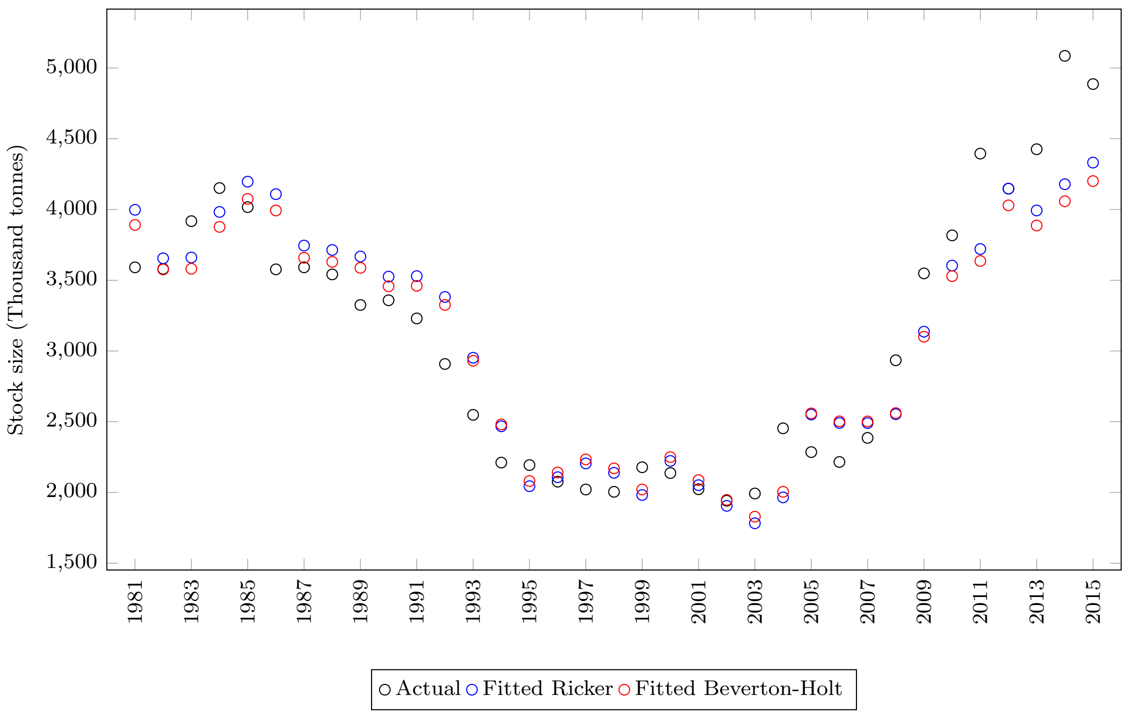

Fig. 2. Actual and fitted development of the mackerel stock 1981–2015.

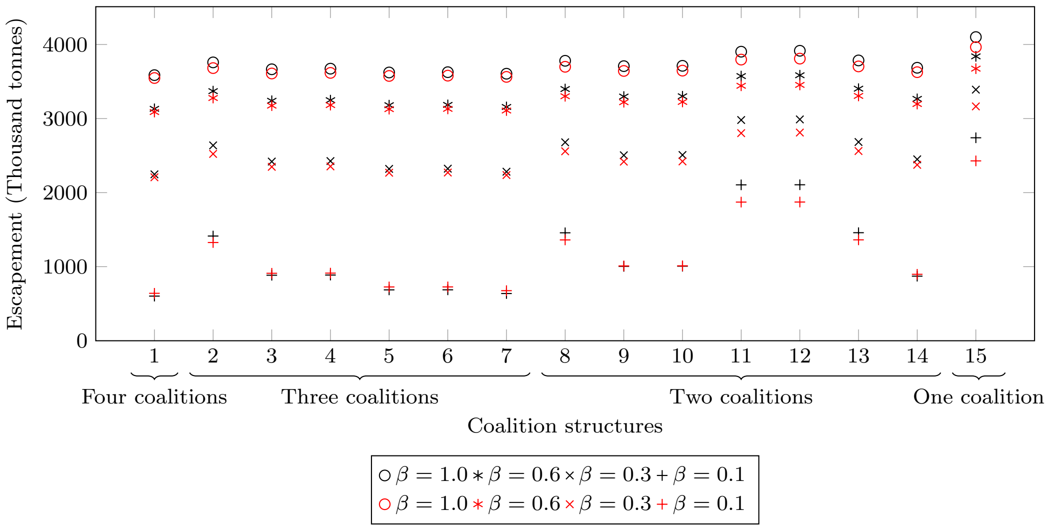

Fig. 3. Aggregate escapement of a coalition structure for the four player game; Ricker (black) and Beverton-Holt (red) functions; and different realisations of stock elasticity, β.

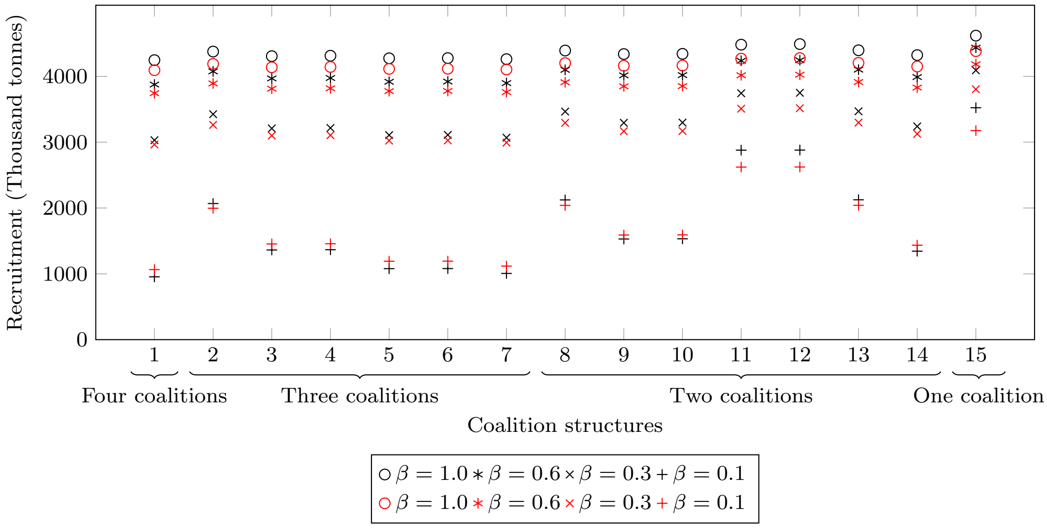

Fig. 4. Aggregate recruitment of a coalition structure for the four player game; Ricker (black) and Beverton-Holt (red) functions; and different realisations of stock elasticity, β.

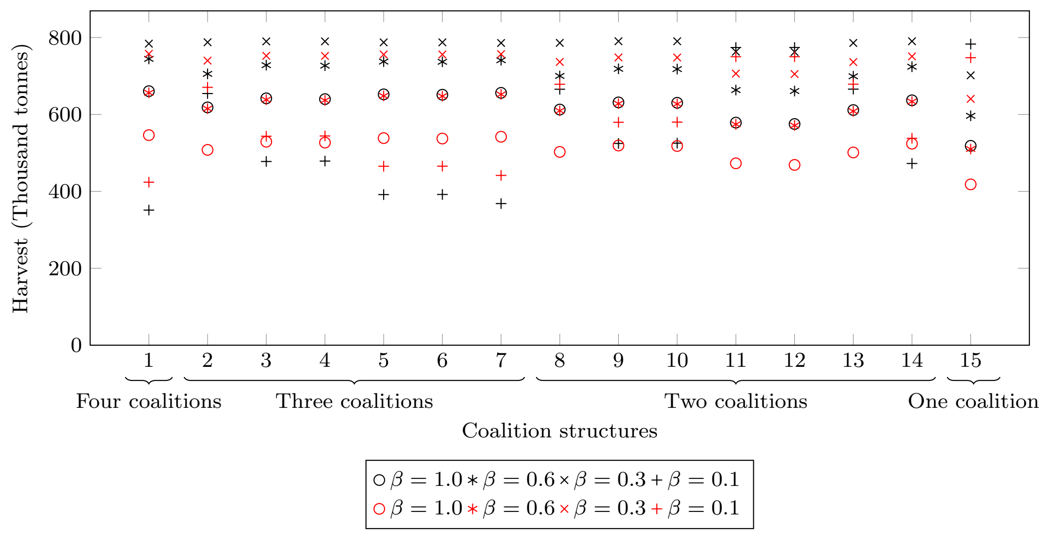

Fig. 5. Aggregate harvest of a coalition structure for the four player game; Ricker (black) and Beverton-Holt (red) functions; and different realisations of stock elasticity, β.

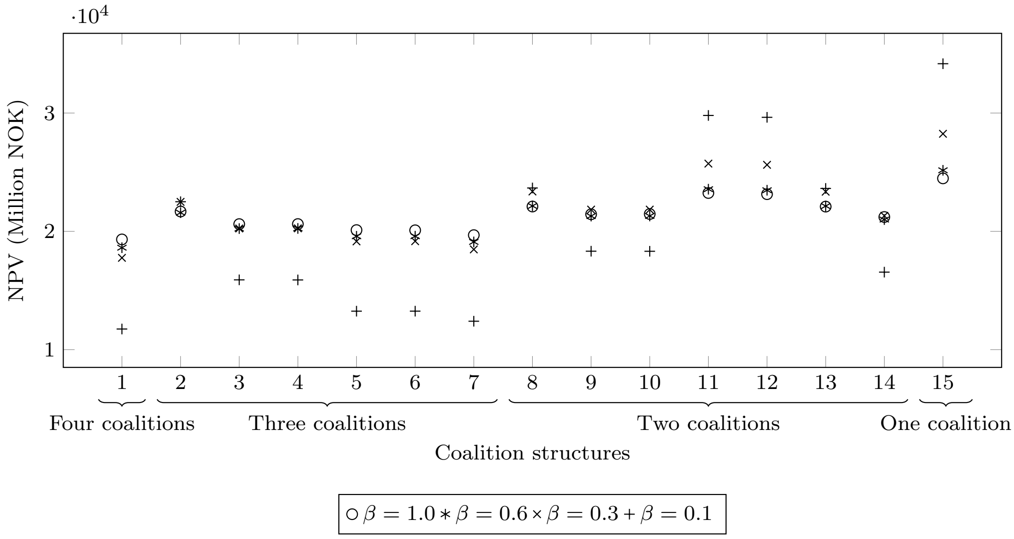

Fig. 6. Aggregate NPV of a coalition structure for the four player game; Ricker function; and different realisations of stock elasticity, β.

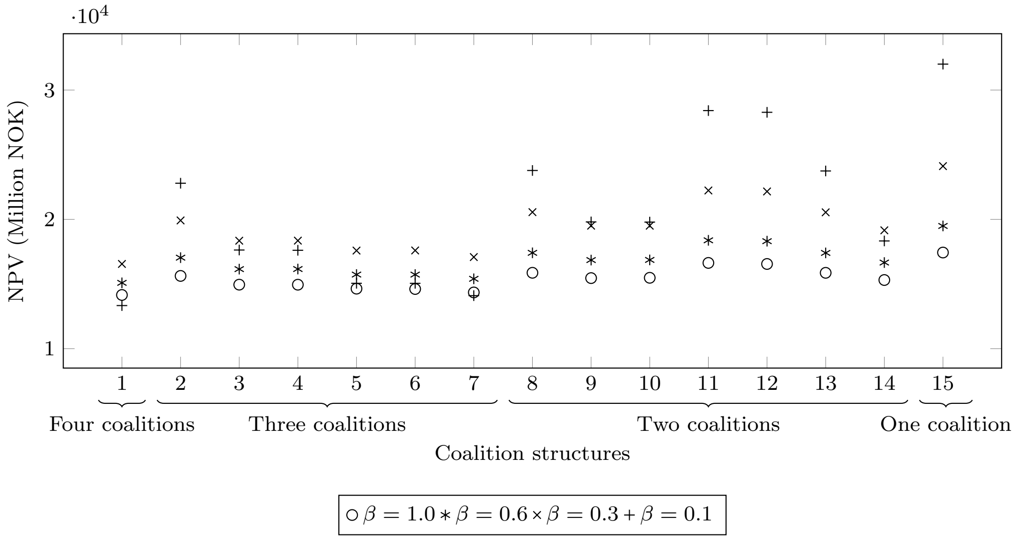

Fig. 7. Aggregate NPV of a coalition structure for the four player game; Beverton-Holt function; and different realisations of stock elasticity, β.

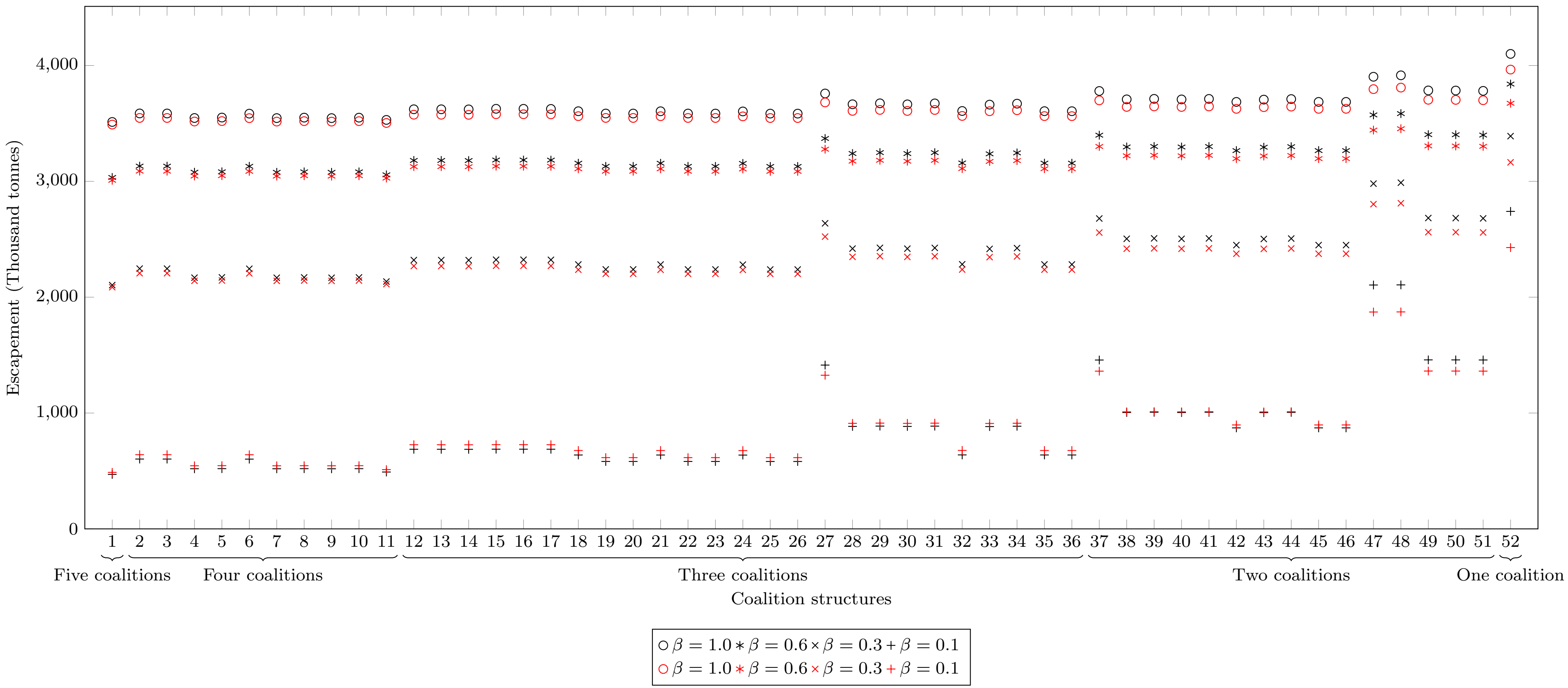

Fig. 8. Aggregate escapement of a coalition structure for the five player game; Ricker (black) and Beverton-Holt (red) functions, and different realisations of stock elasticity, β.

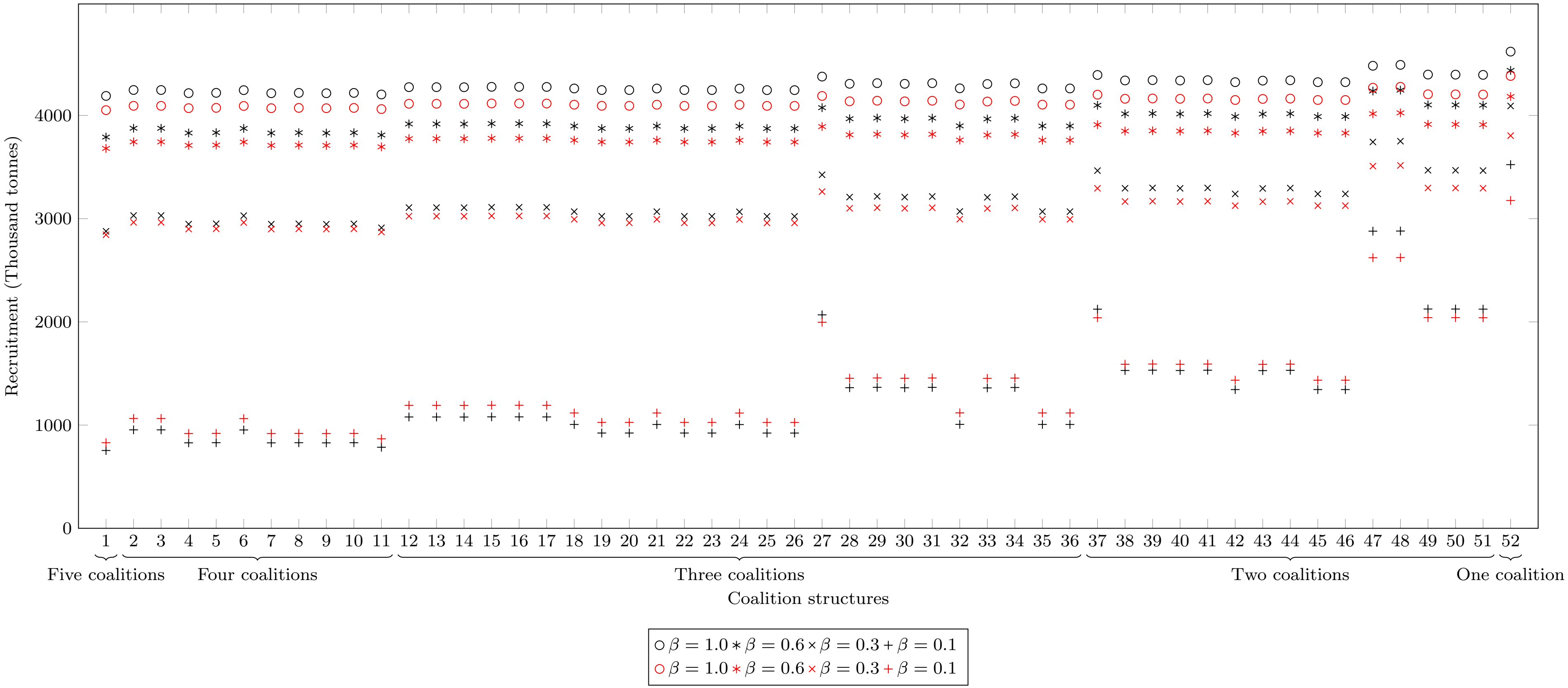

Fig. 9. Aggregate recruitment of a coalition structure for the five player game; Ricker (black) and Beverton-Holt (red) functions, and different realisations of stock elasticity, β.

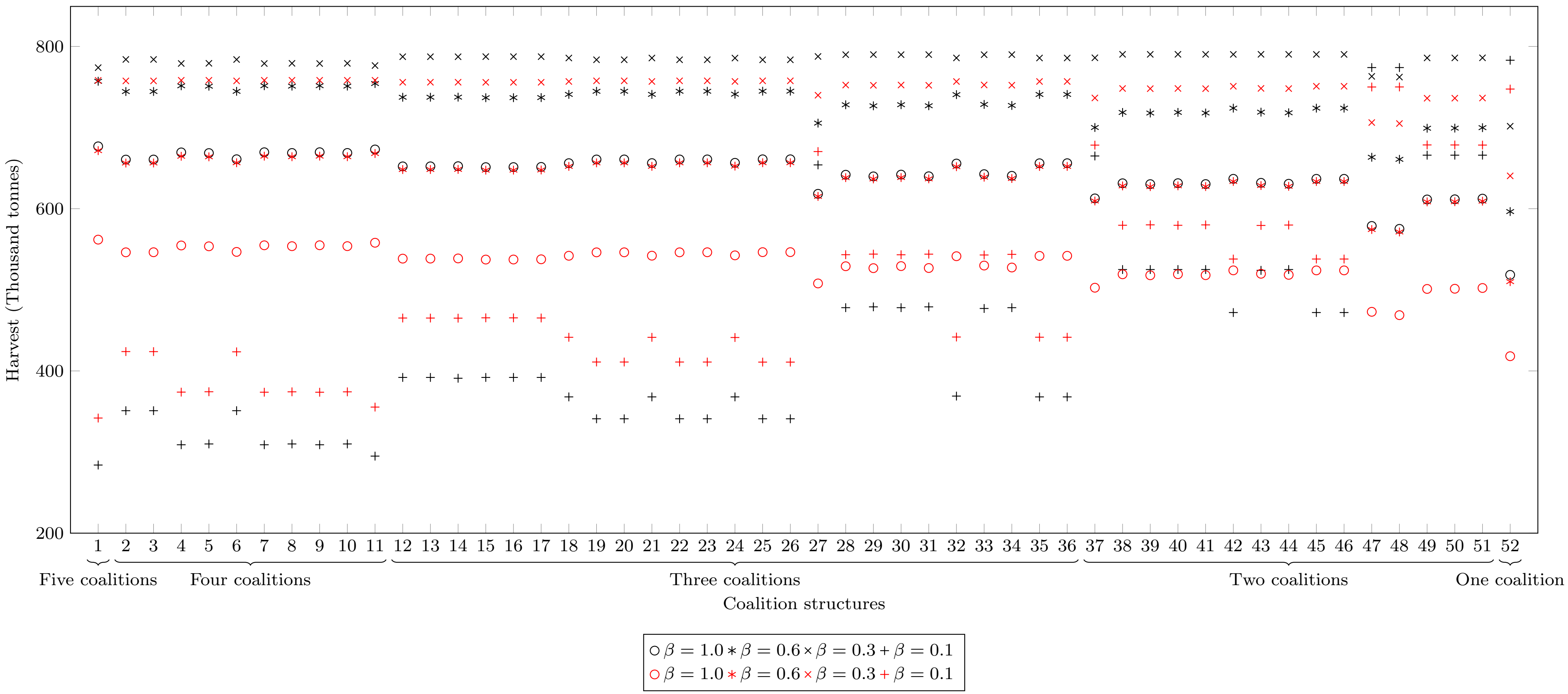

Fig. 10. Aggregate harvest of a coalition structure for the five player game; Ricker (black) and Beverton-Holt (red) functions, and different realisations of stock elasticity, β.

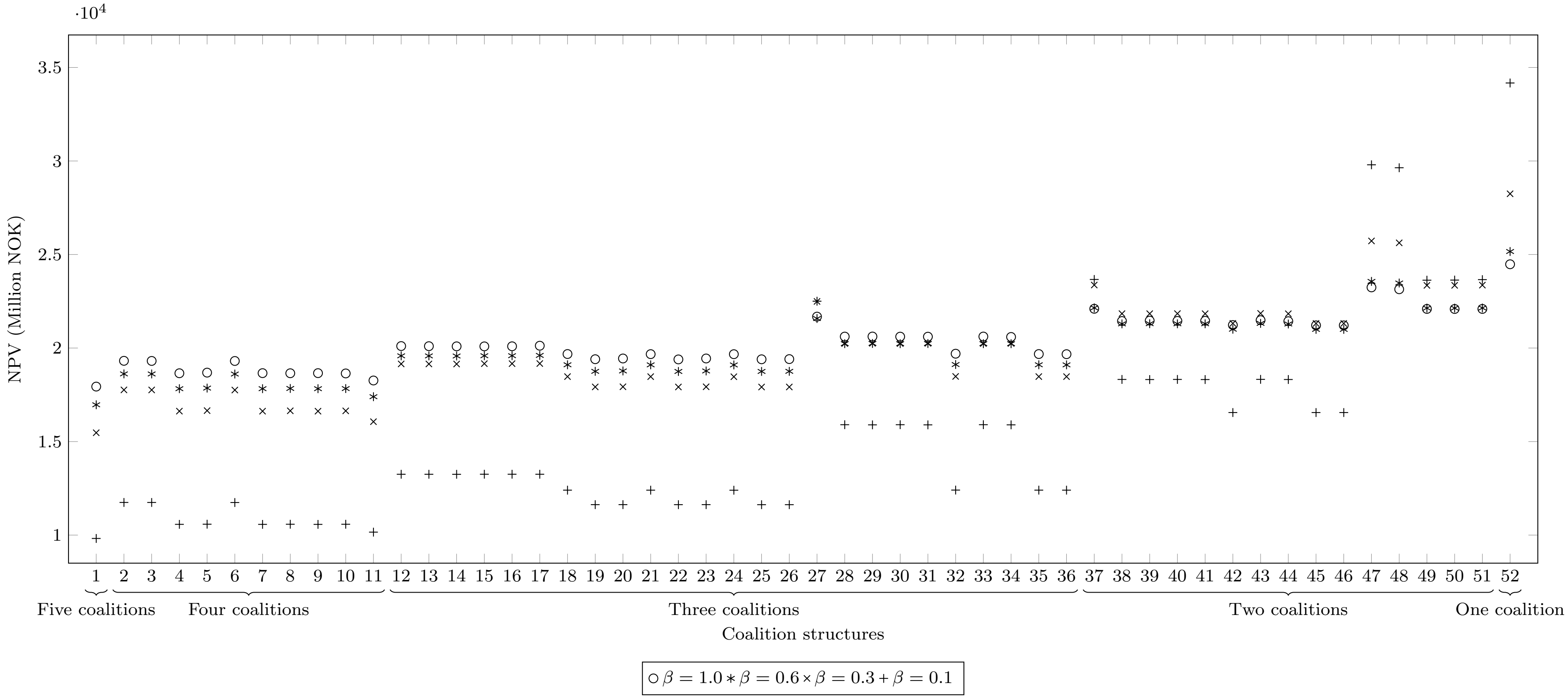

Fig. 11. Aggregate NPV of a coalition structure for the five player game; Ricker function; and different realisations of stock elasticity, β.

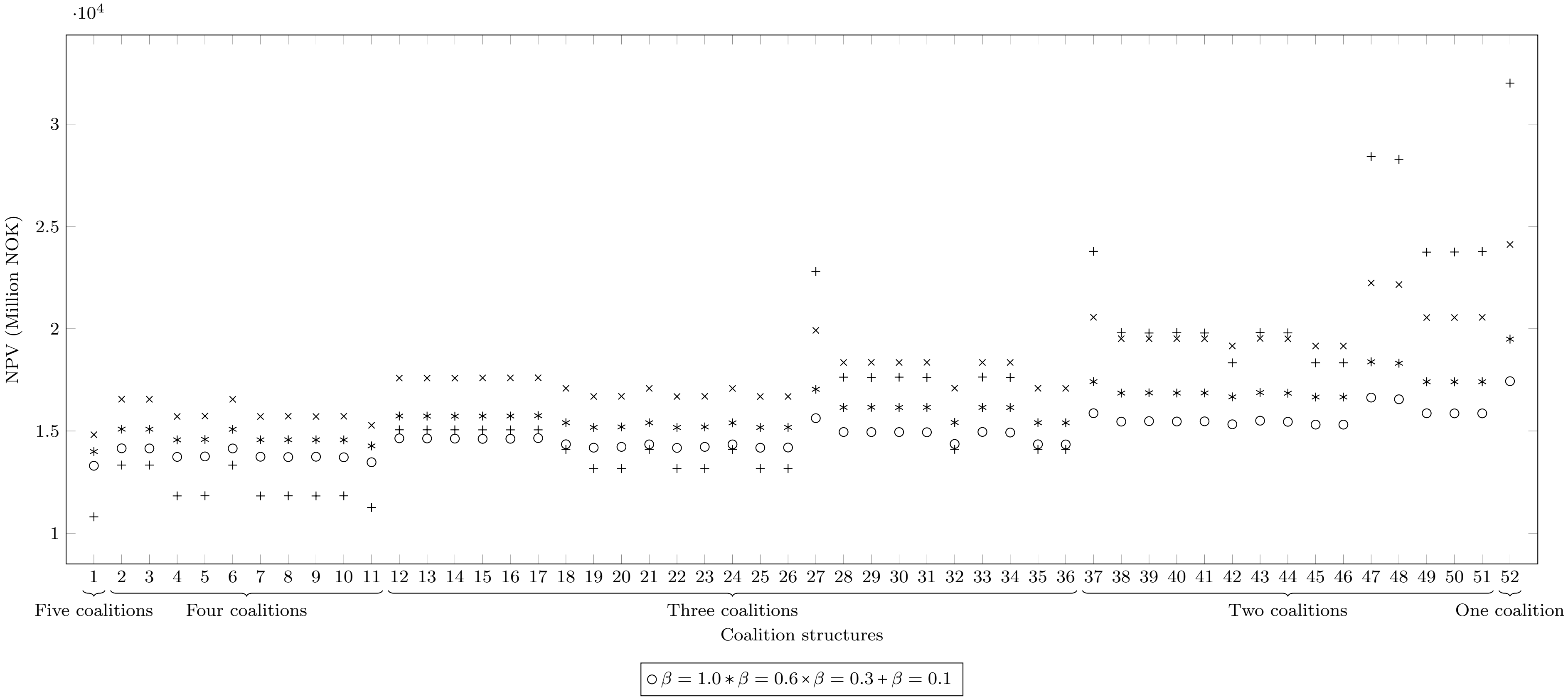

Fig. 12. Aggregate NPV of a coalition structure for the five player game; Beverton-Holt function; and different realisations of stock elasticity, β.