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Game theory and fish wars: The case of the Northeast Atlantic mackerel fishery☆

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ABSTRACT

Simple non-cooperative and cooperative game theory is used to explore the crisis involving the European Union (EU), Norway, Iceland and the Faroe Islands regarding the size and relative allocation of total allowable catches (TACs) in the mackerel fishery in the Northeast Atlantic. The analysis of the mackerel crisis is based on a statistical estimation of relevant functional relations, and the behavior of the players is explained using a fully specified empirical model. Simple, non-cooperative game theory shows that all players have an incentive to act non-cooperatively, a result that is robust to changes in basic assumptions regarding demand and cost functions. Thus, using the estimated parameters and functions, simple, non-cooperative game theory cannot explain the cooperative behavior of EU and Norway during the mackerel crisis. Simple cooperative game theory shows that no player has an incentive to enter a bargaining agreement by forming coalitions, a prediction that is consistent with the actual behavior of the EU, Norway, Iceland and the Faroe Islands between 2010 and 2014 when no bargaining solution was reached. Therefore, the fact that the EU and Norway entered a bilateral agreement in 2010 and that the EU, Norway and the Faroe Islands reached a bargaining solution in 2014 cannot be explained by simple cooperative game theory. However, actual behavior during the mackerel crisis can be explained by opportunity costs, including alternative fishing possibilities and regulations, rather than actual harvest costs, but we do not have information about the opportunity costs of harvesting mackerel.

1. Introduction

1.1. The policy problem

Until 2009, an agreement existed among the European Union (EU), Norway and the Faroe Islands regarding total allowable catches (TACs) for mackerel in the Northeast Atlantic Sea. According to this agreement, which was reached in 1999, each player received a fixed relative share of the yearly TAC (Iversen, 2002). However, in 2009, Iceland was officially recognized as a player in the fishery by the EU, Norway and the Faroe Islands, partly because of the dramatic increase in the Icelandic harvest of mackerel (The Icelandic Ministry of Fisheries, 2009; Table 1).

Table 1 shows that the harvest of mackerel by Icelandic vessels in the Northeast Atlantic increased dramatically during 2008–2012, and according to ICES (2010), this increase was mainly due to changed migration patterns of the mackerel. However, in 2013 and 2014,[1] the harvest of mackerel by Icelandic vessels began to decrease. Table 1 also shows that the harvest of blue whiting by Icelandic vessels decreased dramatically during 2006 and 2011 but increased again in 2013 and 2014. The decline in the harvest of blue whiting arose due to a considerable decline in recruitment for which two explanations can be cited. First, the amount of food for juvenile blue whiting was reduced (Hatun et al., 2009a). Second, the number of mackerel preying on juvenile blue whiting increased (Payne et al., 2012). In the Northeast Atlantic, blue whiting and mackerel are harvested by the same types of vessels thus giving Icelandic vessels the flexibility to shift between these fisheries. Indeed, Hatun et al. (2009a,b) and Andrews and Nichols (2013), claim that vessels previously fishing blue whiting shifted to fishing mackerel.

Due to this increase in the mackerel harvest, Iceland entered into negotiations with the EU, Norway and the Faroe Islands over the size and relative allocations of the TAC for the Northeast Atlantic

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[1] The harvest for 2014 is an estimated value.

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Table 1
Harvest of blue whiting and mackerel by Icelandic vessels in the Northeast Atlantic Sea, 1000 t.

	Blue whiting	Mackerel
2006	40,200	4
2007	39,200	38
2008	5560	112
2009	3624	116
2010	4873	121
2011	3871	159
2012	6579	149
2013	10,491	124
2014	12,130*	113[a]

Source: ICES (2013) and Anon (2013).

[a] Indicates estimated harvest levels.

mackerel, but no agreement among the players was reached. In 2010, the EU and Norway entered into a bilateral agreement over their relative allocations of the TAC for a 10-year period (The Norwegian Ministry of Fisheries, 2010a). Despite this bilateral agreement, Iceland increased its harvest of mackerel by 23% in 2010 while the Faroe Islands increased its harvest by 15% (ICES, 2010). In total, the harvest in 2010 was approximately 930,000 t, which was 40% above biological recommendations (ICES, 2010). In 2010, the EU and Norway responded by banning landings of vessels from Iceland and the Faroe Islands (The Norwegian Ministry of Fisheries, 2010b). After 2011, several rounds of bargaining were attempted, all of which failed. However, in 2014, the EU, Norway and the Faroe Islands entered into an agreement regarding the size and relative allocations of the TAC covering the period from 2014 to 2018 (The Norwegian Government, 2014). According to this agreement, the relative shares of the TAC for the EU and Norway are reduced, while the share for the Faroe Islands is increased. Iceland, however, was not part of this agreement and continues to be sanctioned by the EU and Norway.

Behind the mackerel crisis lays a messy political process. The EU and Norway reacted strongly to the decisions of Iceland and the Faroe Islands to increase their mackerel harvests. The EU and Norway claimed that the mackerel stock had been within safe biological limits, as defined by ICES (2008), before the increase in the harvest but that the stock would eventually fall outside of safe biological limits as a result of the increased harvest (Andrews and Nichols, 2013). Therefore, the EU and Norway decided to ban landings by vessels from Iceland and the Faroe Islands in their harbors. This conflict intensified when a Faroese vessel (the Jupiter) was unable to land fish in a harbor in Aberdeen because Scottish fishermen had blocked entry to the harbor (Orebech, 2013). In the press, the skipper of the Jupiter claimed that the blockade cost him €400,000. However, a Scottish skipper, Ian Gatt, justified the blockade, saying, “It costs thousands of jobs in Scotland and drives the mackerel price down”. In addition, Ian Gatt claimed that environmentally friendly consumers would substitute away from mackerel if the fish stock in the Northeast Atlantic fell below safe biological limits. Following the Jupiter event, the EU, Norway, Iceland and the Faroe Islands entered into negotiations in Oslo to find a solution to the mackerel crisis. However, these negotiations ended without an agreement. The EU then condemned the behavior of Iceland and the Faroe Islands, stating that an Icelandic application for full EU membership would be negatively affected by the crisis (Andrews and Nichols, 2013). In 2012, the mackerel stock was declared to be below safe biological limits by ICES (2012). Following this declaration, the EU and Norway imposed additional trade restrictions on Iceland and the Faroe Islands in 2013. The justification was again the increased mackerel harvest. As a Scottish politician stated in the press, “The mackerel crisis is about jobs, economics, sustainability, and fairness, and the acts by Iceland and Faroe Islands cannot be justified and are not sustainable”. In 2013, Iceland declared that it was willing to reduce its harvest of mackerel by 15%, provided the EU and Norway reduced their harvests by the same amount. However, the EU and Norway rejected the Icelandic proposal, stating that the Icelandic share of the total harvest was too large (Andrews and Nichols, 2013). At the same time, the Faroe Islands threatened to take the EU and Norway to court through the United Nations over trade restrictions. In 2013, the EU declared that Iceland could not become a full member of the EU, in part because of the mackerel crisis (Orebech, 2013). Simultaneously, the EU, Norway, and the Faroe Islands entered into negotiations on a revised management plan for the Northeast Atlantic mackerel stock. However, before these negotiations began, ICES refused to deliver recommendations for a target stock size. Despite this, the three players concluded an agreement (ICES, 2014) that includes a target stock size for 2015 and relative allocations of the TAC over a 5-year period.

1.2. *The main research questions*

The mackerel crisis is an example of a situation in which strategic interactions occur among economic agents (countries). Economists study such interactions using game theory within which there are two main schools of thought. The first is non-cooperative game theory in which no communication, cooperation, or bargaining occurs among players (Friedman, 1979). The second school of thought is cooperative game theory, which involves cooperation (for example, bargaining agreements) among players (Hougaard, 2009). The purpose of this paper is to investigate whether the behavior of the EU, Norway, Iceland, and the Faroe Islands during the mackerel crisis can be explained using simple game theory. Specifically, the paper aims to answer the following three research questions:

1. Why did Iceland and the Faroe Islands decide to increase their harvests in 2010 while the EU and Norway entered into a bilateral agreement?
2. Why was no bargaining solution among the EU, Norway, Iceland, and the Faroe Islands concluded during the period from 2010 to 2014?
3. Why did the EU, Norway, and the Faroe Islands reach a bargaining agreement in 2014?

Non-cooperative game theory is applied to answer the first research question, while cooperative game theory is utilized to answer the second and third research questions. Answering these three research questions requires an empirical model of the mackerel fishery in the Northeast Atlantic, and such a model is presented in this paper.

1.3. *Description of the game*

When investigating the mackerel crisis, a negatively sloped demand function, and inclusion of a resource restriction are assumed. Therefore, strategic interactions occur due to both price effects and fish stock effects. In principle, the model presented in this paper should be solved as a system of several equations and unknowns (Arnason et al., 2000a). However, it is difficult to interpret the results derived from such a procedure, and a simpler solution method is employed. It is assumed that each player harvests a constant share of the fish stock in each period and that payoffs are determined by using the steady-state harvest levels reached by this procedure in the payoff function. With a negatively sloped demand function and a resource restriction, each player acts like a social planner under non-constant prices but without maximizing an objective function. Additionally, the implications of including only one type of strategic interaction have been investigated.[2] With strategic interactions due strictly to price effects, a resource restriction are disregarded, a situation similar to a model in which each player disregards stock effects (that is, a private optimum). When strategic interaction arises from stock size effects, the price is assumed constant, but the resource restriction is incorporated. Thus, each player acts like a social planner under constant prices. In Sections 5.2 and 5.3, the outcomes of these two alternative games are briefly described, and it is argued that the results in the paper do not depend on the nature of the strategic interaction.

1.4. *Existing literature on the Northeast Atlantic mackerel crisis*

The mackerel fish stock in the Northeast Atlantic may have shifted migration patterns northward, which implies a higher concentration of mackerel in the waters around Iceland and the Faroe Islands (ICES, 2010). According to Cheung et al. (2012) and Miller et al. (2013), this altered migration pattern is due to climate change and will reduce the costs of harvesting mackerel for Icelandic and Faroese vessels.[3] However, when analyzing the mackerel crisis in the Northeast Atlantic, the main impact of climate change must be identified. From Table 1, it is clear that the main impact of climate change occurred in 2008 and is represented by the entry of Iceland into the fishery. In this paper, we examine the outcome of the mackerel crisis that occurred from 2010 to 2014. Because we analyze the behavior of the players after the main impact of climate change, the implications of climate change for the mackerel fishery in the Northeast Atlantic are only briefly discussed.

Two other empirical papers examine the mackerel crisis among the EU, Norway, Iceland and, the Faroe Islands in the Northeast Atlantic.[4] Ellefsen (2013) used cooperative game theory, applying a coalition game approach, and considered two models. First, a three-player game involving the EU, Norway and the Faroe Islands was investigated. In this game, the EU receives its largest payoff from a grand coalition, while Norway and the Faroe Islands receive their largest payoffs by acting alone. Second, a four-player game involving the EU, Norway, Iceland, and the Faroe Islands was investigated, and in this case, it is beneficial for the EU and Norway to form coalitions, while Iceland and the Faroe Islands have incentives to act alone. By focusing on games both with and without Iceland (a four-player game in the first case and a three-player game in the second case), Ellefsen (2013) implicitly studied the entry of Iceland into the mackerel fishery. In this paper, we analyze the outcome of the mackerel crisis after Iceland's entry into the fishery; thus, we make an important extension to Ellefsen (2013).[5]

Hannesson (2013) applied non-cooperative game theory to the mackerel crisis by identifying a Nash equilibrium, with the main objective of investigating the implications of changed migration patterns for the Northeast Atlantic mackerel stock, and therefore, four different migration models were introduced. In general, the Nash equilibrium varies with assumptions about migration patterns. Irrespective of this, Hannesson (2013) focused on Iceland's entry by using different migration models. In this paper, the outcome following the entry of Iceland is analyzed. Thus, the present paper extends the work of Hannesson (2013).[6]

The paper is organized as follows. Section 2 presents the solution concepts and procedures to the games and in Section 3, relevant data sources are briefly described. Section 4 presents the relevant functions used in the paper and the empirical estimation while the solutions to both the non-cooperative and cooperative games are discussed in Section 5. The main conclusion is presented in Section 6.

2. Solution concepts and procedures

2.1. *Solution concepts*[7]

In this paper, the mackerel crisis is described as a one-shot game in quantities, which arises when players interact strategically only once and harvest is a strategic variable. A one-shot game is employed because the payoffs are defined as long-run resource rents in a steady-state equilibrium (Section 4.5). An alternative would be to model the mackerel crisis as a dynamic game, but this approach is mainly relevant when adjustments toward equilibrium are being investigated. Another issue in game theory is the information available to players when making decisions, and here, it is assumed that each player has perfect information about the other players' payoffs.

A distinction can be drawn between non-cooperative and cooperative game theory. In the non-cooperative games in this paper, a Nash equilibrium concept is used to explain player behavior during the mackerel crisis.[8] Such an equilibrium exists when no player has an incentive to deviate from their strategy given the behavior of other players. A Nash equilibrium is a particularly strong solution concept if it occurs in dominant strategies. A dominant strategy exists when the behavior of a player is optimal given all possible strategies of other players.

In cooperative game theory, a characteristic function, which is the value of the game for every possible coalition, must be defined. Another important concept in cooperative game theory is side payments, which is economic compensation to players for entering coalitions. In this paper, the core and Shapley value are used as solution concepts of a cooperative game modeling the mackerel crisis.[9] The core represents the largest possible payoff a player can obtain by forming coalitions, while the Shapley value is the average value of the marginal contribution to all coalitions involving a player. A natural condition to impose is that the Shapley value must be within the core if a coalition is to be stable, and such a condition is employed in this paper.

2.2. *The solution procedure*

A strategic variable is also necessary for the empirical analysis in this paper, and here, a measure of the actual steady-state harvest level for each player is used. A resource restriction is included in the model; this constraint is incorporated through a simple procedure.

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[2] The results of the two games with only one type of strategic interaction are available from the authors.

[3] An issue related to climate change is climate variability, which is defined as natural fluctuation in climatic conditions. Fluctuating sea temperature is an example of climate variability. Ishimura et al. (2013) provide a game theoretic analysis of international fishery agreements under climate variability.

[4] Kennedy (2003) studies this fishery before the mackerel crisis; therefore, this paper is not directly relevant to the present study.

[5] In addition, there are at least three important problems with Ellefsen's (2013)analysis. First, constant prices are assumed; therefore, strategic interaction arises only from stock effects. Second, Ellefsen (2013) uses effort as a strategic variable, but from the description in Section 1.1, it is clear that harvest is the main strategic variable and Hannesson (2011) argues that the choice of strategic variable matters for the outcome of a game theoretic analysis of fisheries. Finally, in Ellefsen (2013), nearly all of the functions and parameters are randomly selected. These three problems are resolved in the present paper.

[6] Another criticism of Hannesson (2013) is that constant prices are assumed, which means that strategic interaction only occurs from the resource restriction. In this paper, a negatively sloped demand function is assumed. Therefore, strategic interaction due to price effects is also included.

[7] This section is mainly based on Friedman (1979) and Hougaard (2009).

[8] Other solution concepts for non-cooperative games include Stackelberg equilibrium, iterative dominance strategies and focal point equilibrium.

[9] Other solution concepts for cooperative games include the Nash bargaining solution, the kernel and the nucleolus.

To describe this procedure, it is useful to include a time index, t, for both the harvest level for each player and the mackerel stock size. A normal specification of the resource restriction is then:

$$\Delta x_t = F(x_t) - h_{t\mathrm{EU}} - h_{t\mathrm{NO}} - h_{t\mathrm{IS}} \quad (1)$$

where x_t is the mackerel stock size at time t, $F(x_t)$ is the natural growth function for mackerel at time t, Δx_t is the change in stock size between discrete periods, $h_{t\mathrm{EU}}$ is the EU mackerel harvest at time t, $h_{t\mathrm{NO}}$ is the Norwegian mackerel harvest at time t and $h_{t\mathrm{IC}}$ is the Icelandic/Faroese mackerel harvest at time t.

When determining the harvest level (the strategic variable) for each player ($h_{t\mathrm{EU}}$, $h_{t\mathrm{No}}$, and $h_{t\mathrm{IC}}$), it is assumed that the harvest for each player constitutes a fixed share of the stock size. Based on this assumption, our simple procedure works as follows. Assume that the stock size at an initial time period x_0 is known. From x_0, natural growth in the initial time period $F(x_0)$ can be calculated. Given the constant stock share assumption, harvest levels in the initial period, $h_{0\mathrm{EU}}$, $h_{0\mathrm{NO}}$, and $h_{0\mathrm{IC}}$, can also be determined. From Eq. (1), Δx_0 is calculated, and the stock size for period 1 can then be obtained using $x_1 = x_0 + \Delta x_0$. Given x_1, it is possible to identify $F(x_1)$ and $h_{1\mathrm{EU}}$, $h_{1\mathrm{NO}}$, and $h_{1\mathrm{IC}}$ using the constant stock share rule. Then, $\Delta x_1, x_{2t}, F(x_2), h_{2\mathrm{EU}}, h_{2\mathrm{NO}}$, and $h_{2\mathrm{IC}}$ may be found, and this procedure can be repeated for any number of periods. However, a terminal period must be identified; here it is required that the fish stock must be in steady-state equilibrium. This implies that as $\Delta x_t \to 0$, the desired harvest levels for each player are reached. Therefore, the value of the strategic variable for each player is defined as the steady-state harvest level calculated using the constant share of stock rule. By requiring a steady-state equilibrium stock size, the model is constructed to consider the long run.[10]

Three facts about the procedure in Eq. (1) can be summarized. First, different harvest shares for the players imply different steady-state equilibrium stock sizes. Therefore, each player's harvest level differs with each possible harvest share combination. Second, the model does not involve maximization of an objective function; instead, a constant share of stock rule is assumed. Therefore, the harvest levels are solely determined by the resource restriction. Third, when using the procedure described in Eq. (1), only the harvest levels of the EU, Norway, Iceland and the Faroe Islands are included. Note that other players, including Russia, also harvest mackerel in the Northeast Atlantic, and the harvests of these players should be included in Eq. (1). However, the games involve only the EU, Norway, Iceland and the Faroe Islands, so it is natural to include only those players in Eq. (1). However, it is useful to investigate the implications of excluding players, such as Russia. By excluding players other than the EU, Norway, and Iceland/Faroe Islands, the initial period harvest level is too low, which implies that Δx_0 is too large and, therefore, that x_1, $h_{1\mathrm{EU}}$, $h_{1\mathrm{NO}}$, and $h_{1\mathrm{IC}}$ are too large. Following this line of reasoning, the steady-state equilibrium stock size and harvest levels of the three players are overestimated when players are excluded.

3. Data

The data used in the paper were collected from three main sources:

1. Account statistics and landing statistics for the EU, Norway, and Iceland on individual fleet segment levels by year (Anon, 2011a,b,c, 2014a).
2. Statistics on total stock size and aggregate harvests for all players harvesting mackerel in the Northeast Atlantic Sea (ICES, 2013).
3. Statistics for mackerel prices in the Danish market (Anon, 2014b).

For the EU, Norway, and Iceland, account statistics are collected for a sample. These data are then adjusted and aggregated to cover complete fleet segments. However, for the Faroe Islands, no account statistics are available.

For the EU, Norway, and Iceland, account statistics contain the following data:

1. The total cost of harvesting all species for consumption by individual fleet segment level and year.
2. Revenues from harvesting all species for consumption and from harvesting mackerel alone at the individual fleet segment level and by year.
3. Total landings of all species for consumption and of mackerel at the individual fleet segment level and by year.

Note that the account statistics contain information about actual harvesting costs rather than opportunity costs (Section 5.2).

Only one fleet segment for each player is selected to avoid problems with aggregation of fleet segments. The following fleet segments are included in the analysis:

1. British purse seiners larger than 40 m.
2. Norwegian purse seiners larger than 40 m.
3. All Icelandic pelagic trawlers.

The selected fleet segments are all important players in the mackerel fishery in the Northeast Atlantic. British purse seiners harvest 58% of the total mackerel caught by the EU, Norwegian purse seiners harvest 73% of the total mackerel caught by Norway, and Icelandic pelagic trawlers harvest 98% of the total mackerel caught by Iceland. The selected fleet segments include large vessels (averaging more than 1000 GRT), which are flexible with respect to both fishing methods and target species. For Norwegian purse seiners, account statistics are available from 1985 to 2012, while statistics exist for pelagic freezer trawlers in Iceland from 1997 to 2012. However, for British purse seiners, statistics could only be obtained for the period from 2008 to 2012. Therefore, one year must be selected to determine a cost function (Section 4.2).

The year 2011 was chosen, because it comes after the start of the mackerel crisis. The data in the account statistics for the three players appear to be reliable, partly because the sample covers a large share of the entire fleet segment. For landing statistics, a time series is available for Norwegian purse seiners from 1985 to 2012 and for all Icelandic pelagic trawlers from 1992 to 2012. However, landing information for British purse seiners is only available from 2008 to 2012. The landing statistics are, in general, of high quality, and for the EU and Norway, the account statistics and landings statistics are reported for the same fleet segments. However, for Iceland, the account statistics and landing statistics are not reported for the same fleet segments, raising questions regarding the Icelandic data quality (Section 4.2). For the second data source, time series for stock size and aggregate harvest exist for the period from 1980 to 2012. The data on the aggregate harvest of mackerel in the Northeast Atlantic are reasonably reliable, but it is well known that stock size is difficult to measure and therefore highly uncertain. In the third data source, a time series for the market price of mackerel in

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[10] Note that in the model without resource restrictions, actual harvest in a given year is used as the value of the strategic variable.

Denmark between 1999 and 2011 is available, and this information is very reliable.

4. Functional forms and parameter estimates[11]

4.1. Demand function

For the empirical analysis, a demand function for mackerel in the EU, Norway, Iceland, and the Faroe Islands must be identified. Here, it is assumed that all players supply mackerel to the same market and that there are no other suppliers in the market. Furthermore, the harvest of other fish species (or quantities of other goods) does not influence the price of mackerel.[12] We estimate the following linear demand function:

$$P = a - bh_{\text{EU}} - bh_{\text{NO}} - bh_{\text{IC}}, \tag{2}$$

where a is the intercept of the demand function, b is the slope of the demand function, P is the market price of mackerel. Recall that in Eq. (2), h_{IC} includes the Faroe Islands' harvest because no cost data exist for the Faroe Islands, as noted in Section 3.

When estimating Eq. (2) the prices of mackerel in Denmark from 1999 to 2012 reported in Anon (2014a) and the aggregate harvest from 1999 to 2012 provided by ICES (2013) can be used. Using ordinary least squares (OLS), we obtain[13]:

$a = 1.28$ (12.48) (million Euro)

$b = 0.0003971$ (4.78) (million Euro/1000 t)

$R^2 = 0.847$

$\text{DW} = 1.28$

where the numbers in parenthesis are t-statistics. From the t-statistics and parameter estimates, it is evident that both the intercept (a) and the slope (b) are significant and have the expected signs. The R^2 is reasonably high, so the linear demand function explains the majority of the variation in the time series for the price and the harvest, while the Durbin–Watson test (DW) indicates that there is no autocorrelation. Alternative functional forms for the demand function have also been tested, but the linear function provides the best fit. Overall, the estimation of the demand function appears to be statistically sound.

Five points should be made in connection with the estimated demand function. First, a significant negatively sloped demand function exists, and therefore, it is important to include strategic interactions due to price effects in the model. However, this type of strategic interaction was not consider by Ellefsen (2013) or Hannesson (2013).

Second, the value of the slope parameter indicates that the demand function for mackerel is very flat, a result used to explain the results in Sections 5.2 and 5.3. However, a reasonably flat demand function for fish products is found in most of the empirical literature[14] and may be due to significant integration of markets for fish products.

Third, in estimating Eq. (2) it is assumed that the EU, Norway and Iceland deliver mackerel to the same market and that there are no other suppliers on this market. To support this assumption, Nielsen et al. (2009) showed that the law of one price holds for the mackerel market in Europe, but an issue still arises in measuring the price of mackerel. The mackerel price on the Danish market is used, but from Anon (2011a,b, 2014a), it can be observed that the Icelandic prices are considerable lower than the prices in the EU and Norway. Therefore, a sensitivity analysis has been conducted by applying a weighted average of the prices for each of the three players using expenditure shares. By estimating Eq. (2) using this alternative price, the demand function becomes flatter, but the slope is still significant. The implications of this alternative demand estimation are discussed in Sections 5.2 and 5.3.

Fourth, it can be argued that Eq. (2) is not consistent with standard consumer theory. In consumer theory, demand functions are derived by maximizing utility defined over a basket of goods subject to a budget restriction. Thus, the demand functions depend on the quantity consumed of other goods and the income. If standard consumer theory is to be used in this paper, two approaches could be applied. In the first approach, standard utility functions, such as a Cobb–Douglas or quasi-linear function, could be used. With a Cobb–Douglas function, income is reflected in Eq. (2), while a quasi-linear function implies that both the income and the quantity of other goods must be incorporated (Varian, 1992). In the second approach, it is asked which utility function that generates a local approximation of a demand function that is linear in both income and the quantities of other goods. Here, Alparovich and Weksler (1996) show that many reasonable general utility functions have this property. In a sensitivity analysis, the second approach is used in this paper by estimating a demand function linear in the income measure and quantity of a substitute. For the income measure, the average aggregate household income in the EU, Norway, and Iceland is used, and following Delgado et al. (2003), salmon is considered a substitute for mackerel. The quantity of salmon is calculated as a weighted average of salmon consumption in the EU, Norway, and Iceland using expenditure shares as weights. In this estimation, the slope of the demand function for mackerel becomes steeper and is significant. The implications of this alternative demand function are presented in Sections 5.2 and 5.3, but note that when calculating the payoffs the mean value of the income and quantity of salmon have been used.

Finally, the usual identification problem arises when estimating a demand function (Johnston, 1984). With time series for both price and quantity, it is not possible to determine whether an actual observation occurs due to shifts in the demand or the supply function. One implication of the identification problem is that a separate variable that identifies both the demand and supply functions must be found. Furthermore, the demand and supply functions must be estimated as two simultaneous equations. However, in fisheries economics, it is common to estimate a demand function without taking a supply function into account,[15] a tradition followed in the present paper.

4.2. Cost function

A cost function for each player must also be identified, and here, total costs are defined as the actual variable costs of harvesting mackerel (this definition is discussed in Section 5.2). In addition, a single species assumption is imposed so that the harvest of other species does not influence the cost of harvesting

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[11] The data used in this section to estimate and calculate the parameter values are available from the authors. Details regarding the procedure for estimating and calculating the parameter values can also be obtained upon request.

[12] This implies that the elasticity of substitution between mackerel and other goods is assumed to be zero.

[13] In the model with a constant price (in which strategic interaction arises only from stock effects), it is assumed that the price is unchanged over time. The price can be calculated as a weighted average of yearly prices, a procedure that yields a price of 1.14 million Euro/1000 t.

[14] Asche et al. (2005) contains an overview over empirical studies estimating demand functions for fish products.

[15] Asche et al. (2005) gives an overview of the literature that estimates demand functions for fish products.

Table 2
The value of c_i, million Euros/1000 t.

	EU	Norway	Iceland
c_i	0.004,927	0.006,590	0.005,197

Source: Calculation based on Anon (2011a,b, 2014a).

mackerel.[16] The mackerel fishery is also assumed to be a schooling fishery, which implies that stock effects are excluded from the cost function (Neher, 1990). Naturally, this assumption can be challenged, and it may be argued that, even in an extreme schooling fishery, a small stock effect exists. It can also be argued that the assumption of a schooling fishery is appropriate for an individual vessel but not for an entire fleet segment. Finally, search costs may change over a fishing season even though these costs are constant during a fishing trip. However, including stock effects in the cost function implies that the model cannot be solved using the procedure outlined in Section 2.2. Therefore, it must be assumed that stock effects do not exist in the cost function for each player for the Northeast Atlantic mackerel fishery. A possible specification of the cost function is:

$$C_i\left(h_i\right) = C_i h_i^2 \text{ for } i = \text{EU, NO or IC,} \tag{3}$$

where $C_i(h_i)$ is the total variable cost of landings of mackerel for each player, and c_i is a cost parameter for each player. The main justification for using the quadratic cost function in Eq. (3) is that it is a common specification in game theory (Friedman, 1979; Hougaard, 2009).

Account statistics (cost data) and landing data are only available for the EU for the 2008–2012 period. Given such a short time series, a cost function cannot be estimated through statistical procedures. Instead, the cost parameter for the EU must be calculated using a simple approach, and for consistency reasons, the cost parameter for Norway and Iceland is calculated using the same procedure. In this procedure, the total cost of harvesting mackerel for each player, $C_i(h_i)$, and the landings for each player, h_i, from 2011 is used to calculate the cost parameter as $c_i = C_i(h_i)/{h_i}^2$.[17] The results of calculating the cost parameters are shown in Table 2.

When comparing the cost parameters for each player in Table 2, it is apparent that variations in c_i among the players are small. In addition, compared to both search fisheries (cod) and other schooling fisheries (herring), the marginal cost of harvesting mackerel in the Northeast Atlantic is very small (Arnason et al., 2000b). Additionally, note that, due to the procedure described above, the magnitude of the total cost of mackerel is very important for the value of c_i. Finally, the impact of climate change on the mackerel fishery is to decrease the cost parameter for Iceland and increase the cost parameter for the EU and Norway.

The calculated cost parameter is only based on one observation from 2011. Therefore, the calculated cost parameters are highly uncertain, which may affect the empirical results in three ways. First, the functional form of the cost function given by Eq. (2) cannot be tested. Therefore, the implications of an alternative functional form with constant marginal costs are examined.[18] Under constant marginal costs, a new cost parameter for each player, used to identify a new set of payoffs, must be calculated. In Sections 5.2 and 5.3, the solutions to the game with constant marginal costs are briefly discussed, and here, constant marginal costs are assumed for all players simultaneously. Second, due to the procedure for calculating c_i, the cost parameters in Table 2 are sensitive to outliers and random variation in the cost data. Therefore, the cost parameters in Table 2 are varied by +/− 50% in Sections 5.2 and 5.3, with the cost parameter for each player changed separately corresponding to a comparative static analysis.[19] Third, the presence of stock effects in the cost function cannot be tested. However, due to the procedure for identifying the strategic variable (Section 2.2), a set of payoffs cannot be identified in this case. Therefore, the implication of using a cost function given by $C_i\left(h_i, x\right) = \frac{C_i h_i^2}{x}$ is only briefly verbally discussed. However, even with this cost function, the cost parameters for each player are small and nearly identical.

4.3. *Natural growth function*

To find the payoffs in the game, a natural growth function must also be determined. Here, a standard logistic growth function is chosen:

$$F\left(x\right) = rx\left(1 - \frac{x}{K}\right), \tag{4}$$

where r is the intrinsic growth rate and K is carrying capacity. Note that Eq. (4) is based on a single species assumption since the natural growth function only depends on the stock of mackerel.[20] Alternatives to the logistic specification include Ricker or Beverton-Holt functions (Conrad and Clark, 1987). However, one property of a logistic growth function is that it intersects the x-axis at K. This implies that the steady-state harvest levels, calculated using Eq. (1) in Section 2.2, become reasonable. In contrast, Ricker and Beverton-Holt growth functions may become very flat after the stock size corresponding to the maximum sustainable yield, implying that the harvest calculated using Eq. (1) becomes very large. Given these considerations, a logistic growth function is used in this paper.

Time series data on the stock size and aggregate harvest for each player in the mackerel crisis for the period from 1980 to 2011 were obtained from ICES (2013), while observations for natural growth were calculated from the stock size and aggregate harvest data.[21] Employing these time series to estimate Eq. (3) using OLS, we obtain:

$$r = 0.47\ (1.44)$$

$$K = 8266\ (0.99)$$

$$R^2 = 0.22$$

where the numbers in parenthesis are t-statistics. From these results, it is evident that the estimated logistic growth function performs very poorly based on statistical criteria. Both r and K are insignificant, and R^2 is very low. However, it is common in fisheries economics to obtain poor results when estimating a logistic growth function (Arnason et al., 2000b).[22] Therefore, despite their poor statistical properties, the reported estimates are used in the

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[16] When the harvest of other species influences the cost of harvesting mackerel, economic interactions among fish species occur. A classic paper on economic interaction is Anderson (1975).

[17] The derivation of the total costs of mackerel is based on seven assumptions involving identical costs and revenue shares of mackerel, identical cost functions for all fleet segments, scaling of costs for pelagic freezer trawlers to cover all pelagic trawlers in Iceland, use of actual costs of harvesting, identical output prices for all players and identical cost functions in Iceland and the Faroe Islands.

[18] With constant marginal costs, the cost function is given as $C_i(h_i) = c_i h_i$, and here, $c_{EU} = 0.8886$ (million Euro/1000 t), $c_{NO} = 0.9371$ (million Euro/1000 t), and $c_{IC} = 0.8679$ (million Euro/1000 t).

[19] An alternative would be to vary the cost parameters for all players simultaneously by +/−50%.

[20] Therefore, no biological interaction in the growth function occurs between fish species. A classic economic paper on biological interaction is Anderson (1975).

[21] In calculating the natural growth, the harvest of, for example, Russia is excluded to ensure consistency with the procedure in Eq. (1). However, this implies that the true natural growth is underestimated.

[22] All observations for the natural growth lie to the left of the stock size corresponding to the maximum sustainable yield. However, with Eq. (3), a second-order equation with a maximum at MSY is estimated.

empirical analysis. Also, note that the parameter estimates for r and K are reasonable compared with those of other schooling fisheries studies (Arnason et al., 2000b).

Due to the shape of the natural growth function, it may be argued that a time series for the period from 1980 to 2011 is short. It is therefore natural to consider whether a longer time series can be obtained or whether an estimated growth function from the existing literature can be used. In discussing these two issues, it is useful to distinguish between biological estimation methods and economic estimation methods. Biological estimation in Europe is often based on virtual population analysis, which solves a set of equations simultaneously to identify the biomass for each year-class of a fish stock for a given number of years.[23] This estimation is supplemented by surveys of larvae abundance to estimate recruitment and stock size (Lassen and Medley, 2001). However, in economic analyses, a natural growth function for a fish stock is required, and here, the biologically estimated biomass is a variable that determines this growth. Economists use either the total spawning stock biomass or the total available biomass; therefore biological models estimating the biomass form the basis for economic model applications. In this paper, the total fishable biomass is used, implying that fishing affects the entire biomass and not just the spawning stock biomass. ICES (2013) estimates the total spawning stock biomass and total available biomass for the mackerel fish stock in the Northeast Atlantic, and it is not possible to obtain a longer time series from ICES (2013) because biomass is frequently re-estimated. Re-estimated time series cannot be linked to previous time series estimates. Indeed, ICES (2013) only provides biomass information for approximately 30 years, so by using an estimate covering the period from 1980 to 2011, the maximum number of observations is used.

4.4. Strategic variables

To find the steady-state harvest using the procedure described in Eq. (1), a measure for the harvest as a share of stock size for each possible strategy combination must be obtained. This implies that information about both harvest and stock size under each strategy is necessary. In identifying the harvest, two important game theoretical assumptions must be discussed. First, it is assumed that an individual player does not change strategy if other players change strategy. For example, if the EU plays cooperatively, it will not change its strategy if Norway changes its strategy. This assumption implies that only one observation of a non-cooperative harvest and a cooperative harvest for each player is necessary. Second, all players in the mackerel crisis agreed on a TAC in 2009. In 2010, Iceland and the Faroe Islands decided to increase their harvests considerably, while the EU and Norway entered a bilateral agreement on a TAC. In this paper, these facts are interpreted as follows. Before the mackerel crisis, all players acted cooperatively, while the EU and Norway continued to act cooperatively in 2010, but Iceland and the Faroe Islands acted non-cooperatively. Thus, there is no observation of non-cooperative harvests by the EU and Norway. Here, it is assumed that the relationship between cooperative and non-cooperative harvests is identical for all players. As year for measuring harvest under cooperative behavior 2009 is chosen while 2010 is used as harvest under non-cooperative behavior.

For stock size, it is natural to choose the same years as for the harvest to measure non-cooperative observation and cooperative observations. Therefore, stock size in 2009 is used as a measure under cooperative behavior, while the stock size in 2011 is applied as a measure under non-cooperative behavior. With these assumptions, the harvest as a share of stock size can be calculated for each player under both strategies. The results are presented in Table 3. In interpreting Table 3, note that measurements of stock size involve significant uncertainty (Section 3).

Table 3
Harvest as a share of the stock size under cooperative and non-cooperative behavior, %.

	EU	NO	IC
Cooperative behavior	5	2	3
Non-cooperative behavior	13	6	7

Source: Authors' calculations, based on ICES (2013).

4.5. Payoffs

The payoffs for each player are defined as the total variable profit for all vessels in a long-run, steady-state equilibrium. This profit is often referred to as the long-run economic yield, and therefore, the payoff for each player defined as:[24]

$$\pi_i = (\alpha - \mathrm{bh}_{\mathrm{EU}} - \mathrm{bh}_{\mathrm{NO}} - \mathrm{bh}_{\mathrm{IC}})h_i - c_i h_i^2, \tag{5}$$

where π_i is the payoff (profit) for the EU, Norway and Iceland/Faroe Islands. From Sections 4.1–4.4, all the necessary information is available to calculate the payoffs in Eq. (5). Note that the payoff for each player depends on the behavior of the other players, and this interdependence captures strategic interactions among the players.

5. Payoff and solutions

5.1. Payoffs

It is useful to start by introducing the notation used in this section. Cooperation is denoted C, while non-cooperation is denoted NC, and the payoff is denoted P (EU, NO, IC). Given this notation, P (NC, C, NC) implies that Norway acts cooperatively, while the EU and Iceland/Faroe Islands act non-cooperatively. This captures the fact that the payoff for each individual player depends on the specific strategy combination employed by the players. Thus, the payoffs for each player must be evaluated for every possible strategy combination and P (NC, C, NC) = (3, 2, 1) implies that the EU obtains a payoff of 3, Norway obtains a payoff of 2, and Iceland obtains a payoff of 1. The harvest level for each player is identified using Eq. (1), and the payoffs are calculated using Eq. (5). The results are shown in Table 4.

5.2. Non-cooperative solutions

For the non-cooperative game in Table 4, (NC, NC, NC) is a dominant strategy equilibrium. Thus, irrespective of the behavior of the other players, each player benefits by acting non-cooperatively. In Section 4.4, it is argued that Iceland/Faroe Islands acted non-cooperatively, while the EU and Norway played cooperatively during the mackerel crisis. Thus, (NC, NC, NC) as a dominant strategy equilibrium implies that the actual outcome during the mackerel crisis cannot be explained by the model in this paper. The intuition behind the (NC, NC, NC) as a dominant strategy equilibrium is clear, given a distinction between revenue and cost effects (the two components of the payoff). Regarding the revenue effect it was shown in Section 4.1 that the demand function is flat. This implies that an increase in harvest (acting non-cooperatively) only has a small influence on revenue (the revenue effect is small). As

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[23] Jansen et al. (2012) and Jansen and Gislason (2013) estimate the biomass of mackerel in the Northeast Atlantic Sea using biological methods.

[24] In a game where strategic interaction arises only due to the resource restriction, a constant price is assumed in Eq. (5).

Table 4
Payoffs in the game.

Strategies	Stock size (1000 t)	EU harvest (1000 t)	Norway harvest (1000 t)	Iceland/Faroe Islands harvest (1000 t)	Price (million Euro/1000 t)	Payoffs (million Euro)
C, C, C	6507	325	130	195	1.03	(280, 124, 180)
C, C, NC	5804	290	116	406	0.96	(236, 104, 303)
C, NC, C	5803	290	348	174	0.96	(236, 272, 151)
C, NC, NC	5100	255	306	357	0.92	(201, 233, 261)
NC, C, C	5100	663	102	153	0.92	(390, 88, 128)
NC, C, NC	4397	571	88	308	0.90	(351, 75, 227)
NC, NC, C	4397	572	264	132	0.90	(351, 201, 109)
NC, NC, N, C	3693	480	222	259	0.91	(318, 175, 198)

discussed in Section 4.2, the cost parameter does not vary much for the player, which implies that the EU, Norway and Iceland/Faroe Islands will adopt the same strategy. Furthermore, the cost parameter is small, so an increase in harvest (acting non-cooperatively) will only have a small effect on the costs. Therefore, because both the revenue and cost effects are small, increasing the harvest by acting non-cooperatively is a dominant strategy equilibrium. Note that the game in Table 4 involves strategic interactions as a result of both price and stock effects (Section 1.3), but models with only one type of strategic interaction have also been investigated. For these two models, (NC, NC, NC) remains a dominant strategy equilibrium, so the main result based on Table 4 is robust to variations in the nature of the strategic interaction.

As mentioned in Section 4.1, two types of sensitivity analyses with respect to the demand function have been conducted. First, a weighted average of the prices in the EU, Norway and Iceland has been used instead of the Danish market prices. In this case, (NC, NC, NC) is still a dominant strategy equilibrium, and this follows from the fact that the demand function is flatter than when using average market prices (the revenue effect is even smaller). Second, income and quantity of salmon have been included in the demand function, which leads to a steeper demand function. However, even with this function, (NC, NC, NC) is a dominant strategy equilibrium. Thus, overall, the non-cooperative result in this paper does not depend on the assumptions of the demand function.

However, the main result may also be due to the procedure used to identify the cost function. Therefore, two types of sensitivity analyses have been performed. First, constant marginal costs are assumed, which implies that the relative costs of acting cooperatively increase. Therefore, it is clear that (NC, NC, NC) remains a dominant strategy equilibrium with constant marginal costs because the cost effect is even smaller. Second, each cost parameter has been varied by +/−50% (assuming increasing marginal costs), but for all variations in the cost parameters, (NC, NC, NC) remains a dominant strategy equilibrium. Overall, the result that (NC, NC, NC) is a dominant strategy equilibrium is robust to variations in both the parameter values and the functional form of the cost function.

Based on the above analysis, it is clear that the definition of costs is important for the non-cooperative equilibrium. Therefore, we argue that an opportunity cost concept can explain the actual outcome during the mackerel crisis in two ways. First, a capacity limit on the number of fishing days may exist. A capacity limit implies that an increased harvest of mackerel reduces the number of fishing days that can be used to harvest other fish species. Therefore, revenue from other species is lost when fishing effort is shifted to the mackerel fishery, and this lost revenue is an opportunity cost of harvesting mackerel provided that the cost of effort is constant. Difference in the players opportunity cost can explain why the EU and Norway acted cooperatively while Iceland and the Faroe Islands acted non-cooperatively during the mackerel crisis. The EU and Norway may face capacity limits on the number of fishing days, and therefore, a high opportunity cost of harvesting mackerel may exist for these players (the cost effect is large). For Iceland, the harvest of blue whiting decreased dramatically, and below Table 1, it was argued that Icelandic vessels shifted to mackerel. Thus, the opportunity cost for Iceland of playing non-cooperatively is low. With Iceland facing a small cost effect and the EU and Norway facing large cost effect, (C, C, NC) is a Nash equilibrium, which corresponds to the actual observed behavior during the mackerel crisis.

Second, differences in opportunity costs due to differences in regulation supplement this explanation for behavior during the mackerel crisis. The EU and Norway have a well-developed ITQ system for fishing mackerel in the Northeast Atlantic, while Icelandic vessel harvesting blue whiting are regulated by a total quota. For the EU and Norway, the ITQ for mackerel can be lost if vessels shift to other species, implying a high opportunity costs of harvesting mackerel. However, due to the total quota on blue whiting and effectively no quota on mackerel, Icelandic vessels can shift between these fish species without any a cost, implying that the opportunity cost of harvesting mackerel is low. With high costs in the EU and Norway and low costs in Iceland, the solution (C, C, NC) is a Nash equilibrium. However, these two opportunity cost explanations are not tested empirically in this paper. Including capacity limits and regulation in the paper implies that linear or non-linear programming models must be constructed to quantify the opportunity costs, and constructing such models is beyond the scope of this paper. Therefore, the identification of payoffs using actual harvest costs in Table 4 is useful because it shows that the definition of costs is important for the non-cooperative equilibrium.

The explanations based on opportunity costs are, in principle, based on the game theoretic analysis, but five alternative and plausible economic explanations are deduced from the description in Section 1.1. First, demand for mackerel increases over time, and this increase has been relatively large in Iceland and relatively small in the EU and Norway. Second, following the effective bankruptcy of Iceland in 2008, the country has changed its industry structure toward traditional industries, such as fisheries. Third, migration patterns have not changed but the size of the mackerel fish stock is increasing, which affects Iceland more than the EU and Norway. Fourth, the EU and Norway have a long tradition of entering bargaining agreements, while such a tradition does not exist in Iceland. Finally, the fisheries industry is very important for Iceland but less important for the EU and Norway.

From Section 4.2, it is also clear that stock effects in the cost function may exist. Naturally, it is important to discuss the equilibrium in a non-cooperative game, when including stock effects. When stock effects are included, the cost parameters are still almost identical between players, and therefore, the EU, Norway and Iceland will play the same strategies. However, including stock effects implies that the cost of increasing the harvest (playing non-cooperatively) increases and that (C, C, C) is a more likely a Nash equilibrium. However, the actual Nash equilibrium depends on the empirical size of the stock effect in the cost function.

In the above discussion, the mackerel crisis is analyzed assuming a one-shot game in quantities, and a dominant strategy equilibrium is reached. This analysis is very simple, and the assumptions can be relaxed in two ways. First, other solution concepts, such as a Stackelberg equilibrium, an iterative dominance equilibrium and a focal point equilibrium, can be applied. However, when actual harvesting costs are used, the outcome of the mackerel crisis cannot be explained using other solution concepts because the cost parameters are almost identical between the players. To illustrate, consider a Stackelberg equilibrium. If Iceland has the first mover advantage, (C, C, NC) is a possible Stackelberg equilibrium. However, if the EU moves first, (NC, C, C) is a possible equilibrium. Thus, the outcome during the mackerel crisis cannot be predicted in a consistent way with a Stackelberg solution concept. Second, the mackerel crisis can be modeled by allowing adjustments toward equilibrium. In this case, a dynamic game approach must be used (including open-loop or closed-loop strategies), but even in dynamic games, the basic result will be the same. Because marginal costs are nearly identical for the three players, they will adopt the same strategies on an adjustment path toward equilibrium.

As discussed in Section 1.4, the migration pattern of the mackerel fish stock has shifted northward, that is, toward the coasts of Iceland and the Faroe Islands, due to climate change. The main impact of the changed migration patterns on the mackerel fishery in the Northeast Atlantic is that Iceland entered the fishery in 2008. Therefore, the payoffs in Table 4 capture the situation after the main impact of climate change, and (NC, NC, NC) is a dominant strategy equilibrium after Iceland entered the fishery.

5.3. *Cooperative solutions*

The results of the cooperative games and the intuition for these results are identical to those presented in Section 5.2, so the conclusions in this section are discussed only very briefly. With the payoffs in Table 4, the core of a cooperative game between the EU, Norway and Iceland (the grand coalition) is empty, and from the Shapley value, it is apparent that no player can receive a payoff that corresponds to its marginal contribution to a coalition. The core is also empty, and the Shapley value lies outside the core, for each possible two-player coalition, and all players have an incentive to act alone. Therefore, the empirical model in this paper can be used to explain why the EU, Norway, Iceland and the Faroe Islands did not agree on a bargaining solution during the 2010–2014 period. However, the model does not explain why the EU and Norway entered into a bilateral agreement in 2010 or why the EU, Norway and the Faroe Islands reached a bargaining solution in 2014. The intuition for this result is that the revenue and cost effects are small, and focusing on only one type of strategic interaction does not change this result. The cooperative game theoretical result is robust to changes in the assumptions behind both the demand and cost functions (no incentive to enter coalitions exists). However, using opportunity costs combined with regulation and capacity limits instead of actual costs can potentially explain the actual behavior, and introducing stock effects into the cost function implies an increased incentive to form coalitions. A cooperative game theoretical analysis can also be extended to other solution concepts and dynamic games, but even with this extension, the incentives to form coalitions are unchanged.

However, an explanation of why the Faroe Islands entered into a coalition with the EU and Norway in 2014 (rather than in another year) has not been derived, but three possible explanations can offered based on the description in Section 1.1. First, from Table 1, the harvest of blue whiting increased in 2013; therefore, the opportunity cost of harvesting mackerel for the Faroe Islands increased, making coalition formation more desirable. Second, additional trade restrictions were imposed on the Faroe Islands in 2013, and therefore, the side payments from forming a coalition increased. Third, in 2013, the Faroe Islands stated the possibility of taking the EU and Norway to court, but the cost of a court case might be high therefore increasing the side payments of forming coalition for the Faroe Islands. Overall, it can be explained that it was beneficial for the Faroe Islands to enter a coalition exactly in 2014.

6. Conclusion

Between 2010 and 2014 a crisis on the size and the relative allocation of a TAC for fishing mackerel in the Northeast Atlantic occurred among the EU, Norway, the Faroe Islands and Iceland. This paper investigates whether the mackerel crisis can be explained using simple non-cooperative and cooperative game theory. Based on a fully specified empirical model with a non-constant price and a resource restriction, it is predicted that acting non-cooperatively is a dominant strategy for each player in a non-cooperative game. Thus, the empirical model cannot explain why the EU and Norway acted cooperatively after 2010. In a cooperative game, each player has an incentive to act alone judged by the core and the Shapley value. Thus, the facts that the EU and Norway reached a bilateral agreement in 2010 and that the EU, Norway and the Faroe Islands reached a solution to the mackerel crisis in 2014 cannot be explained. However, actual harvesting costs are used to identify the payoffs in the empirical model, but an alternative is to use opportunity costs combined with differences in regulation and capacity limits. Using this alternative, actual behavior during the mackerel crisis may be explained.

Three major limitations in the empirical model in this paper arise. First, a schooling fishery is assumed, which implies that stock effects are not included in the cost function. However, in almost all fisheries stock effects in the cost function arise and taking these into account increase the costs of acting non-cooperatively. Therefore, existence of stock effects might explain the outcome during the mackerel crisis. However, the actual outcome of the games depends on the empirical size of the stock effect.

Second, the model does not involve maximization of an objective function since the value of a strategic variable (harvest) is determined by the resource restriction. Maximization of an objective function would make it necessary to distinguish between a private optimum and a social optimum. In a private optimum, open-access may exist for the EU, Norway and Iceland/the Faroe Islands, while a social optimum is found by maximizing the resource rent subject to a resource restriction. A well-known result is now that behaving non-cooperatively is optimal in a open-access equilibrium, whereas cooperative behavior is beneficial in the model for a social optimum. Therefore, including the maximization of an objective function may change the basic results in this paper.

Third, a Nash equilibrium and a dominant strategy equilibrium are used in the non-cooperative game, while the core and the Shapley value are applied as sharing rules in the cooperative game. Of course, more complex models employing more advanced solution concepts can be investigated. However, doing so will not change the main results of the paper, as the values of the cost parameters are low and nearly identical for the players.

Despite these limitations, important contributions are made in the paper to two strand of the game theoretical literature on the Northeast Atlantic mackerel crisis. First, Cheung et al. (2012) and Miller et al. (2013) argue that the altered migration pattern of the mackerel fish stock are caused by the climate change involving a higher stock sizes in the waters near Iceland and the Faroe Islands. However, the main impact of climate change is the entry of Iceland entered into the fishery in 2008 while this paper analyzes the outcome during the mackerel crisis between 2010 and 2014. Thus, our contribution to Cheung et al. (2012) and Miller et al. (2013) is to analyze the situation after the main impact of climate change has occurred.

Second, we contribute to empirical papers examining the mackerel crisis in the Northeast Atlantic captured by Ellefsen (2013) and

Hannesson (2013). Ellefsen (2013) uses cooperative game theory to explain the entry of Iceland in 2008 while non-cooperative game theory is applied in Hannesson (2013) to study the implications of the changed migration patterns for the fish stock in 2008. By focusing on the outcome during the mackerel crisis between 2010 and 2014 the work by Hannesson (2013) and Ellefsen (2013) is extended in this paper.

It is mentioned above that the outcome during the mackerel crisis may be explained by using an opportunity cost concept combined with differences in regulation and capacity limits. However, investigating this conclusion empirically requires that the opportunity costs of regulation and capacity limits is quantified and such an analysis is not carried out in this paper. An analysis of these issues could be accomplished by constructing a linear or non-linear programming model and then apply the results from this model to calculate payoffs of the players. Performing such an analysis is an important area for future research.

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