06/15
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REPORT

A Bioeconomic and Game Theoretic Analysis of the Northeast Atlantic Mackerel Dispute

Evangelos Toumasatos
Fo Wang

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A Bioeconomic and Game Theoretic Analysis of the Northeast Atlantic Mackerel Dispute

by

Evangelos Toumasatos
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"Give a man a fish and you feed him for a day. Teach a man to fish and you feed him for a lifetime."

Ancient Chinese Proverb

Abstract

This is an empirical analysis of the so-called Northeast Atlantic Mackerel Dispute between coastal nations such as the EU, Norway, the Faroe Islands and Iceland. In this thesis, firstly, we discuss the relevant biological and managerial aspects of Northeast Atlantic Mackerel. Then we begin to give a full factual depiction of the dispute. Based on the historical accounts of the dispute, we define the research problems of the issue. Further, we lay out the theoretical basis for solving such problems, i.e., fishery economics and game theory. By applying the theoretical framework and adopting the bioeconomic model, we solve the problems with extensive discussion and sensitivity analysis. The solution we find for the Mackerel Dispute is that all coastal nations should cooperate because such cooperation would lead to more NPV, recruitment and escapement levels of the mackerel stock but less harvest collectively. However, only with a proper benefit sharing arrangement, such cooperation may be feasible, resulting in each individual player end up with more benefit than acting on its own.

Keywords: Bioeconomics, Game Theory, Golden Rule, Northeast Atlantic Mackerel, Mackerel Dispute, Profit Allocation, Stock-recruitment.

Aknowledgments

We would like to take this opportunity to express our deep gratitude to Stein Ivar Steinshamn, Professor, in the Department of Business and Management Science of Norwegian School of Economics, for his sincere and valuable guidance, help and support.

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List of Abbreviations

CIA	Central Intelligence Agency
EEZ	Exclusive Economic Zone
EU	European Union
FAO	Food and Agriculture Organisation
GDP	Gross Domestic Product
IBTS	International Bottom Trawl Survey
ICES	International Council for the Exploration of the Seas
IOC	Icelandic Ocean Cluster
IUCN	International Union for Conservation of Nature
MEY	Maximum Economic Yield
MSY	Maximum Sustainable Yield
NEA	Northeast Atlantic
NEAFC	North East Atlantic Fisheries Commission
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development
OLS	Ordinary Least Squares
RFMO	Regional Fisheries Management Organisation
RSE	The Royal Society of Edinburgh
SSB	Spawning Stock Biomass
TAC	Total Allowable Catch
UK	United Kingdom

Chapter 1

Introduction

1.1 Objective and structure of the thesis

This is an empirical study on the recent heated so-called Mackerel Dispute between Iceland as one party and the coalition formed by the European Union (EU), Norway, and the Faroe Islands. In the very beginning of the thesis, we present the main objective and a description of the structure of the thesis.

The main objective of the thesis is to employ bioeconomics as well as game theory to numerically analyse and solve the mackerel issue. In order to better serve such aim, we structure the thesis as follows. In Chapter 1, we introduce the background of the case from biological, historical and the status quo perspectives. The content of mackerel biological aspects we introduce are confined to the relevance and understanding of the problem. Standing upon the knowledge background of the case, research problems are defined in Chapter 2. In order to answer the research questions, in Chapter 3, we lay out both of fishery economics and game theory as our theoretical framework. Then in Chapter 4, extending from the theoretical basis paved out in Chapter 3, the bioeconomic model we adopt is introduced. Extensive mathematical formulation are involved and presented in this process. So far, we have all the background knowledge and tools to enable us to solve the research questions proposed in Chapter 2. Therefore, in Chapter 5, we estimate the parameters of the bioeconomic model and solve the problems under two scenarios, i.e., the cooperative and non-cooperative. Based on the theoretical guiding principles introduced in Chapter 3, on the collective level, cooperation is almost and always more desirable than non-cooperation. However, there are conditions for the viability of cooperation. In Chapter 6, we apply game theory to test the conditions for viability of the cooperation. Due to the limitations embodied in the estimates of some parameters in the bioeconomic model, sensitivity analysis is performed in Chapter 7 to make the findings of the thesis more comprehensive. Extensive discussions are involved in Chapter 5, 6 and 7. In Chapter 8, we conclude based on the results we obtain and discuss the limitations and possibilities of the model.

1.2 Biological traits and the environment

1.2.1 Taxonomy and definition

The name of mackerel is a colloquial fish term and it can be referred to a number of pelagic, swift-moving, and streamlined food and sport fishes (Encyclopaedia Britannica). Therefore, the term of mackerel does not refer to one single species or even one genus in the strict sense of scientific classification. It consists of many species across a number of genera. It could be mostly but not exclusively traced back to the family Scombridae, which is also the family that tuna (tribe Thunnini) belongs to.

The mackerel that this thesis deals with is a special single species called Atlantic Mackerel, Scomber scombrus (Figure 1.1). The geographic range of this species is widely spread in Atlantic: from Labrador to Cape Lookout, U.S. in the western Atlantic; and from Iceland to Mauritania in the eastern Atlantic, including the southwestern Baltic Sea, the Mediterranean Sea and the Black Sea (Figure 1.2).

As can be seen from Figure 1.2, the habitats of the western and eastern Atlantic stocks are depicted separately without geographic linkage. Further, no evidence has been found that there is cross-Atlantic migration of the two separate stocks in previous studies (Jansen and Gislason, 2013).

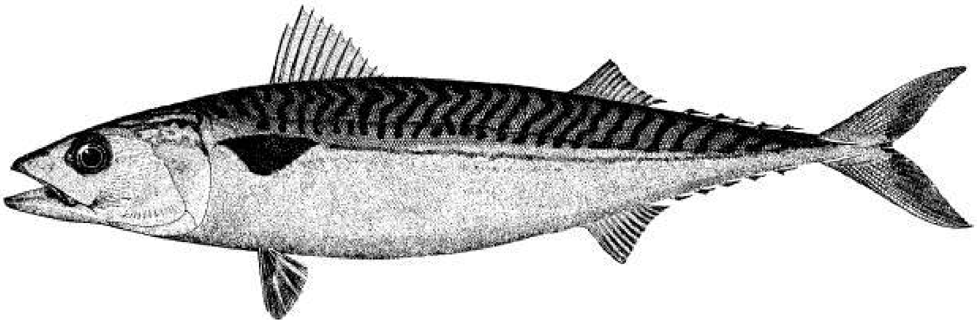

Figure 1.1: Atlantic Mackerel, *Scomber scombrus* (Goode, 1884).

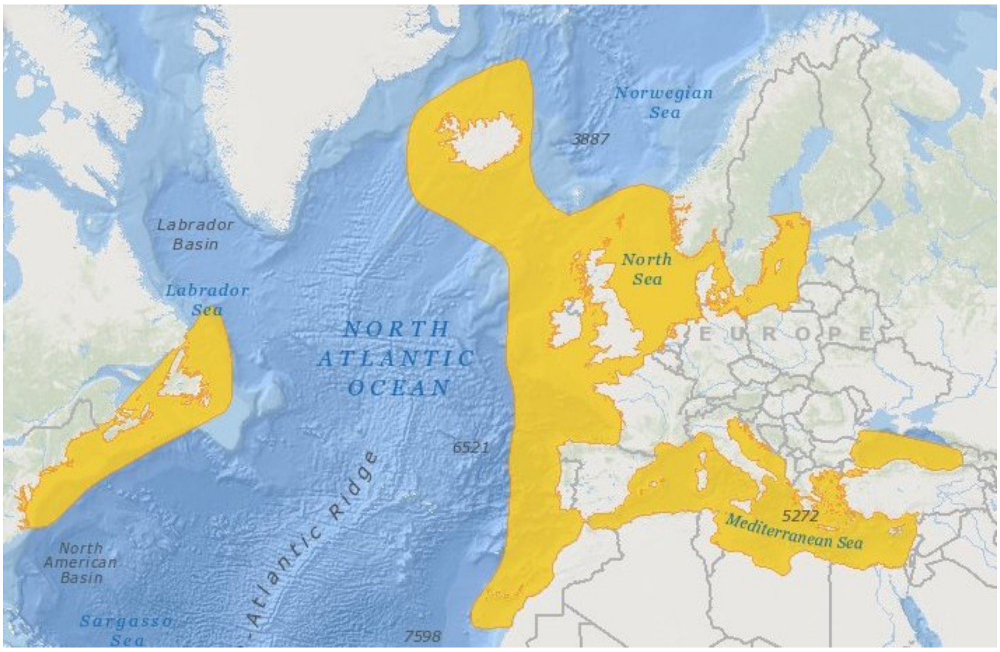

Figure 1.2: The biogeographic distribution range of Atlantic Mackerel (IUCN).

This thesis is written to specifically address the issues of Atlantic Mackerel that lives in the Northeast of Atlantic, of which the management and utilisation cause conflicts of coastal nations such as the EU, Norway, Iceland, the Faroe Islands, termed as the Mackerel Dispute/Issue, sometimes labelled as "Mackerel War" in the mass media. Thus, the biogeographic location is added to the name of the species to more precisely reflect the fish stock, i.e., Northeast Atlantic (NEA) Mackerel.

Also, NEA Mackerel is defined by International Council for the Exploration of the Sea (ICES) as "the (Atlantic) Mackerel present in the area extending from the Iberian peninsula in the south to the northern Norwegian Sea in the north, and Iceland in the west to the western Baltic Sea in east" (ICES, 2014b).

NEA Mackerel is the mackerel stock we are referring to throughout the thesis.

1.2.2 Age and growth

Atlantic Mackerel could grow to a maximum length of more than 60 cm (Muus and Nielsen, 1999) and have an extreme weight of 3.4 kg (Frimodt, 1995). Table 1.1 shows International Bottom Trawl Survey (IBTS) estimates of length, weight and proportion of catch by age (%) for NEA mackerel both in the North Sea and the NEA as a whole (ICES, 2005). The average length and proportion of the matured mackerel at age obtained in IBTS surveys are illustrated in Figure 1.3 and Figure 1.4, based on IBTS data from year 2000 to 2004.

Maturity estimates for NEA Mackerel as a whole indicate that more than half are mature at age 2, with 100% maturity at age 7 (Reid et al., 2001), despite the fact that in Figure 2, IBTS data indicate that in the North Sea more than 90% have reached maturity at age 2.

The longevity is estimated to be approximately 12 years for the western Atlantic stock (Gregoire, 1993) and 18 years for the eastern Atlantic stock (Villamor et al., 2001).

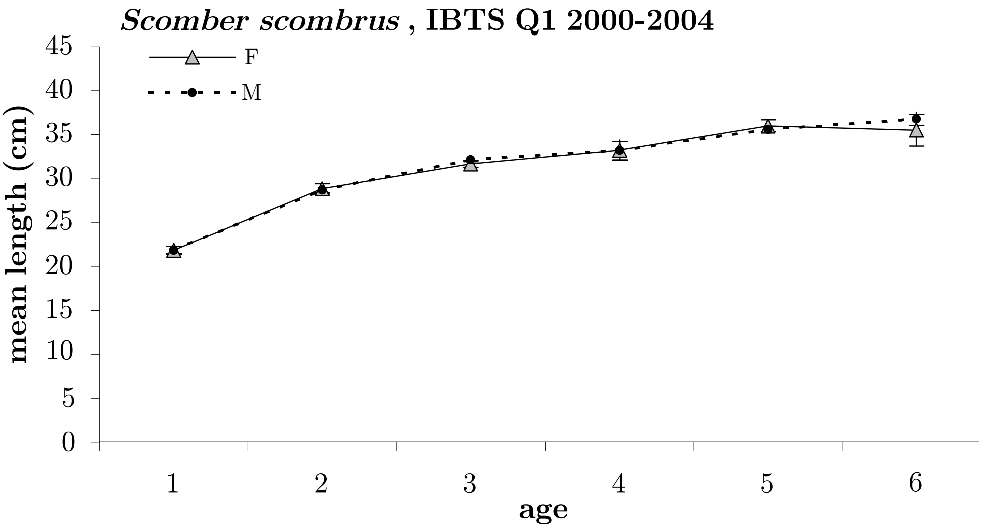

Figure 1.3: The mean length for NEA Mackerel at age in the North Sea and Skagerrak/Kattegat (ICES, 2005).

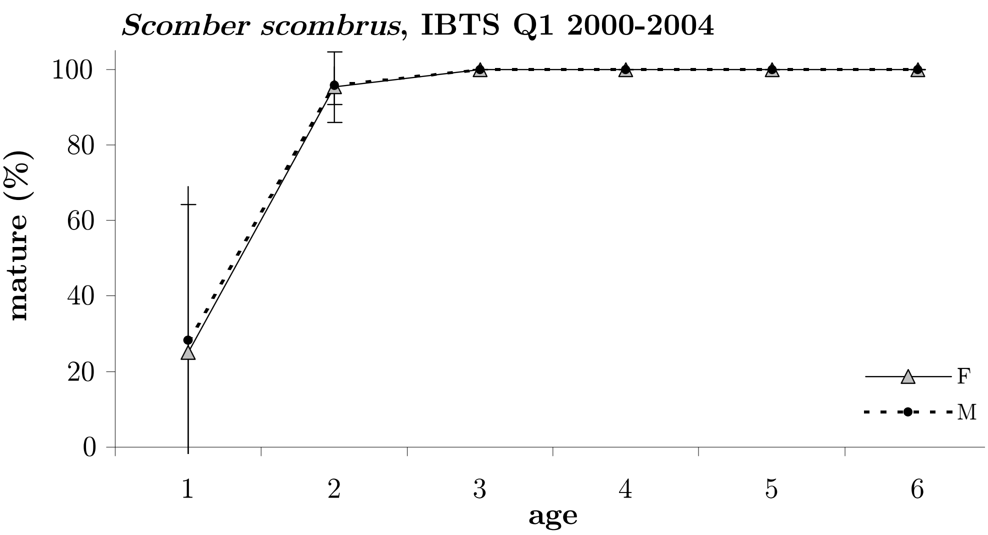

Figure 1.4: The proportion of the matured NEA Mackerel at age in the North Sea and Skagerrak/Kattegat (ICES, 2005).

Table 1.1: Estimates of length (cm), weight (g) and proportion of catch by age (%) for NEA Mackerel in the North Sea and NEA as a whole (ICES, 2005).

	Length (cm)		Weight (g)		Proportion of catch (%)	
Age	North Sea	NEA	North Sea	NEA	North Sea	NEA
0	23.4	22.0	103	81	1	1
1	27.4	27.7	166	170	18	11
2	31.2	31.5	257	269	17	16
3	34.2	33.8	357	337	6	5
4	35.2	35.1	404	388	14	17
5	34.7	36.6	388	440	13	14
6	34.5	37.4	385	478	13	11
7	37.6	38.5	503	525	6	8
8	39.6	39.6	612	576	3	6
9	40.1	40.3	617	617	2	4
10	41.0	40.7	669	637	2	3
11	40.8	41.1	639	654	1	2
12	42.4	41.5	708	685	1	1
13	41.0	42.0	651	731	1	<1
14	42.3	42.4	708	744	1	<1
15	40.8	43.2	671	780	1	<1

1.2.3 Habitat

Atlantic Mackerel is a pelagic fish that lives in the sea and ocean. The depth of its living zone can range from zero to one thousand metres, literally from the near bottom of the ocean to the surface of the sea. However, the usual depth of its habitat is from 0 to 200 metres (Collette and Nauen, 1983).

Also, Atlantic Mackerel prefers to live in cold and temperate water and shelf areas, at above 5°C. It is sensitive to changes in water temperature as well. When water temperatures ranges between 11° and 14°C, Atlantic Mackerel moves closer to shore in spring to spawn.

The feeds of Atlantic Mackerel are mainly zooplankton, crustaceans and small fish. Also, Atlantic Mackerel can be a very opportunistic predator. From one year to another, they may seek any available oceanic areas and exploit them for feeds (Langøy et al., 2012). In the winter time, not only due to insufficient food but also to the fact that most fish stay throughout winter in deep water on the bottom, Atlantic Mackerel fast.

Atlantic Mackerel is a kind of forage fish, which means that it acts as the bait for larger predators. It is an important food resource for various pelagic predators, such as sharks and marine mammals. The youth Atlantic Mackerel can also be eaten by the mature ones.

1.2.4 Spatial-temporal distribution and migration

NEA Mackerel is widespread throughout the NEA. It comprises three spawning components, namely, the Western component, the Southern component and the North Sea component (ICES, 2013). Although in reality, the structure of the stock is probably more complicated than a clear-cut division into the three components (ICES, 2014a; Jansen and Gislason, 2013). Since year 1995, all the three spawning components of NEA Mackerel are evaluated as one stock (Marine Institute, 2009), despite the fact that recent studies have challenged on this stance (Uriarte et al., 2001).

In all the three spawning components, the Western component is the largest, accounting for approximately 75% of the entire NEA Mackerel stock; whereas the Southern component accounts for approximately 22% of the stock. The North Sea component is identified as a separate spawning component with an extremely low level of population since the early 1970s, which amounts to around 3% of the total stock (ICES, 2014a).

Although mackerel landings of each component cannot be attributed specifically to spawning area on biological basis, by convention, ICES separates and distributes the components according to the areas where mackerel is caught. The areas for mackerel and spawning area distribution are presented in Table 1.2 (ICES, 2014a). Also, as a complement to Table 1.2, Figure 1.5 illustrates the ICES division of the NEA.

Table 1.2: Distribtuion for NEA Mackerel and main spawning components (ICES, 2014a).

Distribution of NEA Mackerel		
ICES Subareas and Divisions: IIa, IIIa, IV, V, VI, VII, VIII, IXa, and XIV		
Distribution of main spawning areas		
Western	**Southern**	**North Sea**
VI, VII, VIIIa,b,d,e	VIIIc, IXa	IV, IIIa

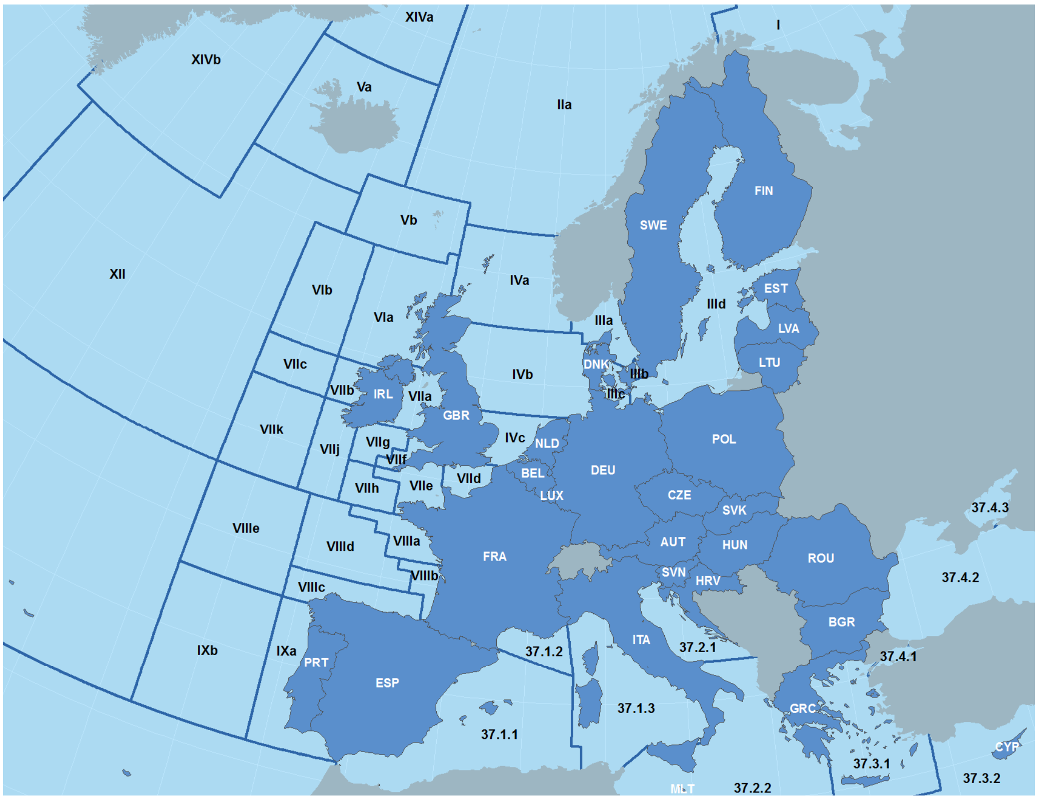

Figure 1.5: ICES division of the NEA.

The sustained swimming speed of Atlantic Mackerel is up to 3.5 body lengths per second, which is equivalent to approximately 4 km/h for a 30 cm mackerel (Wardle and He, 1988). It has once been observed that one tagged specimen of the Western stock had travelled approximately 1,200 km in 13 days (Collette, 1986). Such sustained speed and long distance travelling capabilities could support Atlantic Mackerel seasonal migration for spawning, feeding and overwinter purposes (Molloy, 2004).

Since Atlantic Mackerel does not have a swim bladder, it has to swim constantly, otherwise it would sink. Also, Atlantic Mackerel is a typical shoaling fish, that is, when the mackerel migrates, it travels in groups. It has been reported that they school with large shoals of up to 9 km long, 4 km wide, and 40 m deep (Lockwood, 1988).

The migration pattern of NEA Mackerel can be divided into two elements, i.e., a pre-spawning migration and a post-spawning migration (ICES, 2014a). From late summer to autumn, the pre-spawning migration starts from the feeding grounds in the North and Nordic seas. The Western and Southern components mix with the North Sea component and overwinter in deep water along the edge of the continental shelf, for example, to the north and east of Shetland and along the edge of the Norwegian Trench. When spring comes, the Western component travels southwest along the western Scottish and Irish coasts, mixing with the Southern component, and then spawn in an area stretching from the north of Hebrides to the Bay of Biscay (Simmonds, 2001; Popescu and Poulsen, 2012).

When spawning is finished, the post-spawning migration starts. The Western Mackerel travels back to the feeding grounds in the northern North Sea and Norwegian Sea, returning to the beginning of the migration pattern. Figure 1.6 depicts the major migration pattern until the 2000s of the Western component.

It should be noticed that the migration pattern of the mackerel has been subject to substantial change through time and has not been fully understood by scientists (ICES, 2014a). It can be seen from Figure 1.6 that, the

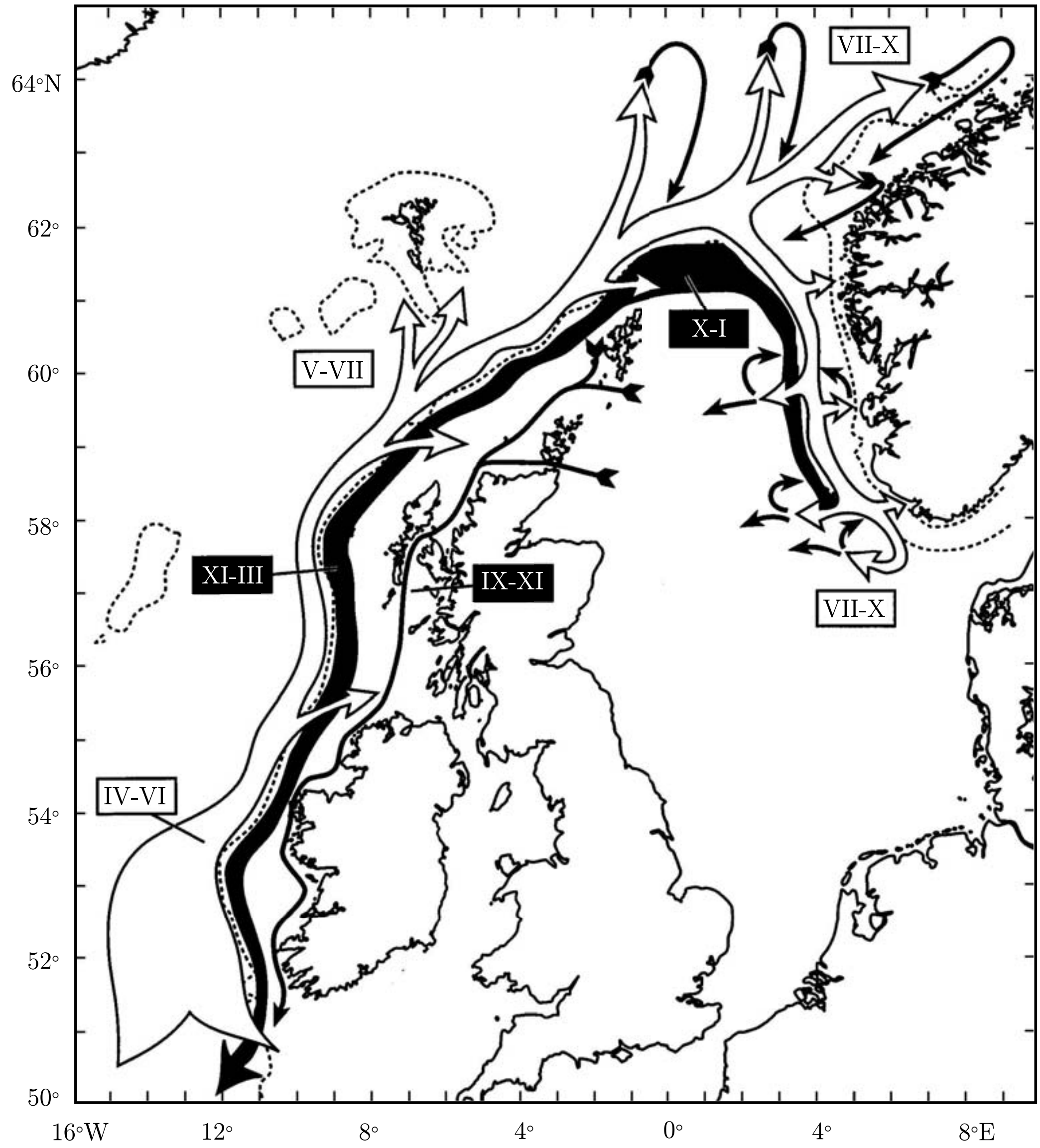

Figure 1.6: The major migration pattern of the Western component until the 2000s. The dark paths show the pre-spawning migration patterns. The thin dark line illustrates the migration pattern in the late 1970s; whereas the thick line shows the pattern in the 1990s. The light path represents the track of the post-spawning migration (Reid et al., 1997).

pre-spawning migration pattern in the 1990s (the thick dark line) had been moved more offshore than in the 1970s (the thin dark line). Additionally, more dramatic change in migration pattern has taken place in the recent decade due to climate change.

1.2.5 Climate change and impact on NEA Mackerel

Originated from the Gulf Stream, the North Atlantic Current is a warm ocean current that continues to the northeast. One of the two major branches of the current continues going north along the coast of northwestern Europe, e.g., the United Kingdom (UK), the Scandinavian nations, Iceland and etc. Scientists generally agree that the North Atlantic Current has a significant warming impact on the climate of northwest Europe and the surrounding waters (Seager et al., 2002). Yet the North Atlantic Current and the local waters of northwestern Europe seem to have been becoming even warmer, believed by many scientists that climate change is the cause.

According to Charles Darwin's theory of evolution, species have adapted to and evolved for certain climate conditions in their habitats. When the temperatures are rising in short-term in their habitats, one possible way for species to adapt is to move away towards the poles of the Earth, where the temperature would have been lower without climate change; yet with climate change, the temperature is adjusted for. This is known as the poleward shift (IPCC, 2007). Recently, marine ecologists from University of Queensland found that the "leading edge or 'front line' of marine species distribution is moving towards the poles at an average rate of 72 km per decade" (Poloczanska et al., 2013).

NEA Mackerel follows this trend but in a much more extreme way. A decade of years ago, Atlantic Mackerel had not been observed in the waters of Iceland. Only until recently, they had been found from time to time in the Icelandic waters. The increased presence of mackerels in certain seasons has been related to a warmer marine climate (Astthorsson et al., 2012; Jonsson and Palsson, 2006).

This could also be caused by the presence and abundance of the feeds of NEA Mackerel such as zooplankton, crustaceans and etc., due to climate change as well. A striking example revealed by Continuous Plankton Recorder survey that has been operating since 1931 shows that, the assemblages of a small crustacean as typical feed of NEA Mackerel, and copepod assemblages (the southern shelf edge assemblage and pseudo-oceanic assemblage) have moved more than 1,100 km polewards over the past 50 years (Beaugrand et al., 2002; Richardson et al., 2006).

Such explanations of the migration pattern change of mackerel are also concluded by ICES. According to ICES, the geographical distributional change of NEA Mackerel may be related to increased water temperature, and may reflect changes in food availability, and/or increased stock size (ICES, 2014b).

Due to the possible reasons, recently, in the warm periods, NEA Mackerel has migrated farther westwards and northwards in the eastern Atlantic during the summer feeding migration (ICES, 2009). Both of the distribution and the abundance of NEA Mackerel in Icelandic waters have increased gradually.

1.3 Management and fishery

1.3.1 Management regime

According to the 1995 United Nations Fish Stocks Agreement (formally, the Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks), straddling fish stocks and highly migratory fish stocks are to be managed by Regional Fisheries Management Organisations (RFMOs). RFMO consists of Coastal States and relevant Distant Water Fishing States (Bjørndal and Munro, 2003; Bjørndal and Ekerhovd, 2014). A Coastal State is a state where a migrating fish stock enters and is found in its exclusive economic zone (EEZ).

The United Nations defines straddling fish stocks as “stocks of fish such as pollock, which migrate between, or occur in both, the EEZ of one or more states and the high seas" (ICES, 2008). In the NEA, Atlantic Mackerel is also a typical straddling stock that is exploited both within the EEZs of Coastal States and on the high seas.

In the NEA, the relevant RFMO is represented by the North East Atlantic Fisheries Commission (NEAFC). Founded in 1980, NEAFC is established by the Convention on Future Multilateral Cooperation in Northeast Atlantic Fisheries, which was put into force in 1982. Figure 1.7 illustrates the Convention Area and Regulatory Area of NEAFC.

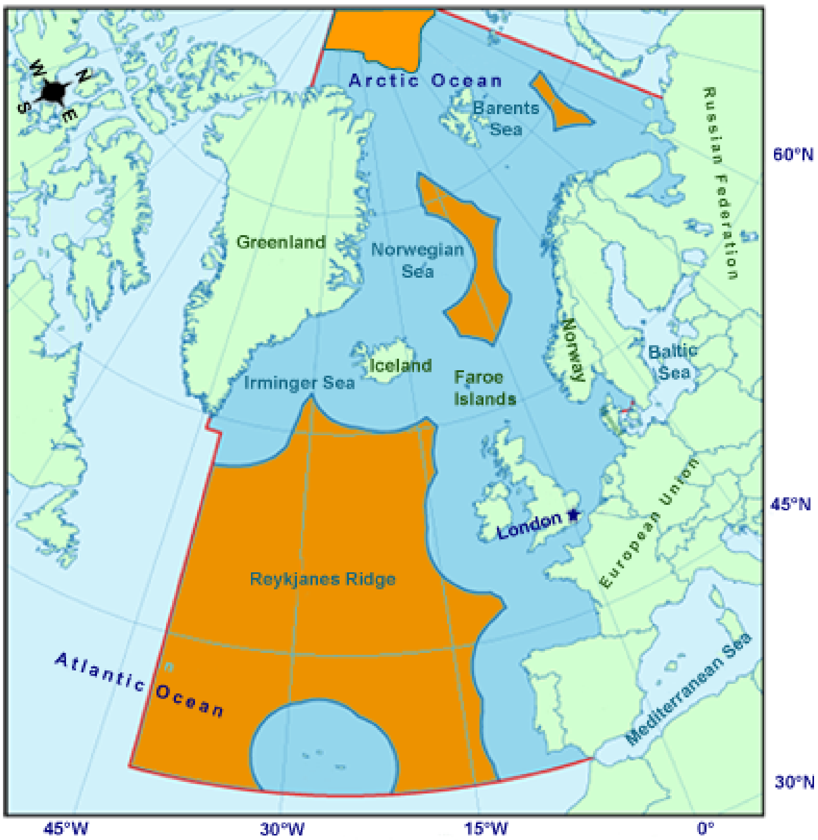

Figure 1.7: NEAFC Convention Area: within the red boarder line; NEAFC Regulatory Area: comprised of high sea block areas in orange colour: the Reykjanes Ridge, the "Banana Hole" of the Norwegian Sea, the Barents Sea "Loophole" and the north-polar area (NEAFC).

NEAFC is formed up of delegations from Contracting Parties. Contracting Parties are Denmark (representing the Faroe Islands and Greenland), the EU, Iceland, Norway and the Russian Federation.

In 1982, a 200 nautical-mile exclusive zone stretching from the baseline of a Coastal State was recognised as the EEZ by the United Nations Convention on the Law of the Sea, applicable to any UN Member States, over which the Coastal State has special rights regarding the exploration and use of marine resources, including energy production from water and wind (UN, 1982). Figure 1.8 illustrates the relationship between EEZ and territory waters as well as other related maritime concepts of a Coastal State. Figure 1.9 depicts the EEZ of Coastal States in the NEA region.

As can be seen from Figure 1.8, the first 12 nautical miles of EEZ overlap with the territory waters of the Coastal State, over which the state has full sovereignty. The area beyond the territory waters but within the EEZ is part of international waters, where the sovereign right to use is conferred to the Coastal State.

Since the 200 nautical mile of EEZs of was put into place in 1982, most of the fish stocks would have been regulated by NEAFC became national zones where national jurisdiction effects. Therefore, according to NEAFC, the management of straddling fish stocks became a matter of bilateral or multilateral responsibility. NEAFC recognises that it does not possess real power or responsibility to manage the fish stocks in the NEA.

However, NEAFC still serves as a forum for consultation and the exchange of information on fish stocks and management for Coastal States. It also makes recommendations concerning fisheries in international waters in the Convention Area. Advised by ICES, NEAFC makes recommendations of measures such as total allowable catch (TAC) of each fish species in order to maintain the rational exploitation of fish stocks in the Regulatory Area.

ICES is a global research organisation. According to its official website, it aims to provide the “best available science for decision-makers to make in-

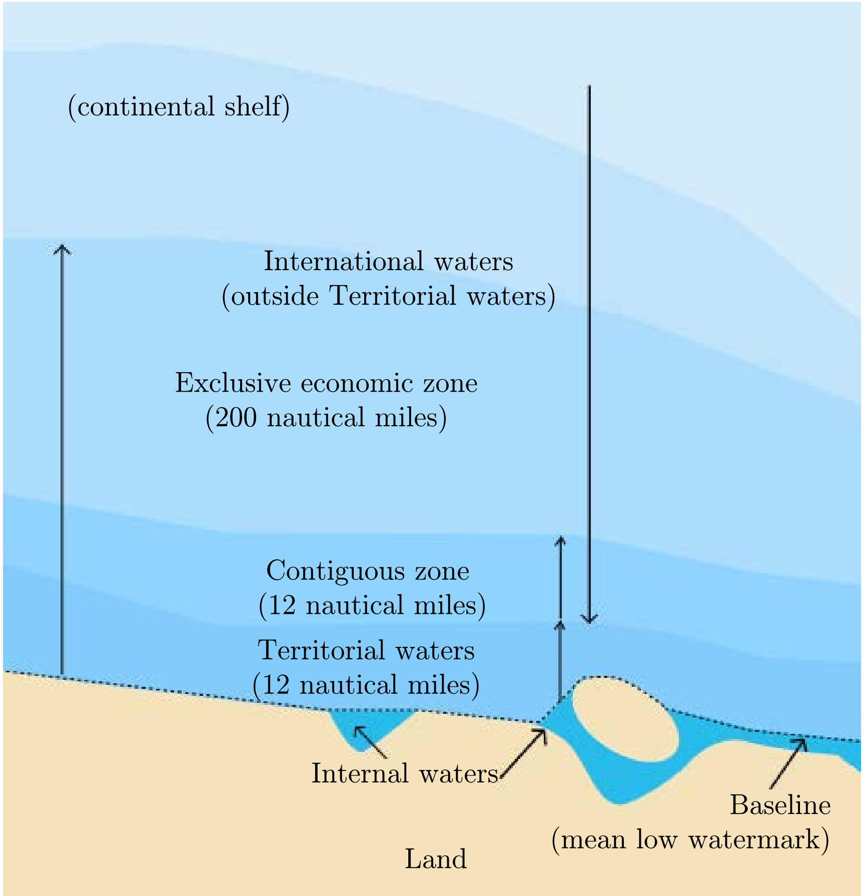

Figure 1.8: Relationship between EEZ and territory waters as well as other maritime concepts of a Coastal State.

formed choices on the sustainable use of the marine environment and ecosystems". ICES has 20 member states from both sides of north Atlantic.

Due to the fact of the so-called Mackerel Dispute/Issue (which is detailed in a later section of the chapter), there has been no consensus by all Coastal States on the management and TAC. In October 2008, a management plan that evaluated by ICES and concluded as precautionary was agreed by Norway, the Faroe Islands, and the EU (ICES, 2008). However, since 2009, there has been no internationally agreed annual TAC, which causes instability and conflicts of Atlantic Mackerel fishing in this region.

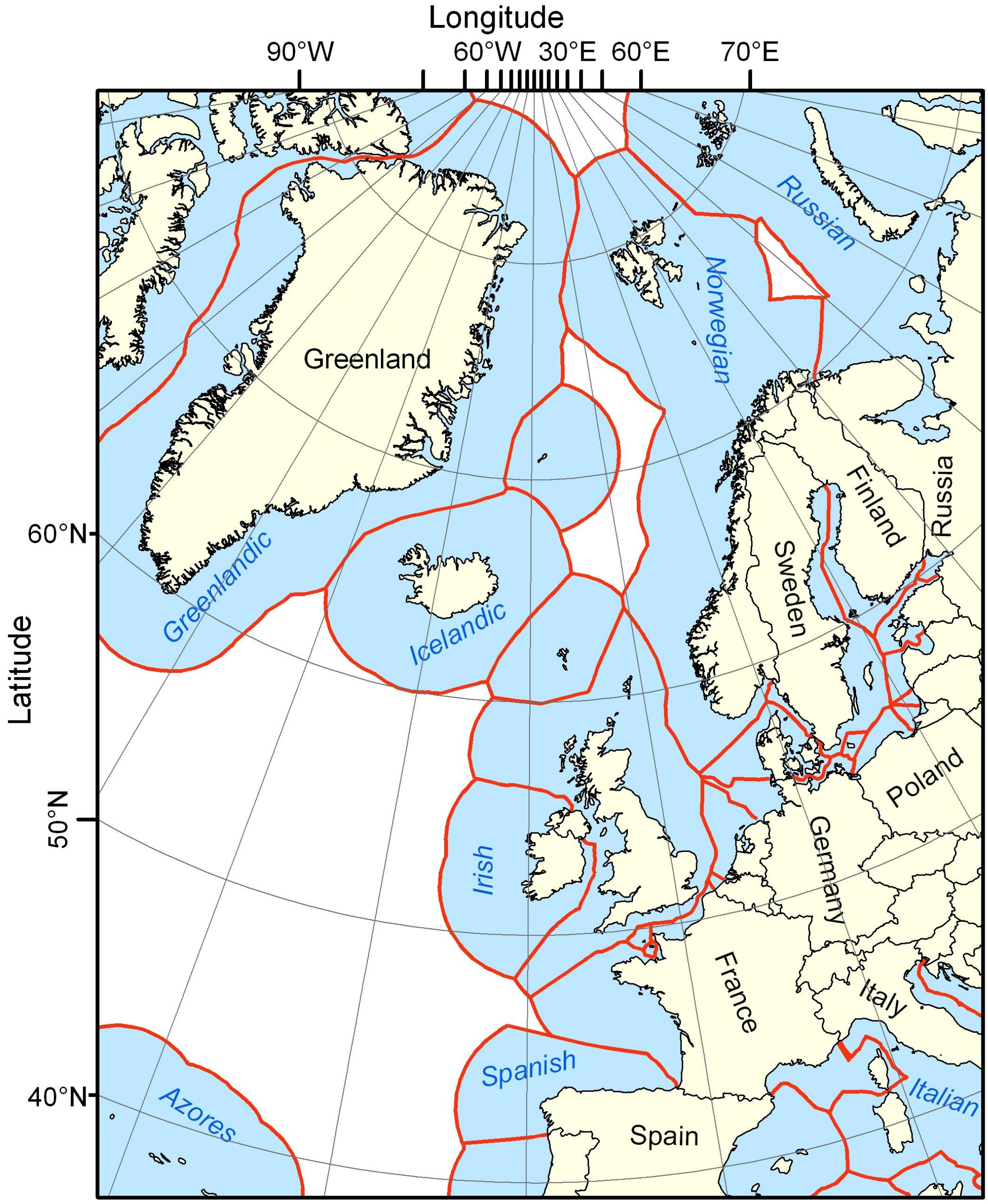

Figure 1.9: EEZs of Coastal States in the NEA region: water territories within the 200 nautical mile from the baseline of Coastal States. Note that the areas of high seas on the map hollowed out from the blue coloured ocean are identical to the orange blocks depicted in Figure 1.7, which is also NEAFC Regulatory Area.

1.3.2 Fishing stock and fishery

Historically, the landings of the Western component were low in the 1960s, but have picked up since and become the most abundant and largest source of the catches. The Southern component is the second largest source of landings, taking around 10% of the total catch.

The North Sea component had experienced heavy exploitation in the late 1960s with landings peaked in 1967 for approximately 1 million tonnes (Popescu and Poulsen, 2012). This lead to the collapse of the North Sea component and catches have reduced significantly since then. It is estimated that in the last decade, the annual catches were only about 10,000 tonnes (Popescu and Poulsen, 2012). At present, protective measures have been applied to the North Sea component for more than two decades, e.g., targeted fishing is banned in the North Sea. Yet the North Sea component has failed to recover and remained depleted since the 1970s.

Since 2002, the spawning stock biomass (SSB) of Atlantic Mackerel has increased. In 2009, ICES recognised the full reproductive capacity status for the stock. However, for the time being, the stock of Atlantic Mackerel is still over exploited, as the total actual catches are still beyond the recommended TAC set by ICES under precautionary principle.

NEA Mackerel is exploited according to its geographical distribution and migratory patterns throughout the year. According to ICES, large fisheries are stretched out from the western and northern coasts of Iberia Peninsular, through the Bay of Biscay, as well as the South, West and North of the UK and Ireland, into the northern North Sea and the Norwegian Sea. In the most recent years, NEA Mackerel fishery industry has expanded northwestwards into Icelandic and east Greenland waters (ICES, 2014a).

A variety of techniques have been employed by different nations based upon both of the national fleet structure and the behaviour of NEA Mackerel (ICES, 2014b). During the time when mackerels overwinter in the North Sea, they are targeted by large Norwegian purse seiners. As mentioned in previous section in this chapter, migration for spawning starts when spring comes. NEA Mackerel travels from the northern North Sea in large shoals to the west first and then move down south along the west coasts of Scotland and Ireland. In this period of time, they are hunted primarily by pelagic trawlers fleets of Scotland and Ireland.

During the spawning season, NEA Mackerel is targeted by the Spanish fleet consisting of both trawlers and a large number of artisanal fishing boats. When spawning season is finished, NEA Mackerel travels northwards for feeding grounds. Pelagic fleets from Russia, Iceland, the Faroe Islands and Greenland join in the hunting activities for mackerels.

The South West Mackerel Box (also referred to as the Cornwall Box), which is off the southwest coast of England, was created to protect juvenile mackerel population. Only smaller scale handliners are permitted to fish in this area (ICES, 2014a).

1.4 Conflicts over fishing

1.4.1 Background and economic significance

Back in the 1970s, Atlantic Mackerel had an image problem in the UK. For a long period of time, people believed that mackerel was a scavenger. Once, there was even folklore telling that mackerel fed on the dead body of sailors. At that time, it was very difficult for the majority of British people to change their mind or diet, being reluctant to depart from more established fish such as cod, haddock or salmon (British Sea Fishing).

However, since the 1990s, the acceptance of Atlantic Mackerel has been increasing for a number of reasons. Firstly, nutrient-wise it has very low mercury but high omega 3 fatty acid, containing nearly twice as much omega 3 per unit weight as does salmon, with a flavour that appeals to some consumers. Also there are many ways to preserve as well as to consume Atlantic Mackerel. It is traded fresh, refrigerated, smoked or canned; and can be eaten fried, broiled or baked (Frimodt, 1995). Finally, since Atlantic Mackerel is pelagic therefore it can be harvested by the fishing gears without destroying the seabed ecology, fitting the choice of eco-conscious consumers. The popularity of this oceanic resource has created a great economic value.

Also, as discussed in previous sections of this chapter, the climate change has lead to warmer ocean waters in the North Atlantic, which possibly increased the presence of mackerels northwestwards in the waters of Iceland and the Faroe Islands. The Faroe Islands is a self-governing country within the Danish Realm yet not part of the EU.

Parallel to the change of migration patterns of NEA Mackerel, in the late of year 2008, triggered by international financial crisis unfolded in 2007 and 2008, all three major Icelandic private commercial banks faced difficulties in refinancing their short-term debts and bank runs, due to the increased perceived risk of Icelandic banking system. It was estimated that relative to the size of its economy, the banking system meltdown in Iceland was the largest experienced crisis by any state in economic history (The Economist, 2008). The financial crisis led to a severe economic depression from year 2008 to 2010 and huge political instability (IMF, 2015).

Additionally, labelled "the ocean cluster" in recent years, fisheries and related sectors are the single most important component of the economy of Iceland, contributing 27.1% of its gross domestic product (GDP) in year 2011 , with more than 40 percent of foreign currency earned from exported goods coming from the export of fish products according to the Icelandic Ministry of Industries and Innovation. It is arguable that all the factors mentioned may cause Iceland to start to have an increasing mackerel quota (IOC, 2011).

To the Faroe Islands, the fishing sector is even more important than that of Iceland. Traditionally, the Faroe Islands has been heavily dependent on fishing activities. The fishing sector normally accounts for about 95% of exports and approximately half of the GDP. Starting from early 2008, the economy of the Faroe Islands began to slow down due to lower amount of fish landings and high oil prices in historical records (CIA, 2014).

The UK has been a traditional major stakeholder in the EU for harvesting NEA Mackerels, taking more than half of the total catch of EU every year. Moreover, the fishing industrial sector in Scotland takes up a great proportion of the whole fishing industry in the UK. A recent inquiry conducted by the Royal Society of Edinburgh (RSE) found that fishing activities yield much greater social, economic and cultural importance to Scotland than it is relative to the rest of the UK (RSE, 2004).

Scotland has just 8.4% of the UK population but the landings of fish at its ports account for over 60% of the total catch in the UK. Many of fishing communities in relatively remote areas such as Fraserburgh, Kinlochbervie or Lerwick are scattered along an extensive coastline. For centuries, these communities have seen fishing as the main source of living and employment (RSE, 2004).

Also, restrictions imposed under the Common Fisheries Policy by the EU affect all EU Member States fishing fleets, but they have particularly limited the Scottish fishing industry in recent years for the demersal or whitefish sector (boats mainly fishing for cod, haddock and whiting), making production capacity of pelagic trawlers fleet idle (RSE, 2004).

On the total level of the EU mackerel fisheries, a 2013 study shows that about 800 EU vessels have a strong economic dependence on Atlantic Mackerel, by which more than 39% of the value of the total catch of a fleet segment were harvested. These vessels maintain over 1,630 jobs and create more than 45 million euros gross added value (Weissenberger, 2013).

Similar to Scotland, the fishery sector has always played a key social and economic role in Norway, both nationally and regionally. It has provided the basis for settlement and employment along the Norwegian coast (FAO). The various degrees of economic dependence on mackerel fishing of all the Coastal States provide historical background and incentives of the confrontation over mackerel fishing, which is described in the next section.

1.4.2 Confrontation and disputes

It has been pointed out that Iceland has a history of conflict with its European neighbours over fishing rights in the North Atlantic waters. The Cod Wars is one of classic examples. During the 1950s and 1970s, the UK and Iceland had a series of confrontations in regard to fishing rights in the North Atlantic, and it is referred to as the Cod Wars. In 1976, the conflict ended with Iceland victory in the sense that the UK recognised the 200 nautical-mile exclusive fishery zone of Iceland (Gilchrist, 1978).

Its latest confrontation has brought Iceland against other Coastal States such as the EU, Norway and the Faroe Islands, over the amount of Atlantic Mackerel to catch. Such confrontation has been named as Mackerel Dispute/Issue. In the mass media, it is not surprising to see such dispute to be labelled as Mackerel War. The brief history of the Mackerel Dispute is described as follows.

Since 1999, under the forum provided by NEAFC, Iceland had requested to be recognised as a Coastal State for the management of Atlantic Mackerel fishing. However, such proposal was not accepted by the other three Coastal States, the EU, Norway and the Faroe Islands, as Iceland was not historically a mackerel-fishing nation.

Denied to be a participant in the discussion held in NEAFC on Atlantic Mackerel TAC share, the negotiations between Iceland and other Coastal States could not really open up. Without approval of the other three coastal nations, Icelandic fishing fleets began fishing Atlantic Mackerel at increasingly large quantities in 2006.

In the end of October 2007, the EU, Norway and the Faroe Islands agreed on long-term management plans for Atlantic Mackerel fishing, advised by ICES. The TAC for mackerel agreed upon for year 2008 amounts to 456,000 tonnes, a reduction of 9% of current TAC (European Commission, 2007).

Starting from 2008, the Government of Iceland began to unilaterally set quotas for Atlantic Mackerel fishing (Ministry of Industries and Innovation of

Iceland). The Icelandic quota for Atlantic Mackerel in 2008 amounted to approximately 112,000 tonnes, up from merely 4,000 tonnes in 2006 and 36,500 tonnes in 2007 (Fiskistofa).

During the Costal States consultation rounds held in 2009, citing the northwestwards shift in Atlantic Mackerel summer feeding migration and abundant presence of Atlantic Mackerel in its EEZ during that period, Iceland requested a large share of catch. Iceland continued to declare a unilateral mackerel quota of 112,000 tonnes for year 2009, which caused the EU to express its "serious concern". The EU regarded Iceland's unilateral action had neither historical or scientific basis (European Commission, 2009a).

During the same consultation rounds, the Faroe Islands followed in turn (Weissenberger, 2013). It also demanded a higher share of the resource. The consultation rounds ended with the withdrawal of the Faroe Islands from the previously agreed long term management plan with the EU and Norway.

In the end of 2009, the EU and Norway were not able to have a mutually satisfactory mackerel quota arrangement for year 2010 (European Commission, 2009b). However, the two parties reached a resolution in the beginning of the next year (European Commission, 2010).

Situation was aggravated by the unilateral declarations of mackerel quotas of Iceland and the Faroe Islands. Iceland increased the TAC to 130,000 tonnes for year 2010, significantly higher than the 2,000 tonnes allotted to it by NEAFC. By pointing to its denied participation to quota negotiations with the other stakeholders and a fast increasing amount of mackerel within its EEZ, Iceland defended this decision. The Faroe Islands also levelled up its quota for its own fleets at 85,000 tonnes for year 2010, which was approximately three times of its previous share. In retaliation, Norway banned landings from Icelandic and Faroese ships in Norwegian ports (FAO Globefish, 2011).

Shortly after the announcement of its TAC, Iceland received invitation and was recognised as a Coastal State for mackerel fishing by the EU, Norway

Table 1.3: The TAC and share set for Atlantic Mackerel agreed in the 5-year arrangement by the EU, Norway and the Faroe Islands (European Commission, 2014b).

Country	TAC (tonnes)	Share (%)
EU	519,512	49.3
Norway	237,250	22.5
Faroe Islands	132,814	12.6
Reserve	164,424	15.6
Total	1,054,000	100

and the Faroe Islands.

During five rounds of consultations that happened between autumn 2011 and early 2012, three series of proposals submitted by the EU and Norway were rejected by Iceland and the Faroe Islands (European Commission, 2012).

In the autumn of 2013, Iceland and the EU had reached a mutual understanding on allocation to Iceland, acceptable by both states, recognising Iceland's demand of at least 11.9% of the TAC. However, not all of the Coastal States could agree on this share for Iceland. Negotiation failed again (Ministry of Industries and Innovation of Iceland).

In March 2014, three of the Coastal States, the EU, Norway and the Faroe Islands signed a 5-year arrangement which Iceland was not a party of. European Commissioner for Maritime Affairs and Fisheries Maria Damanaki referred the signing date of the landmark deal as to a significant day for international fisheries (European Commission, 2014a). According to the 5-year arrangement, the TAC and share set for Atlantic Mackerel is presented at Table 1.3.

Until the completion of the thesis, no significant improvement has made upon the 5-year arrangement of the three coastal nations for all the interest parties. Iceland has still not agreed on the TAC and its share with the other three Coastal States. Table 1.4 summarises the brief history of Mackerel Dispute/Issue. Complementing to the national/regional TACs mentioned in the above paragraphs, Table 1.5 shows the actual catches of different nations in the NEA region from 2001 to 2013 according to ICES (ICES, 2014b).

As can be seen from Table 1.5, over the decade, the total catch has seen a major decrease until around 2006 to 449,700 tonnes then a significant increase in recent years, from 666,800 in 2001 to 923,700 tonnes in 2013.

In 2001, the EU and Norway took up approximately 90% of the total catches of mackerel, amounting to approximately 63% and 27% respectively. However, both of their relative shares have kept decreasing dramatically because of the impact brought by the fishing activities of Iceland and the Faroe Islands. As a result, in 2013, the relative shares of the EU and Norway accounted for around 36% and 18% respectively, aggregated to 54%. The amount of harvest in absolute terms for both the EU and Norway changed from approximately 600,000 tonnes in 2001 to approximately 500,000 tonnes in 2013. While, catches of Iceland and the Faroe Islands have grown from almost zero percent to approximately 17% and 16% in year 2013, respectively. The UK remains the largest stakeholder of the EU, representing almost half of the catches of the EU throughout the years. The share of Russia has remained relatively stable, ranging from approximately 6% to 9% in the decade. In 2013, Greenland had its unprecedented catch of mackerel, amounting to 52,800 tonnes, which account for almost 6% of the total catch.

Table 1.4: Brief history of Mackerel Dispute/Issue.

Year	Party	Event
2007	EU, Norway, Faroe Islands	Long-term management plans for Atlantic Mackerel fishing was established; TAC for year 2008 amounts to 456,000 tonnes, a reduction of 9% of the current TAC. Iceland was not part of this management plan as it was not recognised as a Coastal State for mackerel fishing.
2008	Iceland	The Government of Iceland began to unilaterally set quotas for Atlantic Mackerel fishing, at 112,000 tonnes for year 2008.
2009	Iceland, Faroe Islands	Iceland continued to declare a unilateral mackerel quota of 112,000 tonnes for year 2009, which caused the EU to express its "serious concern"; Faroese withdrew from the previously agreed long term management plan with the EU and Norway and also demanded a higher share of the catch.
2010	Iceland, Faroe Islands	Iceland and the Faroe Islands unilateral declared their mackerel quotas for year 2010, amounting to 130,000 and 85,000 tonnes respectively, significantly greater than the quotas they set before. The European Commission expressed its "grave concern" over the Faroese quota.
2010	Norway	Norway banned landings of mackerel from Icelandic and Faroese vessels.
2010	EU, Norway, Iceland, Faroe Islands	Iceland received invitation and was recognised as a Coastal State for mackerel fishing by the EU, Norway and the Faroe Islands.
2012	EU, Norway, Iceland, Faroe Islands	Despite five rounds of consultations that happened between autumn 2011 and early 2012, no resolution has been reached. Three proposals submitted by the EU and Norway were rejected by Iceland and the Faroe Islands.
2014	EU, Norway, Faroe Islands	Landmark 5-year mackerel deal was agreed between the three Coastal States, leaving Iceland alone. The TAC agreed by the three parties amounts to 1,054,000 tonnes. The shares for the EU, Norway and the Faroe Islands are: 49.3%, 22.5% and 12.6% respectively, leaving 15.6% as "reserve".

Table 1.5: NEA Mackerel actual landings (in thousand tonnes) and relative shares for different Coastal States from year 2001 to 2013 (ICES, 2014b).

	EU																	
	UK		Others		Subtotal		Norway		Iceland		Faroe Islands		Russia		Greenland		Total	
Year	Landing	%	Landing	%	Landing	%	Landing	%	Landing	%	Landing	%	Landing	%	Landing	%	Landing	%
2001	192.6	28.9	228.0	34.2	420.6	63.1	180.4	27.1	-	-	24.2	3.6	41.6	6.2	-	-	666.8	100.0
2002	194.0	28.1	246.7	35.7	440.8	63.8	184.3	26.7	0.1	0.0	19.8	2.9	45.8	6.6	-	-	690.7	100.0
2003	183.0	30.5	199.6	33.3	382.6	63.7	163.4	27.2	0.1	0.0	14.0	2.3	40.0	6.7	-	-	600.2	100.0
2004	214.8	35.8	164.5	27.5	379.3	63.3	157.4	26.3	-	-	13.0	2.2	49.5	8.3	-	-	599.2	100.0
2005	152.8	33.6	132.3	29.1	285.1	62.6	119.7	26.3	0.4	0.1	9.8	2.1	40.5	8.9	-	-	455.4	100.0
2006	95.8	21.3	182.1	40.5	277.9	61.8	122.0	27.1	4.2	0.9	12.1	2.7	33.6	7.5	-	-	449.7	100.0
2007	133.7	23.9	207.4	37.1	341.1	61.1	131.7	23.6	36.7	6.6	13.4	2.4	35.4	6.3	-	-	558.3	100.0
2008	112.4	19.3	193.3	33.1	305.6	52.4	121.5	20.8	112.3	19.2	11.3	1.9	32.7	5.6	-	-	583.5	100.0
2009	157.0	21.7	272.3	37.7	429.3	59.4	121.2	16.8	116.2	16.1	14.1	1.9	41.4	5.7	-	-	722.2	100.0
2010	160.4	18.7	211.5	24.7	371.9	43.4	234.0	27.3	121.0	14.1	71.0	8.3	59.3	6.9	-	-	857.2	100.0
2011	181.0	19.5	185.8	20.0	366.8	39.4	208.1	22.4	159.3	17.1	122.1	13.1	73.6	7.9	0.1	0.0	929.8	100.0
2012	169.7	19.5	189.6	21.7	359.3	41.2	176.0	20.2	149.3	17.1	107.6	12.3	74.6	8.6	5.3	0.6	872.2	100.0
2013	163.8	17.7	167.5	18.1	331.3	35.9	164.6	17.8	151.2	16.4	143.0	15.5	80.8	8.7	52.8	5.7	923.7	100.0

Chapter 2

Research problem

Based on the historical facts and discussions presented in Chapter 1, the interest parties of NEA Mackerel fishing can be divided into two distinct players, i.e., Iceland (hereinafter referred to as "Player 1") and the Coalition consisting of the EU, Norway and the Faroe Islands (hereinafter referred to as "Player 2"). The essence of the dispute is that one party does not agree with the TAC and its share set by the other party, for instance, Iceland has continuously been disputing on the TAC and its share set by the EU, Norway and the Faroe Islands.

Recognising such political reality as well as the given facts and data, we want to know how much should each player harvest in its own best interest. To clarify this proposition, we formulate such problem into questions in order to address them accurately. In order to see the viability of cooperation between Player 1 and Player 2, we need to compare the outcomes of two scenarios, namely, cooperative scenario vs. non-cooperative scenario.

- First, in the cooperative scenario, what is the financial benefit, the effects on mackerel stock levels and the amount of harvest?
- Second, in the non-cooperative scenario, what is the financial benefit of each player acting in its own best interest? And what are the effects on mackerel stock levels and the amount of harvest?

Intuitively, one of the criteria for players to cooperate is that each player benefits from cooperation. In other words, each player ends up with more value of catch than it acts on each own and competes with each other. And this leads to a greater total value of catch. This is the very foundation allowing cooperation to exist. We propose the two questions above so that we are able to know if the financial benefit under cooperation is greater than the aggregated financial benefit of the two players without cooperation. However, another condition for the viability of cooperation is that, each player cannot financially worsen off from cooperating. Therefore, we propose the research question below.

- Third, given the argument as above, assuming the financial benefit under cooperation is large enough for cooperation to exist, what should each player's share of the financial benefit be?

The three bulleted questions are the research problem the thesis is trying to address. In Chapter 3, we layout the theoretic basis for solving the research problem.

Chapter 3

Theoretical basis

3.1 Fishery economics

Natural fish stock is a typical common good as it has both rivalrous and non-excludable nature. In economics, a good is rivalrous when the consumption of such good by one person precludes its consumption by another; whereas exclusivity means that it is possible to stop a person who have not paid for it from having access to it.

The rivalrous nature of common fish stock results in externality as well. That is, the catch of one extra unit of the fish stock by one person results in one extra unit less for others to fish. Therefore, without management and regulation, fishery stock in public waters such as lakes, rivers or oceans cannot prevent people from accessing and racing to catch it. This is referred to as "open access" case in the context of fishery. Such individual rationale according to each self's interest usually behaves in contrary to the best interests of the whole group and always result in over-exploitation and non-sustainability, i.e., overfishing and stock collapse in the fishery case. Such phenomenon is denoted as tragedy of the commons by American ecologist Garrett Hardin (1968). By management and regulation, individual fisherman acts under co-ordination towards collective interest as a single owner of the stock, and this is referred to as the "sole-owner" case in fishery management.

In economics, to correct the market failure resulted from open access to a common resource, government intervention such as management and regulation is needed. There are several approaches to deal with the issue such as privatisation, access limit and etc. In the case of fishery, the task of sustainable utilisation of fishery stock lies in the notion of fishery management.

FAO defines the goals of fishery management in normative terms, that is, it should be based on political objectives with transparent priorities (FAO, 2009). Here is a shortlist of political objectives when exploiting a fish resource:

- Maximise sustainable biomass yield (or maximum sustainable yield in short, MSY)
- Maximise sustainable economic yield (or maximum economic yield, MEY)
- Secure and increase employment
- Secure protein production and food supplies
- Increase export income

Nevertheless, it should be noted that such political goals can conflict with each other (Duzgunes and Erdogan, 2008).

In the thesis, to answer the research questions, we are most interested in MSY and MEY. According to Organisation for Economic Co-operation and Development (OECD), MSY is the largest long-term average catch or yield that can be taken from a stock under prevailing ecological and environmental conditions. The concept of MSY aims to keep the stock size at maximum growth rate by catching the reproduced amount of fish that would be introduced to the stock in order to let the stock continue to reproduce at maximum growth rate indefinitely. MEY is reached by maximising the difference between total revenue and total cost. In other words, where marginal revenue is equal to marginal cost. To work out MSY and MEY, bioeconomic modelling which establishes a mathematical relationship between fishing activities (harvest) and the change of the stock size, can be adopted. The bioeconomic model we adopt for the case in the thesis is presented in Chapter 4.

Though MSY and MEY can be calculated based on bioeconomic models and used to make informed decisions, precautionary principle should also be taken into account in decision-making process. In a general sense, the precautionary principle suggests that when an action or policy could potentially cause harm, it should not be act upon unless it can be scientifically proven to be safe. Specific to fishery management, FAO advises that the precautionary principle should be applied when "ecosystem resilience and human impact are difficult to forecast and hard to distinguish from natural changes" (Cochrane and Garcia, 2009).

To implement fishery management policies, there are broadly three types of management, under which many techniques are potentially useful. The management techniques are summarised in Table 3.1.

Table 3.1: Fishery management techniques.

Output/Harvest	Input/Effort	Economic incentive
Total allowable catch	Licence	Tax
Individual catch quotas	Vessel characteristica	Subsidy
Individual transferable quotas	Time restriction	
	Marine reserves	

Different types of management techniques under each management category have both advantages and disadvantages and aim to achieve different objectives. The principles of the management techniques are not the focus of the thesis and a description of NEA fishery management regime of the case is given in Chapter 1.

3.2 Game theoretic perspective

As discussed in previous section, to correct the market failure caused by open access to a common fish stock that leads to over-exploitation, it requires government intervention. However, in the case of straddling fish stock such as

Atlantic Mackerel, there is no “international government” which has superior political power over the sovereignty of Coastal States. Therefore, to effectively manage a common fish stock, international cooperation is needed. In the context of game theory, we refer the sole-owner case to as cooperation.

There are two issues that involve in the problem of cooperation: building the coalition and sharing benefits (bearing losses or costs). Based on game theoretic analysis, a stable coalition of cooperative management regime can only be established under certain circumstances. The most crucial condition is referred to as the rationality condition, which asserts that for individual players, the payoff from cooperation must be at least as great as under non-cooperation. For instance, each player cannot worsen off from cooperating, which also leads to a greater or equal benefit than the aggregated individual total benefit without cooperation.

However, how to split the benefits affects the payoff of individual players. Several guiding principles of sharing benefits are available such as: egalitarian method, altruistic method, Shapley value and etc.

As the name tells, egalitarian method splits the benefits based on the egalitarian principle, i.e., to share the benefit equally among the players. Altruistic allocation asserts that the share of each player under cooperation should be equal to each stand-alone benefit over the total sum of the stand-alone benefit. Shapley value is a method that captures the importance of each player contribution to the coalition. The mathematical formulations of all three different methods are presented in Chapter 6.

However, under cooperation, by a benefit allocation method, if the benefit of one player is worsened off comparing to its stand-alone benefit and results in a loser-winner situation, side payment can be introduced. If such side payment paid out by the winner can potentially make the loser financially indifferent whether joining the coalition or not, yet still make the winner better off than standing alone, then such side payment increase the scope for bargaining. Also, it enhances the flexibility and the resilience of the cooperation.

3.3 Literature review

As discussed in previous section of this chapter, MSY aims to keep the stock size at maximum growth rate by catching the largest reproduced amount so that to maintain the stock sustainable in the long term. Such mechanism of managing fish stock has traditionally become a main objective of fishery management. The 1950s has seen the most of MSY's popularity in history (Larkin, 1977). In 1958, it was established by UN Conference on the Law of the Sea that MSY serves as the basic objective in fisheries management (Mardle et al., 2002). Later on, numerous regional fisheries management organisations as well as individual countries adopted MSY as a primary management goal (Mace, 2001). FAO also granted considerable support and emphasis to fishery management based on MSY (Punt and Smith, 2001; Hoshino, 2010).

However, in the literature, the appropriateness and effectiveness of setting MSY as an management objective was challenged in 1970s (Gulland and Boerema, 1973; Doubleday, 1976; Beddington and May, 1977; Larkin, 1977; Sissenwine 1978). Among other things, one of the disadvantages of implementing fishery management based on MSY is misleading and undesirable from economic point of view. Scott Gordon argued that to maximise resource rent, the optimal allocation of fishing effort to a fishery would occur at the point at which marginal cost equals marginal revenue, which is the MEY (Gordon, 1954). As at MEY, the size of fishery stock that produces the largest discounted economic profit is normally greater than the stock size of generating MSY. Such argument has been repeatedly demonstrated in the literature (Clark, 1990; Grafton et al., 2007). In the recent decades, MEY has gained more attention in the literature and among policy makers. It was even argued by Dichmont et al. (2010) that fisheries management has been experiencing “a paradigm shift from a focus on managing the resource to a focus on managing resource users” (Hoshino, 2010).

Chapter 4

Bioeconomic model

According to the theoretical framework discussed in Chapter 3, a bioeconomic model needs to be adopted to capture the essential properties of NEA Mackerel. The size of NEA Mackerel stock is subject to change. The major forces contributing to this change are its biological expansion, mortality and human fishing activities. These processes are highly dynamic and interrelated to each other, such that cannot be encompassed by simple continuous time models. Also, as presented in Chapter 1, the fishable stock of NEA Mackerel may only occur several years after the spawning of the existing adult population. Moreover, the entire life history of mackerel and other organisms is generally subject to strong seasonal or period influences such as reproduction, migration and so on (Clark, 1990; Clark, 2010).

To avoid to model such complicated biological dynamics, in simplified terms, that is, to ignore the biological inter-relationship between mackerel birth, growth and death happening simultaneously to the stock, the population change of NEA Mackerel can be related only to the variable of time, that is, a lumped parameter model. It can further be conceptualised that, there are time cycles, between which the population size at one cycle is a function of the population size at the previous cycle, such as:

$$x_{t+1} = f(x_t)$$

where x denotes the mackerel stock at t-th cycle. Such model is called discrete-time metered model (Clark, 1990). However, within each cycle we take human fishing activities into account. To specifically address the mackerel case, our bioeconomic model for NEA Mackerel is

$$R_{t+1} = F(S_t), \quad t = 0, 1, 2, \ldots \tag{4.0.1}$$

$$S_t = R_t - H_t, \quad S_0 \text{ given} \tag{4.0.2}$$

where R_t denotes recruitment in cycle t. Recruitment is the amount of mature fish population, which is ideally subject to human fishing activities. H_t is the harvest or specifically referred to as fish landed (landings) in the fishery context, which is the amount of catches taken from the recruitment. Deducting harvest from recruitment, what is left in the fish stock is referred to as escapement, S_t, which constitutes the spawning population, being potentially the birth-givers for the stock in the next period. Figure 4.1 illustrates the relationship between recruitment, harvest and escapement in discrete time cycles. In the thesis, time cycles (periods) are defined as years because NEA Mackerel spawns once a year as introduced in Chapter 1.

The function $F(\cdot)$ captures the relationship between escapement and recruitment between the cycles. It is also named as the spawner-recruit or stock-recruitment relationship according to fishery economics literature (Clark, 1990). The stock-recruitment function that we adopt is the one proposed by Ricker in 1954 and can be written as

$$F(S) = aSe^{-bS} \tag{4.0.3}$$

where a is the recruitment per unit of escapement and b describes how recruitment levels decline with increasing escapement levels (Paz and Larraneta, 1992). Also, this model has the property of overcompensation, which means that a high escapement level results in a decline in recruitment level for the next period. We believe that this property of Ricker's model captures the cannibalistic behaviour of NEA Mackerel as described in Chapter 1. Figure 4.2 is the graphical illustration of Ricker's model.

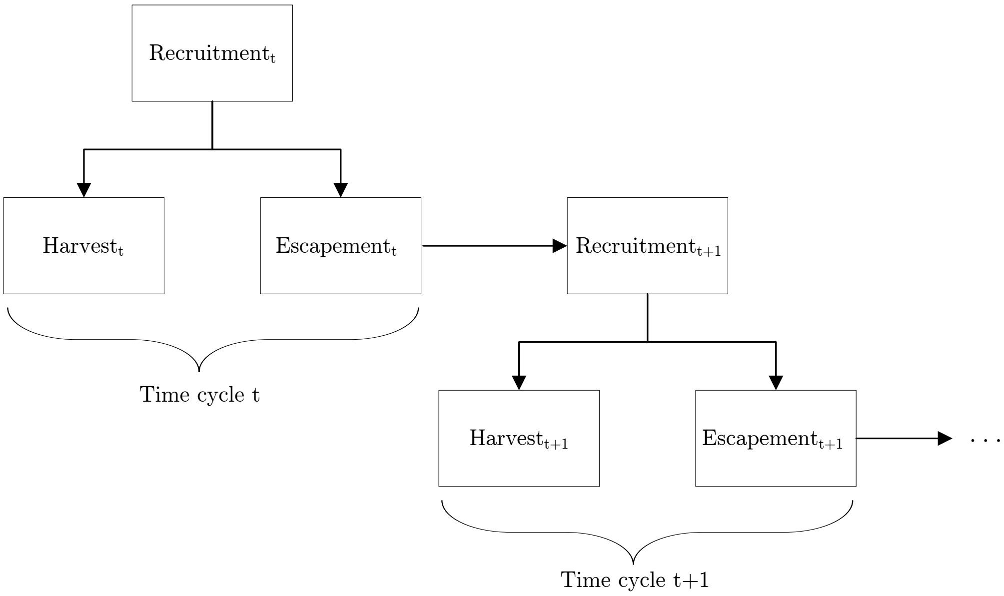

Figure 4.1: Graphical illustration of the discrete-time metered model.

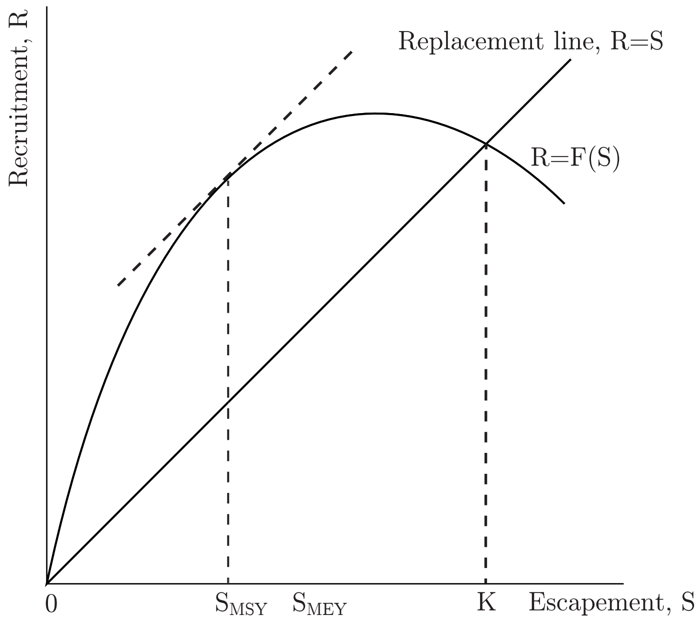

Figure 4.2: Graphical illustration of Ricker's stock-recruitment model.

As can be seen from Figure 4.2, MSY is reached when the first order derivative of the stock-recruitment function is equal to one, $F'(S_{MSY}) = 1$, which maximises the vertical distance $F(S) - S$ between the recruitment curve $R = F(S)$ and the replacement line $R = S$ (Clark, 2010). Point $S = K$ is the equilibrium of an unexploited stock, which is termed as the carrying capacity of the stock. The point S_{MEY} is the escapement level reached when the discounted perpetual economic profit is maximised, i.e., MEY is reached. MEY escapement level S_{MEY} always lies in between the MSY escapement level S_{MSY} and the carrying capacity K.

Also, from Equation 4.0.2 it can be seen that human fishing activities are incorporated within each cycle; whereas the biological properties of mackerel, such as birth, growth and death, are manifested as the parameters a and b of the Ricker's model in Equation 4.0.3, which cause the changes of mackerel stock sizes from one cycle to another in Equation 4.0.1. Combining all the concepts discussed above, the bioeconomic model we adopt is an aggregated biomass lumped parameter stock-recruitment model.

As mentioned in Chapter 2, Player 1, namely Iceland, competes for mackerel resource in the NEA with Player 2, the coalition consisting of the EU, Norway and the Faroe Islands. In the next sections of this chapter, we further detail our mathematical analysis into two scenarios respectively: cooperative and non-cooperative.

4.1 Cooperative scenario

Since the bioeconomic model we adopt is complicated, under this section we present and discuss the mathematical concepts and components of the bioeconomic model separately.

Net present value

Harvest is the amount of mackerel caught, yielding economic value. In this scenario, it is in the best interest of all interest parties to collaborate together and to maximise the net present value (NPV) of the future mackerel landings. NPV is defined as the discounted future cash flows of net profit earned from mackerel landings:

$$NPV = \sum_{t=0}^{\infty} \gamma^t \Pi(t)$$

where γ is the discount factor and $\Pi(t)$ is the net profit of time cycle t.

Discount factor

If K_t is the future payment of K_0 in a discrete time period t, compounded with interest rate represented by r, then

$$\begin{aligned} K_t &= (1+r)^t K_0 \Leftrightarrow \\ K_0 &= \frac{1}{(1+r)^t} K_t \Leftrightarrow \\ K_0 &= \left(\frac{1}{1+r}\right)^t K_t \Leftrightarrow \\ K_0 &= \gamma^t K_t \end{aligned}$$

where γ is the discount factor, expressed as

$$\gamma = \frac{1}{1+r}$$

Net profit function

Net profit from mackerel landings for a given period t can be expressed as the difference between total revenue TR earned from selling landed mackerels and the total cost TC associated to effort inputs of harvesting the mackerels, such as number of vessels. Therefore, it can be written as:

$$\Pi(t) = TR_t - TC_t \tag{4.1.1}$$

where total revenue is the price p of mackerel times the amount of mackerel landings, for instance,

$$TR_t = pH_t \tag{4.1.2}$$

and here, we assume total cost is proportionate with effort E

$$TC_t = cE_t \tag{4.1.3}$$

where c is the cost parameter, expressed as cost in monetary terms per unit of effort.

Harvest and effort

Here we specify the harvest production function as

$$H_t = qE_t x_t \tag{4.1.4}$$

where E is predefined as fishing effort, i.e., number of vessels, x is the size of mackerel stock at time t and q is a catchability coefficient, which represents the share of mackerel landings H from mackerel stock x by one standard vessel within time cycle t. For the remaining of the thesis, we define the catchability coefficient to be identical to one, i.e., $q \equiv 1$, therefore Equation 4.1.4 becomes

$$H_t = E_t x_t$$

By doing so, we need to change the way we measure fishing effort. Fishing effort E is likely to change within each time cycle, thus for any t-th cycle

$$E = \int_0^t E(\tau) d\tau \tag{4.1.5}$$

where $\tau = 0$ is the beginning of the time cycle and $\tau = t$ is the end. The stock $x(\tau)$ at $\tau = 0$ is the recruitment, $x(0) = R$, and at $\tau = t$ the escapement, $x(t) = S$. Also, for the duration of the time cycle the change of the stock is the harvest, meaning that

$$\frac{dx}{d\tau} = -E(\tau)x(\tau), \quad 0 \leq \tau \leq t$$

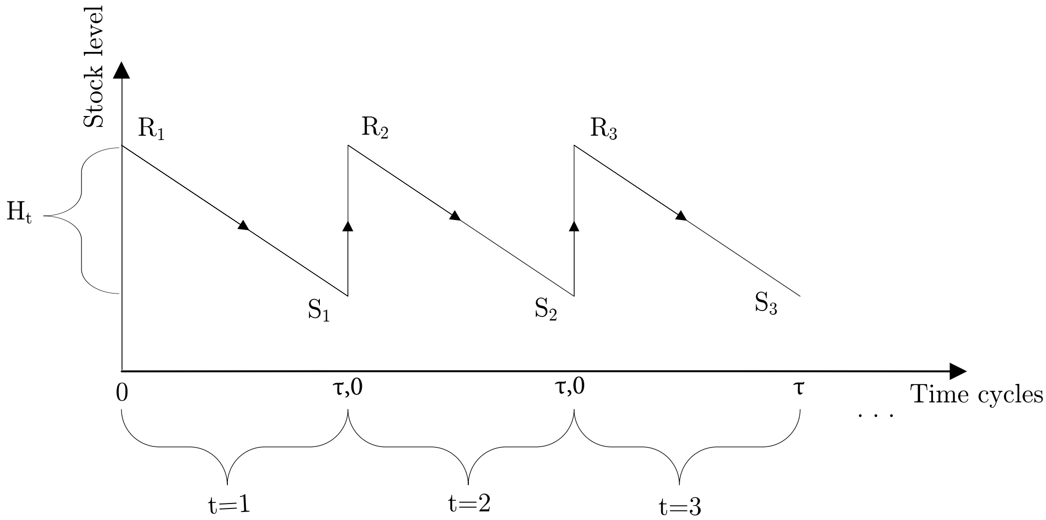

Figure 4.3: Graphical illustration of the relationship between recruitment, escapement and harvest within a time cycle.

or equivalently

$$E(\tau) = -\frac{1}{x(\tau)}\frac{dx}{d\tau} \tag{4.1.6}$$

Figure 4.3 illustrates such process.

Substituting Equation 4.1.6 in 4.1.5, we obtain

$$\begin{aligned} E = \int_0^t E(\tau)d\tau &= \int_0^t -\frac{1}{x(\tau)}\frac{dx}{d\tau}d\tau \\ &= \int_{x(0)}^{x(t)} -\frac{1}{x}dx = \int_R^S -\frac{1}{x}dx \\ &= \int_S^R \frac{1}{x}dx = \Big[ln(x)\Big]_S^R \end{aligned}$$

or equivalently

$$E = ln\left(\frac{R}{S}\right) \tag{4.1.7}$$

It can be seen from the Equation 4.1.7 that for any given time cycle fishing effort is equal to the natural logarithm of the ratio of recruitment and escapement. Therefore, the general form of Equation 4.1.7 for t-th cycle is

$$E_t = ln\left(\frac{R_t}{S_t}\right) \tag{4.1.8}$$

NPV maximisation

As discussed previously in the cooperation scenario, all interest parties are bound to collaborate together, aiming to maximise the NPV of their mackerel landings over infinite future periods. Before jumping into the maximisation problem immediately, we need to substitute and rearrange the mathematical formulation of the NPV in steps.

First, we need to obtain the total cost TC_t as a function of recruitment R_t and harvest H_t, therefore we substitute Equation 4.1.8 into Equation 4.1.3, and obtain

$$TC_t = cE_t = c{\cdot}ln\left(\frac{R_t}{S_t}\right)$$

or equivalently

$$TC(R_t, H_t) = c{\cdot}ln\left(\frac{R_t}{R_t - H_t}\right) \tag{4.1.9}$$

since escapement S of period t has already been defined as the difference between harvest H and recruitment R of period t. Equation 4.1.9 can also be expressed as

$$TC(R_t, H_t) = \int_{R_t - H_t}^{R_t} \frac{c}{x} dx \tag{4.1.10}$$

Second, we substitute Equation 4.1.10 and 4.1.2 into Equation 4.1.1, and we obtain net profit as a function of recruitment and harvest

$$\Pi(R_t, H_t) = pH_t - \int_{R_t - H_t}^{R_t} \frac{c}{x} dx \tag{4.1.11}$$

Now we can mathematically formulate the maximisation problem. The objective function NPV can be expressed as a function of recruitment and harvest. However, such problem is constrained by the stock-recruitment relationship. Overall, it can be presented as follows:

$$\begin{aligned} \underset{H_t}{\text{maximise}} \quad & \sum_{t=0}^{\infty} \gamma^t \Pi(R_t, H_t) \\ \text{subject to} \quad & R_{t+1} = F(R_t - H_t) \\ & 0 \ \le \ H_t \ \le \ R_t \end{aligned} \tag{4.1.12}$$

To unfold the maximisation problem, we re-write Equation 4.1.11 as follows:

$$\begin{aligned} \Pi(R_t, H_t) &= pH_t - \int_{R_t - H_t}^{R_t} \frac{c}{x} dx \\ &= \int_{R_t - H_t}^{R_t} (p - \frac{c}{x}) dx \end{aligned} \tag{4.1.13}$$

because harvest is the change of the stock size from recruitment to escapement. Next, we define the marginal net profit $\pi(x)$ as

$$\pi(x) = p - \frac{c}{x}$$

where x is the stock size. Assuming that $\phi(x)$ is the antiderivative of $\pi(x)$ we can express Equation 4.1.13 as below:

$$\Pi(R_t, H_t) = \int_{R_t - H_t}^{R_t} \pi(x) dx = \Big[\pi(x)\Big]_{R_t - H_t}^{R_t} = \phi(R_t) - \phi(R_t - H_t)$$

where

$$\phi'(x) = \pi(x)$$

Therefore

$$NPV = \sum_{t=0}^{\infty} \gamma^t (\phi(R_t) - \phi(R_t - H_t)) \tag{4.1.14}$$

Using the stock-recruitment constraint $R_t = F(R_{t-1} - H_{t-1})$ for $t \geq 1$, we have

$$\begin{aligned}
\sum_{t=0}^{\infty} \gamma^t \phi(R_t) &= \phi(R_0) + \sum_{t=1}^{\infty} \gamma^t \phi(F(R_{t-1} - H_{t-1})) \\
&= \phi(R_0) + \sum_{t=0}^{\infty} \gamma^{t+1} \phi(F(R_t - H_t))
\end{aligned}$$

Finally, combining the equation above with Equation 4.1.14, we obtain

$$\begin{aligned}
NPV &= \phi(R_0) + \sum_{t=0}^{\infty} \gamma^{t+1} \phi(F(R_t - H_t)) - \sum_{t=0}^{\infty} \gamma^t (\phi(R_t - H_t)) \\
&= \phi(R_0) + \sum_{t=0}^{\infty} \gamma^t [\gamma \cdot \phi(F(S_t)) - \phi(S_t)]
\end{aligned}$$

Now we are enabled to set out the optimal harvest strategy, namely, to choose the escapement level S_t for each time cycle $t = 0, 1, 2, \ldots$ by maximising

$$\gamma \cdot \phi(F(S_t)) - \phi(S_t)$$

If $S_t = S^*$ maximises this expression, the optimal strategy is given by

$$\begin{aligned}
H_0 &= R_0 - S^* \\
H_t &= F(S^*) - S^* \quad \text{for} \quad t \geq 1
\end{aligned}$$

that is, for the initial period the harvest is the difference of the initial recruitment subtracted by optimal escapement; for the remaining periods the optimal steady state is reached, where the optimal harvest is the difference of the optimal recruitment deducted by optimal escapement. This immediate approach to steady state is referred to the bang-bang approach with equilibrium escapement S^* (Clark, 2010). Since $\phi'(x) = \pi(x)$, by taking the first order derivative and equate it to zero, we obtain

$$\begin{aligned}[\gamma \cdot \phi(F(S^*)) - \phi(S^*)]' = 0 \Leftrightarrow \\ \gamma \cdot \phi'(F(S^*)) \cdot F'(S^*) - \phi'(S^*) = 0 \Leftrightarrow \\ \gamma \cdot \pi(F(S^*))F'(S^*) = \pi(S^*)\end{aligned}$$

or equivalently

$$F'(S^*)\frac{\pi(F(S^*))}{\pi(S^*)} = \frac{1}{\gamma} \tag{4.1.15}$$

This formula is called the Golden Rule. The Golden Rule points to an economically optimal equilibrium escapement level S^* (Clark, 2010).

4.2 Non-cooperative scenario

In the non-cooperative scenario, each player acts on its own, aiming to maximise its own NPV, which is potentially detrimental to other players. For this case, as previously defined in Chapter 2, there are only two players involved, i.e., Iceland as Player 1 and the coalition of EU, Norway and the Faroe Islands as Player 2.

To simplify the issue of mackerel presence in different EEZ of the Coastal States as well as in the international waters during different seasons, we ignore the fact that NEA Mackerel travels through the high seas. That is, they reside either in the EEZ of Player 1 or in the EEZ of Player 2 and never appear in the international waters. This is a fair assumption according to Chapter 1 because the size of the international water territory where NEA Mackerel potentially travels through is relatively small and remote (the "Banana Hole" of the Norwegian Sea and the Barents Sea "Loophole" in Figure 1.7), compared to the rest habitat of NEA Mackerel. Please be reminded that such simplification does not change the common goods nature of NEA Mackerel due to its migratory behaviour.

To simply ration the mackerel stock between the players, we introduce a parameter θ_i that defines the share of NEA Mackerel stock that only appears in the EEZ of Player i for a whole year. Since in the case of the thesis, there are only two players, therefore $\theta_2 = 1 - \theta_1$. Parameter θ consists of two dimensions, i.e., time and space. For the dimension of time, based on Chapter 1, it is known that mostly during the summer season, NEA Mackerel travels northwestwards to feeding grounds and appear in Icelandic waters. This is when Icelandic fishermen most actively engage in fishing mackerels. Also, for the spatial dimension, for now let us assume approximately half of the total mackerel stock appears in the Icelandic waters during the summer feeding season. Therefore, the portion of NEA Mackerel that Iceland could potentially harvest during a year is $\theta_1 = 1/4 \times 1/2 = 1/8$ or 12.5%. Therefore, Player 2 can enjoy the rest portion of the stock for the same year, that is, $\theta_2 = 1 - \theta_1 = 87.5\%$. However, please note that such θ_i estimates may not be a true representation of the reality because mackerel migration patterns are highly dynamic and difficult to measure and also subject to change from year to year. To overcome such problem, sensitivity analysis for θ is performed in Chapter 7.

As discussed in Chapter 1, though NEA Mackerel is a straddling fish stock, that is, it migrates through more than one EEZ, the stock-recruitment relationship still holds for the aggregated population level, that is, $R_{t+1} = F(S_t)$. With the introduction of θ_i, within one cycle, we are enabled to work out the share of the recruitment R_i for each player, $R_i = \theta_i R$. After mackerel harvesting activities H_i performed by both players, the escapement of the fish from EEZ of each player S_i can be calculated and combined in the end of the cycle, $S_i = R_i - H_i$, $S = \sum_{i=1}^{2} S_i$. Through the stock-recruitment relationship on the aggregated stock level, total recruitment for the next cycle is determined by the total escapement of the current cycle. Then, cycle t repeats. Figure 4.4 illustrates this process.

Given the fact that one of the two players knows the TAC (an approximation of actual harvest) of its counterpart, depending on who announces the TAC first. If the knowing player believes in the stock-recruitment relationship

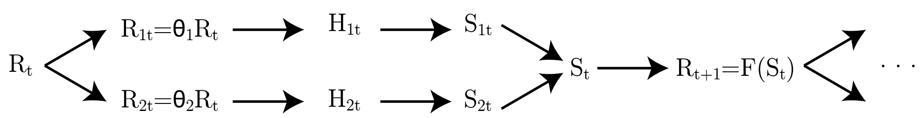

Figure 4.4: Graphical illustration of the stock-recruitment relationship in the non-cooperative scenario.

specified in the thesis, then the knowing player can maximise its own NPV by determining its own escapement, given the fact that it knows the TAC therefore the escapement of its counterpart ($S_i = R_i - H_i$). In reality, the timing of announcing TAC is subject to administrative demand, policy implementation and other practical issues. Also, TAC is usually announced one year before the fishing year. If each player has such agenda of maximising its own NPV based on the harvest of the other player, each player would most likely to calculate its own TAC based on the predicted harvest of the counterpart, i.e., the previous year's actual harvest of the counterpart. That is to say, each player would rather not wait the announcement of the TAC of its counterpart for next fishing year but acts on the other player's historical harvest. In the thesis, since the Golden Rule solves for the escapement S and determines the harvest H, therefore the optimal strategy for each player mentioned as above is expressed in the escapement level S_i rather than the harvest level H_i. And such strategy is named as optimal escapement strategy for both of the players. Such maximisation problem can be formulated as follows:

$$
\begin{aligned}
\underset{H_{it}}{\text{maximise}} \quad & \sum_{t=0}^{\infty} \gamma^t \Pi(R_{it}, S_{it}) \\
\text{subject to} \quad & H_{it} = R_{it} - S_{it} \\
& S_t = \sum_{i=1}^{2} S_{it} \\
& R_{t+1} = F(S_t) \\
& R_{it} = \theta_i R_t \\
& 0 \ \leq \ H_{it} \ \leq \ R_{it}
\end{aligned}
\tag{4.2.1}
$$

The underlying assumption of this maximisation problem is that harvest of the counterpart will not change in the future and so is the escapement level. However, if both counterparts implement the same maximisation strategy, each counterpart's harvest is likely to change. Therefore, such self-NPV-maximisation would only hold temporarily for one cycle because the other player will react based on the new information, generated by its counterpart. Such dynamic problem repeats for n periods until steady-state is reached.

To make it clear, here we adopt mathematical notation as example to clarify what we have discussed above. Initially, i.e., $t = 0$, Player 1 determines its own optimal escapement strategy $S^*_{1,0}$ based on the prediction that Player 2 will harvest the same amount as last cycle, therefore the escapement $S_{2,0}$ of Player 2 can be known by Player 1. In the next cycle, $t = 1$, Player 2 is enabled to determine its own optimal escapement strategy $S^*_{2,1}$ also based on the prediction that Player 1 will harvest the same as last cycle, $t = 0$, thus the escapement $S_{1,1}$ of Player 1 is known to Player 2. This process repeats for n periods until no player can further change its harvest amount in order to increase its NPV, resulting in steady-state.

Having defined the individual player's NPV maximisation problem as well as how each player will reach to its own optimal escapement strategy S^*_i we can derive the Golden Rule for the above maximisation problem.

The cost function of player i is specified similar to the cost function in the cooperative scenario:

$$TC(R_{it}, S_{it}) = c_i{\cdot}ln\left(\frac{R_{it}}{S_{it}}\right)$$

which can also be expressed as

$$TC(R_{it}, S_{it}) = \int_{S_{it}}^{R_{it}} \frac{c_i}{x_i} dx_i$$

the mathematical proof for deriving the cost function of each player is similar to the one demonstrated in the cooperative scenario.

The net profit of each player can be written similarly to the one in the cooperative scenario as well:

$$\begin{aligned}\Pi(R_{it}, S_{it}) &= pH_{it} - \int_{S_{it}}^{R_{it}} \frac{c_i}{x_i} dx_i \\ &= \int_{S_{it}}^{R_{it}} (p - \frac{c_i}{x_i}) dx_i\end{aligned}$$

where again,

$$\pi(x_i) = p - \frac{c_i}{x_i}$$

$\pi(x_i)$ is the marginal net profit of player i when the stock is at x. Assuming that $\phi(x_i)$ is the antiderivative of $\pi(x_i)$, we can express the net profit of player i as

$$\Pi(R_{it}, S_{it}) = \int_{S_{it}}^{R_{it}} \pi(x_i) dx_i = \Big[\pi(x_i)\Big]_{S_{it}}^{R_{it}} = \phi(R_{it}) - \phi(S_{it})$$

where

$$\phi'(x_i) = \pi(x_i)$$

Therefore,

$$NPV_i = \sum_{t=0}^{\infty} \gamma^t (\phi(R_{it}) - \phi(S_{it})) \tag{4.2.2}$$

Using the constraint of the recruitment of player i, $R_{it} = \theta_i F(S_{t-1})$ for $t \geq 1$, we have

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

Finally, combining the equation above with Equation 4.2.2, we obtain

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

Now player i is enabled to set out the optimal escapement strategy given the assumption that its counterpart will retain its previous cycle escapement strategy, namely, player i to choose the escapement level S_{it} for each time cycle $t = 0, 1, 2, \ldots$ by maximising

$$\gamma \cdot \phi(\theta_i F(S_t)) - \phi(S_{it})$$

given the fact that the escapement of the counterpart is constant and known.

If $S_{it} = S_i^*$ maximises this expression, the optimal strategy is given by

$$\begin{aligned} H_{i0} &= R_{i0} - S_i^* \\ H_{it} &= \theta_i F(S) - S_i^* \quad \text{for} \quad t \geq 1 \end{aligned}$$

that is, for the initial period the harvest of player i is the difference of the initial recruitment of player i minus the optimal escapement of player i; for the remaining periods the optimal steady state is reached, where the optimal harvest of player i is the difference of the optimal recruitment of player i deducted by optimal escapement of player i. Please keep in mind that such optimal steady state will occur as long as the counterpart will not react to player's i optimal escapement S_i^* by adjusting its own optimal escapement.

Since $\phi'(x_i) = \pi(x_i)$, by taking the first order derivative and equate it to zero, we obtain

$$\begin{aligned} [\gamma \cdot \phi(\theta_i F(S)) - \phi(S_i^*)]' = 0 \Leftrightarrow \\ \gamma \cdot \phi'(\theta_i F(S))\theta_i \frac{\partial F(S)}{\partial S_i^*} - \phi'(S_i^*) = 0 \Leftrightarrow \end{aligned}$$

$$\gamma \cdot \pi(\theta_i F(S))\theta_i \frac{\partial F(S)}{\partial S_i^*} = \pi(S_i^*) \tag{4.2.3}$$

It can be proved that the partial derivative of the Ricker stock-recruitment function with respect to the escapement of player i, $\partial F(S)/\partial S_i$, is equal to the derivative of Ricker's function with respect to total escapement, $F'(S)$.

To demonstrate the proving process, first we calculate the first order derivative of Ricker's stock-recruitment function as follows:

$$F'(S) = (aSe^{-bS})' = ae^{-bS} + aSe^{-bS}(-b) = ae^{-bS}(1 - bS)$$

Then, we calculate the partial derivative of Ricker's stock-recruitment function with respect to the escapement of Player 1, yet the process is the same for Player 2.

$$\frac{\partial F(S)}{\partial S_1} = \frac{\partial[a(S_1 + S_2)e^{-b(S_1+S_2)}]}{\partial S_1} = ae^{-b(S_1+S_2)} + a(S_1 + S_2)e^{-b(S_1+S_2)}(-b)$$

Since $S = S_1 + S_2$, the equation above can be expressed as

$$\frac{\partial F(S)}{\partial S_1} = ae^{-bS} - baSe^{-bS} = ae^{-bS}(1 - bS) = F'(S)$$

Therefore, expression 4.2.3 can be written as:

$$\theta_i F'(S) \frac{\pi(\theta_i F(S))}{\pi(S_i^*)} = \frac{1}{\gamma} \tag{4.2.4}$$

This formula is the Golden Rule for the non-cooperative scenario and points to an optimal escapement level S_i^* for player i given the fact that its counterpart will not change its escapement level. The economic optimal equilibrium escapement for both players is achieved after solving such Golden Rule for n times.

Chapter 5

Empirical analysis and solution

5.1 Parameter estimation

In Chapter 4, we define the bioeconomic model and derive the Golden Rule for the cooperative and non-cooperative scenarios. Now we are to calculate the optimal escapement strategy for those two scenarios based on our estimations for the parameters of our bioeconomic model.

In order to be able to solve both Golden Rules under the cooperative and non-cooperative scenarios, several parameters need to be estimated, namely:

- p, price
- r, discount rate
- a and b, Ricker's stock-recruitment function parameters
- cost parameters
  - c for the cooperative scenario
  - c_1 for the non-cooperative scenario: Player 1 (Iceland)
  - c_2 for the non-cooperative scenario: Player 2 (the EU, Norway and the Faroe Islands)

Price and discount rate

For the price of mackerel, according to historical data the prices have roughly centred around 10 Norwegian kroner per kilogram (NOK/kg), plus or minus a couple of NOKs. For simplicity of the case, we assume the price is constant at 10 NOK/kg throughout the thesis.

Since, fishery stock is a long-term perpetual asset, the comparable benchmark discount rate would be the Norwegian 30-year bond yield, which is approximately at 2.5% per annum. Allowing some room for economic rent, we assume that the discount rate is 5% and remain constant.

Ricker stock-recruitment function

In order to capture the relationship between recruitment and escapement, as discussed in Chapter 4, Ricker's stock-recruitment function is adopted:

$$R_t = aS_{t-1}e^{-bS_{t-1}} \tag{5.1.1}$$

Such function is a non-linear, therefore in order to estimate parameter a and b, linearisation is needed. To do so we take the natural logarithm for both sides of the Equation 5.1.1, and we have

$$\begin{aligned}
ln(R_t) &= ln(aS_{t-1}e^{-bS_{t-1}}) && \Leftrightarrow \\
ln(R_t) &= ln(a) + ln(S_{t-1}) + ln(e^{-bS_{t-1}}) && \Leftrightarrow \\
ln(R_t) - ln(S_{t-1}) &= ln(a) - bS_{t-1} && \Leftrightarrow \\
ln\left(\frac{R_t}{S_{t-1}}\right) &= ln(a) - bS_{t-1} && (5.1.2)
\end{aligned}$$

Ordinary least squares (OLS) regression is used to estimate parameter a and b in Equation 5.1.2. In the regression process, the data used are described as follows. In Chapter 4, recruitment R is defined as the total biomass of all adult fish in the beginning of the time cycle and escapement S as the remaining biomass of all adult fish at the end of the time cycle. According to ICES, SSB is defined as the total weight of all sexually mature fish in the

Table 5.1: NEA Mackerel SSB and landings in thousand tonnes, as reported by ICES (ICES, 2014b), the escapement is taken as the difference between the two variables.

Year	SSB	Landings	Escapement
1980	3,965	735	3,230
1981	3,595	754	2,841
1982	3,584	717	2,867
1983	3,894	672	3,222
1984	4,139	642	3,497
1985	4,053	614	3,439
1986	3,624	602	3,021
1987	3,638	655	2,983
1988	3,580	680	2,900
1989	3,332	586	2,746
1990	3,362	626	2,736
1991	3,214	676	2,538
1992	2,856	761	2,096
1993	2,506	825	1,681
1994	2,169	819	1,350
1995	2,152	756	1,396
1996	2,057	563	1,494
1997	2,049	573	1,476
1998	2,053	666	1,387
1999	2,233	640	1,593
2000	2,176	739	1,437
2001	2,033	737	1,295
2002	1,899	771	1,128
2003	1,916	679	1,237
2004	2,362	660	1,701
2005	2,274	550	1,724
2006	2,263	481	1,781
2007	2,451	586	1,865
2008	3,039	623	2,416
2009	3,682	738	2,944
2010	3,969	876	3,093
2011	4,515	947	3,569
2012	4,181	892	3,288
2013	4,299	932	3,368

stock. Therefore, the data of SSB obtained from ICES are used as a proxy for recruitment R. Furthermore, the difference between SSB and total NEA Mackerel landings (also obtained from ICES) is used as a proxy for escapement S. Table 5.1 shows SSB and landings from year 1980 to 2013 as reported by ICES as well as the difference between them, which is the escapement.

The parameters a and b in Equation 5.1.2 are estimated using data from Table 5.1 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 5.2.

Table 5.2: Results from fitting recruitment and escapement data on Ricker's function.

Constant ($a = e^{ln(a)}$)	Slope (b)	$\bar{R}^2$
1.76417	0.00012	.49
(0.00)[1]	(0.00)	

[1]p-values in parentheses

As can be seen from Table 5.2 the estimates of parameter a and b are statistically significant at 1% and equal to 1.76417 and 0.00012, respectively. The adjusted R^2 of the regression is 49%.

Cost function

As discussed in Chapter 4 the cost function is derived as a function of recruitment R and escapement S

$$TC(R_t, S_t) = c{\cdot}ln\left(\frac{R_t}{S_t}\right) \tag{5.1.3}$$

Due to the lack of information on total cost for NEA Mackerel harvest of both players, we assume that the average unit cost of mackerel harvest for both of the players is equal. We obtain data from profitability survey of the Norwegian fishing fleet from year 2006 to 2013 (the Norwegian Directorate of Fisheries) to calculate the average unit cost of harvest. The average unit cost

Table 5.3: Operation costs and harvest in the licensed Norwegian purse seine fishery as well as the deflation process.

Year	Total cost (million NOK)	Total harvest (000 tonnes)	Average unit cost (NOK/kg)	Index (2013=1)	Deflated average unit cost (NOK/kg)
2006	2,223	1,068	2.08	0.87	2.39
2007	2,489	1,150	2.16	0.86	2.51
2008	2,669	1,100	2.43	0.81	3.00
2009	2,580	1,077	2.40	0.86	2.79
2010	2,867	1,061	2.70	0.95	2.84
2011	3,186	845	3.77	0.95	3.97
2012	2,765	791	3.49	0.85	4.11
2013	2,533	695	3.65	1	3.65

of harvest is calculated as the total operation costs of all licensed Norwegian purse seiners in million NOK divided by their total harvest in thousand tonnes. In order to get rid of the inflation effect, we convert the average unit cost into real terms by deflating it with price index. We use year 2013 as the base year and we deflate the cost by Norwegian Price Index of First Hand Domestic Sales obtained from Statistics Norway.

Then, we multiply the deflated average unit cost of harvest by the harvest of each player during those years in order to obtain their total costs. The harvest of Player 1 and Player 2 is the Icelandic harvest and the aggregated harvest of the EU, Norway and the Faroe Islands respectively, as reported from ICES (ICES, 2014b). Please be reminded that the corresponding individual harvest of Coastal States are presented in Table 1.5 in Chapter 1. Table 5.3 shows operation costs and harvest in the licensed Norwegian purse seine fishery and the average unit cost as well as the deflation process. Table 5.4 shows each player mackerel harvest and its corresponding total cost. Also, the mackerel harvest and total cost for both players are summed up in order to estimate the cost parameter c for the cooperative scenario.

In order to proceed with the estimation of the cost parameters we need data for recruitment and escapement for both players individually and aggregately. For the cooperative scenario SSB is used as a proxy for total recruitment and

Table 5.4: Harvests (in thousand tonnes) and total costs (in million NOK) for both individual players and in aggregate.

Year	Player 1		Player 2		Combined	
	Harvest	Cost	Harvest	Cost	Harvest	Cost
2006	4	8.78	412	856.80	416	865.59
2007	37	79.28	486	1,050.18	523	1,129.47
2008	112	272.85	438	1,065.46	551	1,338.31
2009	116	278.78	565	1,355.04	681	1,633.82
2010	121	326.72	677	1,827.58	798	2,154.30
2011	159	600.42	697	2,627.24	856	3,227.66
2012	149	520.99	643	2,244.08	792	2,765.07
2013	151	552.01	639	2,331.97	790	2,883.98

the difference between SSB and the total harvest of both players is used as a proxy for total escapement. For the non-cooperative scenario recruitment for each player R_i is calculated using the parameter θ_i that is defined in Chapter 4 as the share of NEA Mackerel stock that only appears in the EEZ of Player i. In the same Chapter, θ_1 is estimated as 12.5%, meaning that 12.5% of total recruitment lies in in the EEZ of Player 1. Table 5.5 shows the aggregated and individual recruitment and escapement levels.

Table 5.5: Recruitment and escapement levels (in thousand tonnes) for both individual players and in aggregate.

Year	Player 1		Player 2		Combined	
	Recruitment	Escapement	Recruitment	Escapement	Recruitment	Escapement
2006	283	279	1,980	1,568	2,263	1,846
2007	306	270	2,145	1,658	2,451	1,928
2008	380	268	2,659	2,221	3,039	2,488
2009	460	344	3,222	2,657	3,682	3,001
2010	496	375	3,473	2,796	3,969	3,171
2011	564	405	3,951	3,254	4,515	3,659
2012	523	373	3,658	3,015	4,181	3,388
2013	537	386	3,762	3,123	4,299	3,509

Table 5.6 shows the results from the regression of the total cost function

under the cooperative and non-cooperative scenarios. As can be seen from the results, all cost parameters are statistically significant at 1% and the adjusted R^2 for all three regressions are above 68%.

Table 5.6: Results from the regression of the total cost function.

	Cooperative scenario	Non-cooperative scenario	
		Player 1	Player 2
Slope (c)	9,365 (0.00)[1]	1,316 (0.00)	7,777 (0.00)
$\bar{R}^2$	0.70	0.77	0.68

[1]p-values in parentheses

5.2 Results and discussion

Having estimated all of our parameters we are enabled to compute the optimal escapement levels for the cooperative and non-cooperative scenarios. Here in this section, we first calculate MSY for the mackerel stock and then present the results for both scenarios respectively.

MSY

As stated in Chapter 4, the MSY escapement level is when the growth of mackerel stock is maximised, i.e., the first order derivative of the stock-recruitment function is equal to 1, $F'(S) = 1$. Based on the estimates of the parameters a and b of Ricker's stock-recruitment function, our steady-state MSY escapement level is 2,188,000 tonnes, which grows to 2,968,000 tonnes of recruitment, corresponding to 780,000 tonnes of harvest.

Cooperative scenario

For the cooperative scenario the optimal escapement level is derived by solving the Golden Rule, Equation 4.1.15, with respect to escapement S. Table 5.7 shows the parameters and the results for the cooperative scenario.

Table 5.7: Parameters and optimal solution for the cooperative scenario.

Symbol	Description	Result	Unit	Remark
Parameters:				
r	Discount rate	5%		
a	Ricker's function parameters	1.76417		see Table 5.2
b		0.00012		
p	Price	10	NOK/kg	
c	Cost parameter	9,365		see Table 5.6
Optimal solution:				
R^*	Recruitment	3,251	Thousand tonnes	
S^*	Escapement	2,483	Thousand tonnes	
H^*	Harvest	768	Thousand tonnes	
NPV	Net present value	108,230	Million NOK	

As can be seen from Table 5.7, for cooperative scenario, NPV is maximised to approximately 108.2 billion NOK when the stock reaches steady-state. At steady-state, optimal recruitment and escapement are 3,251,000 and 2,483,000 tonnes respectively, resulting in 768,000 tonnes harvest of NEA Mackerel. Such results answer the first question of the research problem defined in Chapter 2.

Table 5.8 summarises the comparison between the steady-state equilibria at both MEY and MSY. As can be seen, under the steady-state equilibrium at MEY, a small drop in the harvest results in relatively large increases in the NPV, recruitment and escapement levels.

Table 5.8: Comparison between MEY and MSY. Note that the unit for all recruitment, escapement and harvest is thousand tonnes; and for NPV is million NOK.

	NPV	Harvest	Recruitment	Escapement
MEY	108,230	768	3,251	2,483
MSY	103,795	780	2,968	2,188
Difference	4,435	-12	283	295

Table 5.9: Parameters for the non-cooperative scenario.

Symbol	Description	Result: Player 1	Result: Player 2	Unit	Remark
r	Discount rate	5%			
a	Ricker's function parameters	1.76417			see Table 5.2
b		0.00012			
p	Price	10		NOK/kg	
c	Cost parameter	1,316	7,777		see Table 5.6
θ	Recruitment share	12.5%	87.5%		

Non-cooperative scenario

For the non-cooperative scenario, the optimal escapement level for both players will be determined after n periods by solving the Golden Rule for non-cooperation, Equation 4.2.4, n times. Table 5.9 shows the parameters for the non-cooperative scenario.

As discussed in Chapter 4, each player determines its optimal escapement level S_i^* given the escapement strategy of the other player. Assuming in the initial time cycle, $t = 0$, Player 1 is to determine its optimal escapement level first. That is to say, Player 1 has to arbitrarily assign a value to Player's 2 escapement $S_{2,0}$ at time zero $t = 0$, e.g., $S_{2,0} = 1,500,000$ tonnes. Player 1 maximises its NPV at $t = 0$ based on the escapement value of Player 2 it assigns. In the next time cycle, $t = 1$, by implementing the strategy in the previous time cycle, Player 1 signals Player 2 how much it harvested in the previous cycle. Similar to what Player 1 did in the initial cycle, Player 2 maximises its NPV using the same strategy in the second cycle, $t = 1$. That is, maximising its NPV based on the escapement of Player 1 in the previous cycle. In the next time cycle, $t = 2$, Player 1 repeats what Player 2 did in the previous cycle, $t = 1$. This process continues for n cycles until no player can further increase or decrease its NPV. That is, the steady-state is reached for both players.

In our case, such steady-state is reached after $n = 3$ time cycles. As Table

5.10 shows, at steady-state, the NPV of each player is maximised and can no longer change at approximately 19.3 billion NOK for Player 1 and 76.5 billion NOK for Player 2, resulting in an aggregated NPV of 95.8 billion NOK. The aggregated harvest for both players is 777,000 tonnes and consists of 211,000 and 566,000 tonnes for Player 1 and 2, respectively. Total recruitment and escapement are 2,833,000 and 2,056,000 tonnes, respectively. Such results address the second question of the research problem defined in Chapter 2.

Table 5.10: Results for the non-cooperative scenario. Note that the unit for all escapement, recruitment and harvest is thousand tonnes; and for NPV is million NOK.

Time	Symbol	Description	Player 1	Player 2
	$S^*_{i,t}$	Escapement of player i at t	142	1,500
	S_t	Total escapement at t	1,642	
	R_t	Total recruitment at t determined by $F(S_0)$	2,379	
$t = 0$	$R^*_{i,t}$	Recruitment of player i determined by θ_i	297	2,082
	$H^*_{i,t}$	Harvest of player i determined by $R^*_{i,t} - S^*_{i,0}$	155	582
	H_t	Total harvest at t	737	
	$NPV_{1,t}$	Player's i NPV at t	12,190	68,611
	$S^*_{i,t}$	Escapement of player i at t	143	1,913
	S_t	Total escapement at t	2,056	
	R_t	Total recruitment at t determined by $F(S_0)$	2,833	
$t = 1$	$R^*_{i,t}$	Recruitment of player i determined by θ_i	354	2,479
	$H^*_{i,t}$	Harvest of player i determined by $R^*_{i,t} - S^*_{i,0}$	211	566
	H_t	Total harvest at t	777	
	$NPV_{1,t}$	Player's i NPV at t	19,283	76,502
	$S^*_{i,t}$	Escapement of player i at t	143	1,913
	S_t	Total escapement at t	2,056	
	R_t	Total recruitment at t determined by $F(S_0)$	2,833	
$t = 2$	$R^*_{i,t}$	Recruitment of player i determined by θ_i	354	2,479
	$H^*_{i,t}$	Harvest of player i determined by $R^*_{i,t} - S^*_{i,0}$	211	566
	H_t	Total harvest at t	777	
	$NPV_{1,t}$	Player's i NPV at t	19,283	76,512

As can be seen from Table 5.11, compared to the cooperative scenario, under non-cooperative scenario the NPV is lower by approximately 11.4%, amounting 12.4 billion NOK. Yet, under non-cooperative scenario the harvest is larger by 9,000 tonnes. At the same time, under non-cooperative scenario the aggregated recruitment is lower by 12.9%, amounting 418,000 tonnes.

Table 5.11: Comparison between the cooperative and non-cooperative scenarios. Note that the unit for all recruitment, escapement and harvest is thousand tonnes; and for NPV is million NOK.

	NPV	Harvest	Recruitment	Escapement
Cooperative	108,230	768	3,251	2,483
Non-cooperative[1]	95,795	777	2,833	2,056
Difference	12,435	-9	418	427

[1]The figures are the aggregate numbers for both Player 1 and Player 2.

Please note that, in order to solve the non-cooperative scenario we assume that Player 1 starts first and determines its optimal escapement strategy by assigning an arbitrary value to the escapement of Player 2. Then Player 2 maximises its own NPV based on the escapement that Player 1 yield in the previous time cycle. Such process goes on until neither of the players can further improve their own NPVs. If we assume that Player 2 starts first and Player 1 follows, the steady-state for both players would yield the same results. However, in the process of reaching the steady-state, the number of time cycles and the corresponding results of each time cycle may be different.

Chapter 6

Game theoretic analysis

Given the results under both cooperative and non-cooperative scenarios in Chapter 5, we apply game theory as introduced in Chapter 3 to analyse if and under what circumstances should Player 1, i.e., Iceland, join the coalition of the EU, Norway and the Faroe Islands, that is, Player 2.

According to Table 5.11 the comparison made in Chapter 5, under cooperative scenario, NPV is maximised to approximately 108.2 billion NOK, whereas in the non-cooperative scenario, the NPV of each player is maximised at approximately 19.3 billion NOK for Player 1 and 76.5 billion NOK for Player 2, aggregating to 95.8 billion NOK, which is 12.4 billion NOK lower than under cooperation. This satisfies the foundation for cooperation because each player can potentially benefit more by cooperating than competing with each other for NEA Mackerel.

To see exactly how much each player benefits from cooperation, the benefit needs to be allocated between the players. As discussed in Chapter 3, the methods we use to split the NPV are the egalitarian method, altruistic method and Shapley value. Here, we present and analyse the NPV sharing solution under each method. This chapter answers the third research question as defined in Chapter 2.

Table 6.1: NPV share arrangement under the egalitarian method. Note that all NPVs are expressed in million NOK.

Participant	Non-cooperation	Cooperation		Difference	
	NPV	NPV	Portion	Amount	Percentage
Player 1	19,283[1]	54,115	50%	34,832	181%
Player 2	76,512[1]	54,115	50%	-22,397	-29%
Total	95,795	108,230[2]	100%	12,435	11%

[1]Results obtained from the non-cooperative scenario, see Table 5.10.
[2]Results obtained from the cooperative scenario, see Table 5.7.

Egalitarian

Egalitarian method split the benefit, i.e., NPV under cooperation, equally among the players. For our case, it is calculated as follows:

$$\text{Player } i \text{ share} = \frac{\text{NPV under cooperation}}{\text{Number of Players}} = \frac{108,230}{2} = 54,115 \text{ million NOK}$$

According to egalitarian method, both Player 1 and Player 2 share the NPV equally and end with 54.1 billion NOK each. As can be seen from Table 6.1, Player 1 enjoys a huge financial improvement compared to its stand-alone financial situation, at the expense of Player 2. If such benefit sharing arrangement is implemented, then it is not Iceland who does not want to co-operate but rather the coalition made up of the EU, Norway and the Faroe Islands. Assuming this is true, then side payment made by Iceland to the coalition can be adopted to keep the coalition cooperating with Iceland. In the simplest case, i.e., only financial terms are taken into account, the minimum side payment from the pocket of Iceland is the payment to make the coalition financially indifferent whether it joins the coalition or stands alone. The maximum side payment Iceland is willing to pay is the payment that results in indifferent financial situation for Iceland whether keep the coalition or go by itself.

Nevertheless the egalitarian method does not truly capture the notion of fairness because Coastal States vary with different sizes and populations. If we

Table 6.2: NPV share arrangement under the "fairness" method as we defined. Note that all NPVs are expressed in million NOK.

Participant	Non-cooperation	Cooperation		Difference	
	NPV	NPV	Portion	Amount	Percentage
Player 1	19,283[1]	27,058	25%	7,775	40%
Player 2	76,512[1]	81,172	75%	4,660	6%
Total	95,795	108,230[2]	100%	12,435	11%

[1]Results obtained from the non-cooperative scenario, see Table 5.10.
[2]Results obtained from the cooperative scenario, see Table 5.7.

define fairness as every country in this region that is entitled with the same share of NEA Mackerel, then the results would be different.

Here we calculate the NPV share arrangement to approach "fairness" as we defined above. Player 1 consists of one country, namely Iceland, and Player 2 is formed up of three countries (the EU and the Faroe Islands are treated as two single countries), that is, the EU, Norway and the Faroe Islands. Therefore, Player 2 should take three quarters of the NPV under the cooperative scenario. The results are presented in Table 6.2.

As can be seen in the Table 6.2, under our "fairness" assumption both players enjoy a financial improvement compared to their stand-alone situations. The rationality condition as discussed in Chapter 3 is satisfied. Therefore, at least in financial terms, such cooperation can stand.

Altruistic

Under the altruistic method the share of each player is proportional to its stand-alone NPV over the total sum of the non-cooperative NPVs of both players. It can be calculated as follows:

$$\text{Player } i \text{ share} = \text{NPV under cooperation} \times \frac{\text{Stand-alone NPV of Player } i}{\text{Sum of stand-alone NPVs}}$$

Substituting the results in Chapter 5 in the equation above, we obtain

$$\text{Player 1 share} = 108,230 \cdot \frac{19,283}{(19,283 + 76,512)} = 21,786 \text{ million NOK}$$

$$\text{Player 2 share} = 108,230 \cdot \frac{76,512}{(19,283 + 76,512)} = 86,444 \text{ million NOK}$$

According to the altruistic method, Player 1 and Player 2 end up with 21.8 and 86.4 billion NOK, respectively, with the same increase percentage. As can be seen from Table 6.3 the rationality condition stands, and the foundation of cooperation suffices.

Table 6.3: NPV share arrangement under the altruistic method. Note that all NPVs are expressed in million NOK.

Participant	Non-cooperation	Cooperation		Difference	
	NPV	NPV	Portion	Amount	Percentage
Player 1	19,283[1]	21,786	20%	2,503	13%
Player 2	76,512[1]	86,444	80%	9,932	13%
Total	95,795	108,230[2]	100%	12,435	11%

[1]Results obtained from the non-cooperative scenario, see Table 5.10.
[2]Results obtained from the cooperative scenario, see Table 5.7.

Shapley Value

The Shapley value was introduced by Lloyd Shapley in 1953 as a method that allows each player to prior assess the benefits it would expect from playing a game. Such value assigns player i the average of the marginal benefits it could achieve when entering all possible coalitions (Roth and Verrecchia, 1979). The general form of the Shapley value is formulated as follows:

$$u_i = \sum_{M \subseteq N} \frac{(|N| - |M|)!(|M| - 1)!}{|N|!} \times [\nu(M) - \nu(M - \{i\})] \quad \forall\, i < N$$

where N is the set of players, $N = \{1, 2\}$ and M is a subset of N defining all possible coalitions, $M = \{\{1\}, \{2\}, \{1, 2\}\}$. Symbol $| \cdot |$ stands for the number of players in a coalition, e.g., $|M = \{2\}| = 1$ but $|M = \{1,2\}| = 2$. Function $\nu(M)$ describes the total benefit to the coalition M, that is, the NPV of players standing alone or cooperating; $\nu(M - \{i\})$ is the benefit of the coalition M without player i, e.g., $\nu(\{1,2\} - \{1\}) = \nu(\{2\})$ and $\nu(\{1\} - \{1\}) = \nu(\emptyset) = 0$. The calculation of Shapley values for Player 1 and Player 2 are:

$$
\begin{aligned}
u_1 &= \frac{(|\{1,2\}| - |\{1\}|)!(|\{1\}| - 1)!}{|\{1,2\}|!} \times [\nu(\{1\}) - \nu(\{1\} - \{1\})] \\
&+ \frac{(|\{1,2\}| - |\{1,2\}|)!(|\{1,2\}| - 1)!}{|\{1,2\}|!} \times [\nu(\{1,2\}) - \nu(\{1,2\} - \{1\})] \\
&= \frac{(2-1)! \cdot (1-1)!}{2!} \times [\nu(\{1\}) - \nu(\emptyset)] + \frac{(2-2)! \cdot (2-1)!}{2!} \times [\nu(\{1,2\}) - \nu(\{2\})] \\
&= \frac{(2-1)! \cdot (1-1)!}{2!} \times NPV_1 + \frac{(2-2)! \cdot (2-1)!}{2!} \times (NPV - NPV_2) \\
&= \frac{1! \cdot 0!}{2!} \times 19{,}283 + \frac{0! \cdot 1!}{2!} \times (108{,}230 - 76{,}512) = 25{,}500.5 \text{ million NOK}
\end{aligned}
$$

$$
\begin{aligned}
u_2 &= \frac{(|\{1,2\}| - |\{2\}|)!(|\{2\}| - 1)!}{|\{1,2\}|!} \times [\nu(\{2\}) - \nu(\{2\} - \{2\})] \\
&+ \frac{(|\{1,2\}| - |\{1,2\}|)!(|\{1,2\}| - 1)!}{|\{1,2\}|!} \times [\nu(\{1,2\}) - \nu(\{1,2\} - \{2\})] \\
&= \frac{(2-1)! \cdot (1-1)!}{2!} \times [\nu(\{2\}) - \nu(\emptyset)] + \frac{(2-2)! \cdot (2-1)!}{2!} \times [\nu(\{1,2\}) - \nu(\{1\})] \\
&= \frac{(2-1)! \cdot (1-1)!}{2!} \times NPV_2 + \frac{(2-2)! \cdot (2-1)!}{2!} \times (NPV - NPV_1) \\
&= \frac{1! \cdot 0!}{2!} \times 76{,}512 + \frac{0! \cdot 1!}{2!} \times (108{,}230 - 19{,}283) = 82{,}729.5 \text{ million NOK}
\end{aligned}
$$

According to Shapley value, Player 1 and Player 2 end up with 25.5 and 82.7 billion NOK, respectively, with the same NPV increase. As can be seen from Table 6.4 the rationality condition stands, therefore players have incentives to cooperate.

Table 6.4: NPV share arrangement under Shapley value. Note that all NPVs are expressed in million NOK.

Participant	Non-cooperation	Cooperation		Difference	
	NPV	NPV	Portion	Amount	Percentage
Player 1	19,283[1]	25,500.5	24%	6,217.5	32%
Player 2	76,512[1]	82,729.5	76%	6,217.5	8%
Total	95,795	108,230[2]	100%	12,435	11%

[1]Results obtained from the non-cooperative scenario, see Table 5.10.
[2]Results obtained from the cooperative scenario, see Table 5.7.

Table 6.5: Summary of NPV arrangement under different methods. Note that all NPVs are expressed in million NOK.

Participant	Non-cooperation	Cooperation			
		Egalitarian		Altruistic	Shapley value
		by participants	by countries		
Player 1	19,283	54,115	27,058	21,786	25,501.5
Player 2	76,512	54,115	81,172	86,444	82,729.5
Total	95,795	108,230	108,230	108,230	108,230

Table 6.5 summarises the results for the four different NPV arrangement methods. Except for the egalitarian method by participants (Player 1 and Player 2 share the NPV under cooperation equally), all the other three methods satisfy the rationality condition, so that they provide the necessary foundation for cooperation between Player 1 and Player 2. According to the results the egalitarian method by countries is the most desirable method for Player 1, with Iceland ending up with 27.1 billion NOK; while the altruistic method is the most preferable method for Player 2, with the three-coastal-state coalition taking 86.4 billion NOK. The results for Shapley value fall in the middle of the two methods discussed above. In reality, all the NPV arrangement methods for cooperation adopted in the thesis provide numerical guidance for interest parties to negotiate. However, the negotiations are also subject to other realistic constraints, for example how the national population relies on one's fishery economy.

Chapter 7

Sensitivity analysis

In Chapter 5, we give estimates to the parameters of the bioeconomic model. For some parameters, the process of making estimates are constrained by data availability such as the share of recruitment of player i, θ_i, and the cost parameter c and the price p. In this chapter, we vary parameter θ and c to see how the model influences our results (as said before, for simplicity we keep assuming p as a constant at 10 NOK/kg). The sensitivity analysis for θ_1 ($\theta_2 = 1 - \theta_1$) and c are as follows.

Parameter $\boldsymbol{\theta}$

Parameter θ only affects the results in Chapter 5 under the non-cooperative scenario. Table 7.1 shows how sensitive the NPV, recruitment, escapement and harvest to the change of θ for both players and the aggregated total. Please note that every time θ changes, it affects the cost parameter c_i of each player. This is due to the reason that in order to estimate the individual cost parameters, θ is taken into account. For detailed explanation, please see Chapter 5. Also, because of this effect that the variation of θ brings to the cost parameters, when θ_1 is zero, the results are different from the results under cooperation. As under the cooperative scenario, we incorporate the cost parameter c_1 of Player 1 (dependent on $\theta_1 = 12.5\%$) into calculation. To some extent, when θ_1 is zero, such situation is similar to the situation when Iceland had not harvested mackerels before year 2006. Also, this situ-

Table 7.1: Sensitivity analysis for parameter θ_1. Note that the unit for all recruitment, escapement and harvest is thousand tonnes; and for NPV is million NOK.

θ_1	Participant	NPV	Recruitment	Escapement	Harvest
	Player 1	-	-	-	-
0%	Player 2	110,072	3,235	2,465	769
	Total	110,072	3,235	2,465	769
	Player 1	19,283	354	143	211
12.5%[1]	Player 2	76,512	2,479	1,913	566
	Total	95,795	2,833	2,056	777
	Player 1	20,611	413	179	234
15.0%	Player 2	71,881	2,341	1,801	540
	Total	92,492	2,754	1,980	774
	Player 1	22,119	520	255	265
20.0%	Player 2	64,021	2,080	1,583	497
	Total	86,140	2,600	1,838	762
	Player 1	22,379	615	334	281
25.0%	Player 2	57,951	1,845	1,379	466
	Total	80,330	2,460	1,713	747
	Player 1	21,884	702	418	284
30.0%	Player 2	53,459	1,639	1,192	447
	Total	75,343	2,341	1,610	731
	Player 1	21,107	787	506	281
35.0%	Player 2	50,288	1,461	1,026	435
	Total	71,394	2,248	1,532	716
	Player 1	20,399	873	598	275
40.0%	Player 2	48,199	1,309	879	430
	Total	68,597	2,182	1,477	705

[1] Initial results obtained from Chapter 5, see Table 5.10.

Table 7.2: Comparison between the non-cooperative scenario where θ_1 is equal to zero and the cooperative scenario. Note that the unit for all recruitment, escapement and harvest is thousand tonnes; and for NPV is million NOK.

Scenario	NPV	Recruitment	Escapement	Harvest
Non-cooperative ($\theta_1 = 0$)	110,072	3,235	2,465	769
Cooperative	108,230	3,251	2,483	768
Difference	1,842	-16	- 18	1

ation would mimic the situation where Player 2 excluded Player 1 from the consultation rounds.

As can be seen from Table 7.2, under the non-cooperative scenario where θ_1 is equal to zero, there is some improvement of NPV while maintaining relatively stable levels of recruitment, escapement and harvest. The NPV under the non-cooperative scenario where θ_1 is equal to zero is 1.8 billion NOK higher than under the cooperative scenario. Comparing the situation under the non-cooperative scenario where θ_1 is equal to zero to the non-cooperative scenario where θ_1 is equal to 12.5%, that is, the default stand alone cases for both Player 1 and Player 2, side payment can be introduced to make Iceland financially indifferent or even with some incentive not to catch any mackerel until to the point that the indifferent financial situation is reached for the coalition. The side payment ranges from 19.3 to 33.6 (110.1 - 76.5) billion NOK. The upper limit of 33.6 billion NOK side payment represents the most financial gain Iceland could achieve to bargain with the coalition in theory.

As a holistic sensitivity analysis, it can be seen from from Table 7.1, under non-cooperative scenario as θ increases, the general trend is that all of the total NPV, recruitment, escapement and harvest decrease. However, until θ_1 reaches approximately 25%, the NPV and harvest of Player 1 increases; then, it decreases. That is to say that Iceland peaks its NPV and harvest with a θ approximately equal to 25%. For the recruitment and escapement, as θ_1 becomes larger Player 1 enjoys an increasing share of those two. For Player 2, for all the NPV, recruitment, escapement and harvest the trend for its share is to descend as θ_1 increases.

Parameter θ_1 represents the share of NEA Mackerel that shows up in Icelandic EEZ. Due to climate change, θ_1 is anticipated to become larger as more and more mackerels go to Icelandic waters to feed. From the figures presented in Table 7.1, it can be implied that Iceland benefits most with 25% presence of NEA Mackerel stock in Icelandic waters both financially and in terms of physical catches. In all cases, as the share of NEA Mackerel for Iceland grows, the loss of the three-coastal-state coalition keeps increasing and the size of the stock continues decreasing. A strong incentive for the three-coastal-state coalition to cooperate with Iceland can be inferred.

If we do not constrain Player 1 only to Iceland, the trend depicted in Table 7.1 could also suit for countries which are more located in the north, such as Greenland and the Faroe Islands, or any coalition consisting of any partnership between Greenland, the Faroe Islands and Iceland.

Cost parameter

Cost parameter affects the results in Chapter 5 for both cooperative and non-cooperative scenarios. As a unit cost per effort, parameter c is obtained by treating historical cost data. It is based on the assumption that the average unit cost, for both Player 1 and Player 2 whether acting individually or collectively, is equal. Such average unit cost is calculated using data of the Norwegian purse seiner fishery, which has the lowest cost per unit of harvest compared to the Scottish and Icelandic fleets (Lappo, 2013). However, the likelihood for the real cost parameter being greater than the estimate we currently use is much higher than it being smaller. Therefore, we stage more cases of a higher cost parameter in our sensitivity analysis.

Table 7.3 and Table 7.4 show how sensitive the NPV, recruitment, escapement and harvest is to the change of the cost parameter under the cooperative and non-cooperative scenarios, respectively.

As can be seen from Table 7.3, as cost parameter c increases, NPV and harvest decrease. In contrast, recruitment and escapement level increases. This implies that higher cost conserve the fish resource.

Table 7.3: Sensitivity analysis for cost parameter c under cooperation. Note that the unit for all recruitment, escapement and harvest is thousand tonnes; and for NPV is million NOK.

Change	c	NPV	Recruitment	Escapement	Harvest
-25%	7,024	120,999	3,140	2,364	776
-[1]	9,365	108,230	3,251	2,483	768
+25%	11,706	96,075	3,359	2,603	756
+50%	14,048	84,558	3,465	2,725	740
+75%	16,389	73,692	3,568	2,848	720
+100%	18,730	63,491	3,670	2,973	697
+200%	28,095	29,710	4,053	3,496	557

[1]Initial results obtained from Chapter 5, see Table 5.7

As can be seen from Table 7.4, as cost parameter c_i increases, similar to the cooperative case, NPV decreases. In contrast, again, recruitment and escapement level increase. The harvest has seen an increase and peaks at around 25% cost increase, then it decreases. The share of individual players follow the same trend as the aggregated figures except for the harvest. The harvest for Player 1 decreases all the way as the cost parameter increases. However, the harvest for Player 2 increases first until around 75% increase of the cost parameter, then it decreases. Nevertheless, once again, it can be implied from the figures that higher cost conserve mackerel resources.

In comparing the cooperative scenario with the non-cooperative scenario, all cases except the 200% increase, the collective NPV under cooperation is larger than the aggregated individual NPV under non-cooperation. However, such trend reversed after the increase reaches 100%, e.g., when the increase is at 200%, the collective NPV under cooperation (29.7 billion NOK) is smaller than the aggregated individual NPV under non-cooperation (30.9 billion NOK).

Table 7.4: Sensitivity analysis for cost parameter c_i under non-cooperation. Note that the unit for all recruitment, escapement and harvest is thousand tonnes; and for NPV is million NOK.

Change	Participant	c_i	NPV	Recruitment	Escapement	Harvest
-25%	Player 1	987	24,189	335	109	226
	Player 2	5,833	81,671	2,345	1,802	543
	Total		105,860	2,680	1,911	769
-[1]	Player 1	1,316	19,283	354	143	211
	Player 2	7,777	76,512	2,479	1,913	566
	Total		95,795	2,833	2,056	777
+25%	Player 1	1,645	15,417	373	176	197
	Player 2	9,721	70,835	2,611	2,028	583
	Total		86,252	2,984	2,204	780
+50%	Player 1	1,974	12,280	391	209	182
	Player 2	11,666	64,832	2,739	2,145	594
	Total		77,112	3,130	2,354	776
+75%	Player 1	2,303	9,689	409	242	167
	Player 2	13,610	58,655	2,863	2,264	599
	Total		68,343	3,272	2,506	766
+100%	Player 1	2,632	7,529	426	274	152
	Player 2	15,554	52,428	2,982	2,385	597
	Total		59,957	3,408	2,659	749
+200%	Player 1	3,948	1,989	488	401	87
	Player 2	23,331	28,879	3,416	2,881	535
	Total		30,868	3,904	3,282	622

[1]Initial results obtained from Chapter 5, see Table 5.10

Chapter 8

Conclusion

In Chapter 5, we present the results for both cooperative and non-cooperative scenarios by solving the bioeconomic model. In Chapter 6, various game theoretic allocation methods are applied to obtain the possible outcomes of cooperation between Player 1 and Player 2. Since some of the parameters we adopt are susceptible to change, therefore sensitivity analysis is performed in Chapter 8.

The harvest level we obtain for the cooperative scenario in Chapter 5 is 768,000 tonnes, which is significantly lower than the recommendation given by ICES, amounting to a range between 927,000 and 1,011,000 tonnes in 2014 (831,000 - 906,000 tonnes in 2015) (ICES, 2014b). Also, it is even lower than the 5-year arrangement agreed by the EU, Norway and the Faroe Islands in 2014 (please see Table 1.3). The discrepancy between our results and the ICES recommendation could be resulting from the various simplistic assumptions we make as well as data in-availability. However, such assumptions are discussed extensively throughout the thesis so that the limitations of our model can be inferred by the reader.

The NPV, recruitment and escapement levels associating with the harvest level mentioned above under the cooperative scenario are 108.2 billion NOK, 3,251,000 tonnes and 2,483,000 tonnes respectively. Assuming in reality, what Iceland and the three-coastal-state coalition are doing is exactly the same as the non-cooperative scenario depicts in the thesis with exactly the same corresponding figures (because we do not know the real numbers), then the analysis in Chapter 5 tells us there is a 12.4 billion NOK financial gain and 418,000 tonnes increase in the stock size of Atlantic Mackerel under the cooperative scenario, creating the basis for the cooperation and sustainable use of NEA Mackerel resource. Or we could even further postulate that what Iceland and the three-coastal-state coalition are doing in reality is sub-optimal to the non-cooperative scenario in the thesis because the actual combined harvest of the two players are much more than what we suggest under the non-cooperative scenario. Therefore, the gain for cooperation should be at least the same as the comparison made between the cooperative and non-cooperative scenarios, and could well be much larger potentially.

Also, such comparison is based on the results under the assumption that the share of mackerel stock appear in Icelandic waters is 12.5%. However, with the projection of increase of the Icelandic mackerel share due to climate change, the results are subject to change, experiencing first increasing but later decreasing aggregated NPVs of the two players, as well as decreasing aggregated recruitment and escapement levels of the NEA Mackerel stock. It is worthy of noting that under the non-cooperative scenario, the results are the most desirable for Iceland when about 25% of the mackerels present in the EEZ of Iceland in a given year. Under such scenario, Iceland has the most of its NPV and harvest among all the scenarios, amounting to approximately 22.4 billion NOK and 281,000 tonnes, making the cooperation most expensive to afford by the three-coastal-state coalition.

Furthermore, it should be noted that in the model we adopt itself, there are limitations as well. For example, for both cooperative and non-cooperative scenarios, the model is a bang-bang approach, that is, to deplete the mackerel stock to the desired level in order to reach the steady-state as soon as possible. Yet, such approach is constrained in reality as there may not be sufficient idle fishing capacity to employ. Furthermore, to maintain the steady-state, sufficient fishing capacity is needed and subject to the same constraint in reality. Therefore, it could become too expensive or infeasible to implement such strategy as the model dictates.

Nevertheless, we believe our model still serves as a simplistic guidance for resolving the Mackerel Dispute or any dispute for migratory pelagic fish stock. In the foreseeable future, as the NEA gets warmer and warmer it can be anticipated that Greenland might also get involved in this dispute of sharing mackerel quotas with other Coastal States. Then such analysis can be re-applied.

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This is an empirical analysis of the so-called Northeast Atlantic Mackerel Dispute between coastal nations such as the EU, Norway, the Faroe Islands and Iceland. In this thesis, firstly, we discuss the relevant biological and managerial aspects of Northeast Atlantic Mackerel. Then we begin to give a full factual depiction of the dispute. Based on the historical accounts of the dispute, we define the research problems of the issue. Further, we lay out the theoretical basis for solving such problems, i.e., fishery economics and game theory. By applying the theoretical framework and adopting the bioeconomic model, we solve the problems with extensive discussion and sensitivity analysis. The solution we find for the Mackerel Dispute is that all coastal nations should cooperate because such cooperation would lead to more NPV, recruitment and escapement levels of the mackerel stock but less harvest collectively. However, only with a proper benefit sharing arrangement, such cooperation may be feasible, resulting in each individual player end up with more benefit than acting on its own.

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