# Evaluating the spatio-temporal impacts of environmental, political and economic changes on the stocks of Northeast Atlantic mackerel and North Sea herring and fisheries

# Dissertation

With the aim of achieving a doctoral degree at the Faculty of Mathematics, Informatics and Natural Sciences

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University of Hamburg

Submitted by

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2020 in Hamburg

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# *CONTENTS*

**The truth is rarely pure and never simple.**

*Oscar Wilde*

## SUMMARY

The future availability of fisheries resources is highly dependent on international coordination of management decisions, environmental conditions as well as fleet behaviour. Managing straddling and transboundary stocks (i.e. crossing Exclusive Economic Zone boundaries into adjacent international waters) is currently especially difficult due to many changes. Two such stocks, that are highly valuable for European fleets and provide many job opportunities, are the Northeast Atlantic (NEA) mackerel (*Scomber scombrus*) and North Sea autumn spawning (NSAS) herring (*Clupea harengus*) stocks. Current conflicts resulting from lack of management coordination or changes in environmental conditions seem, however, to threaten the status of those two stocks. These, in turn, can massively impair the livelihood of European fleets and corresponding employees targeting NEA mackerel and NSAS herring. It is therefore important to evaluate the effects of new management measures and other major impact factors on both the resource availability as well as the fleet behaviour as they are interdependent. Dynamic bio-economic models are now more commonly used as tools for fisheries management. They incorporate anthropogenic as well as natural processes to generate a better understanding of feedback mechanisms between the two systems. This thesis addresses the need to evaluate the impacts of current environmental, economic and political issues on the highly valuable NEA mackerel and NSAS herring stocks and the corresponding fisheries by applying and further developing the FishRent model. It is an age-structured simulation and optimization model that incorporates detailed stock and fleet dynamics on a short- to mid-term time-frame. By identifying the optimal effort allocation under a set of constraints, it can determine the equilibrium state that optimises a certain target variable, i.e. net profit.

In the **first chapter,** the structure of eight pelagic fleets was investigated in order to understand the underlying data and illustrate possible differences. Furthermore, an existing version of FishRent was adapted from a demersal fishery to the pelagic and impacts of external factors (i.e. changes in recruitment, fish and fuel prices and an adaptation of the quota repartition key) on fleet net profit and stock biomass availability were determined on a temporal scale. In all scenarios, the Irish and German fleets were most vulnerable due to being very close to the economic break-even point. The implementation of a new quota repartition key according to biomass distribution of NEA mackerel and NSAS herring had the largest effect on all fleets, leading to losses of the German, Dutch and Danish fleets. The UK and Irish fleets, on the other hand, more than doubled their profit within a year. Alterations in fish and fuel prices had the second largest impacts on the eight fleets and the UK, Icelandic and large-scale Irish fleets had to disinvest nearly half of their fleet due to reporting losses. Reduced recruitment and a continued NSAS herring recruitment failure had the least influence on fleet profit compared to the other scenarios tested within this Chapter.

The **second chapter** investigated the necessary degree of spatial complexity in order to incorporate seasonal migration patterns and tested if the model could predict the economic consequences of a theoretical NSAS herring spawning ground closure. Results highlighted the need for a relatively high resolution when trying to understand effects on fleet behaviour but for impacts on the general trend of pelagic stocks, a temporal version of the model does suffice. During the process, the limits (e.g. the relatively static fleet behaviour generated by the underlying data) were illustrated. Closing the major spawning grounds in order reduce the fishing pressure on the NSAS herring stock and therefore aid in its recovery, did not have the expected effect. The impact on biomass levels were relatively small.

In the **third chapter,** dynamic migration patterns, in which the spatial spread of the stock is determined by the biomass level, were incorporated to consider density dependent mechanisms. Furthermore, different fishing pressures were tested in three levels by implementing different total allowable catches: 1) according to ICES advice (low TAC), 2) business as usual (continuation of current TAC level), or 3) continuing without any agreement concerning the share of the NEA mackerel stock (high TAC). The reduced TAC scenario was the only one in which biomass levels were high enough to generate a north-western expansion of the NEA mackerel stock. This primarily benefitted the Irish and UK fleets, while effects on the Icelandic fleet were neutral. When continuing business as usual or even further increasing the TAC, the NEA mackerel biomass always decreased to the precautionary limit (Bpa) on the long-term, generating a retreat to its core areas. All fleets, except for the Danish, were negatively affected and indicated losses.

## *ZUSAMMENFASSUNG*

Die zukünftige Verfügbarkeit von Ressourcen hängt in hohem Maße von der internationalen Management-Zusammenarbeit der Nationen, Management Entscheidungen, Umweltbedingungen sowie dem Flottenverhalten ab. Aufgrund von Veränderungen in allen drei Bereichen ist die derzeitige Bewirtschaftung gebietsübergreifender Bestände besonders schwierig. Zwei betroffene Fischbestände, die für europäische Flotten sehr wertvoll sind und viele Beschäftigungsmöglichkeiten bieten, sind Makrele im Nordost Atlantik (*Scomber scombrus*) und herbstlaichender Hering (*Clupea harengus*) in der Nordsee. Aktuelle Konflikte, z. B. infolge von Veränderungen der Umweltbedingungen, scheinen jedoch den Status dieser beiden Bestände zu gefährden. Dies wiederum kann die Existenzgrundlage der europäischen Flotten, die auf Makrele und Hering abzielen, massiv beeinträchtigen. Daher ist es wichtig, die Auswirkungen neuer Managementmaßnahmen und anderer Einflussfaktoren sowohl auf die Ressourcenverfügbarkeit als auch auf das Flottenverhalten zu bewerten, da beide voneinander abhängig sind. Dynamische bioökonomische Modelle werden zunehmend als Instrumente für das Fischereimanagement eingesetzt. Sie integrieren sowohl anthropogene als auch natürliche Prozesse, um ein besseres Verständnis der Rückkopplungsmechanismen zwischen den beiden Systemen zu generieren. Diese vorliegende Arbeit befasst sich mit der Notwendigkeit, die Auswirkungen aktueller ökologischer, wirtschaftlicher und politischer Fragen auf die hochwertvollen Makrelen- und Heringsbestände und die entsprechende Fischerei zu quantifizieren, indem das FishRent-Modell angewendet und weiterentwickelt wurde. Es handelt sich um ein altersstrukturiertes Simulations- und Optimierungsmodell, das eine detaillierte Bestands- und Flottendynamik über einen kurz- bis mittelfristigen Zeitrahmen enthält. Durch die Ermittlung der optimalen Aufwandszuweisung unter einer Reihe von Bedingungen kann ein Gleichgewichtszustand bestimmt werden, der eine bestimmte Zielvariable optimiert, in diesem Fall der Nettogewinn.

Im **ersten Manuskript** wurde die Struktur von acht pelagischen Flotten untersucht, um die zugrundeliegenden Daten zu verstehen und mögliche Unterschiede zu veranschaulichen. Darüber hinaus wurde eine bestehende Version von FishRent von einer Grundfischerei an die pelagische Fischerei angepasst und Auswirkungen externer Faktoren (d. h. Änderungen bei der Rekrutierung, Fisch- und Kraftstoffpreise und Anpassung des Quotenschlüssels) auf die Rentabilität der Flotte und die Verfügbarkeit von Biomassebeständen über die Jahre ermittelt. In allen Szenarien waren die irische und die deutsche Flotte am verwundbarsten, weil sie dem ökonomischen Break-Even-Punkt sehr nahe waren. Die Einführung eines neuen

Quotenschlüssels aufgrund der Biomasseverteilung von Makrele und Hering hatte den größten Einfluss auf alle Flotten, was zu Verlusten der deutschen, niederländischen und dänischen Flotte führte. Die britischen und irischen Flotten hingegen mehr als verdoppelten jedoch ihren Profit innerhalb eines Jahres. Änderungen der Fisch- und Kraftstoffpreise hatten die zweitgrößten Auswirkungen auf die acht Flotten, denn die britischen, isländischen und großen irischen Flotten mussten ihre Flottengröße fast halbieren. Ein anhaltendes Versagen bei der Herings-Rekrutierung hatten im Vergleich zu den anderen in diesem Manuskript getesteten Szenarien den geringsten Einfluss auf die Flottenrentabilität.

Das **zweite Manuskript** untersuchte den notwendigen Grad an räumlicher Komplexität, um saisonale Migrationsmuster zu integrieren. Mit diesem Modell wurden die ökonomischen Folgen einer Laichgebietssperrung getestet. Die Ergebnisse zeigten die Notwendigkeit einer relativ hohen räumlichen Auflösung, um Auswirkungen auf das Flottenverhalten zu verstehen, aber für Auswirkungen auf die allgemeine Entwicklung der pelagischen Bestände genügt eine zeitliche Version des Modells ohne räumliche Auflösung. Dabei wurden die Daten-Grenzen des relativ statischen Flottenverhaltens sichtbar, welches sich aus den besonderen Anforderungen an die Produktqualität und der speziellen Biologie des Herings ergibt. Die Schließung der wichtigsten Laichgründe, um den Fischereidruck auf den Heringsbestand zu verringern und somit bei seiner Erholung zu helfen, hatte nicht die erwartete Wirkung. Die Auswirkungen auf die Biomasse waren demnach relativ gering.

Im **dritten Manuskript** wurden dynamische Migrationsmuster, in denen die räumliche Ausbreitung durch die Gesamtbiomasse bestimmt wird, eingebaut, um dichteabhängige Mechanismen zu berücksichtigen. Darüber hinaus wurden drei Levels des Fangdrucks durch die Einführung verschiedener zulässiger Gesamtfangmengen getestet: 1) nach ICES-Empfehlung (niedriger TAC), 2) eine Weiterführung des momentanen Zustandes (jetziges TAC Level bleibt) oder 3) keine Vereinbarung über den Anteil des Makrelenbestands (hoher TAC). Das reduzierte TAC-Szenario war das einzige, bei dem die Biomasse hoch genug war, um eine Ausweitung des Makrelenbestands in Richtung Nordwestatlantik zu erlauben. Dies begünstigte in erster Linie die irische und die britische Flotte, während die Auswirkungen auf die isländische Flotte neutral waren. Bei der Fortsetzung des momentanen TAC-Levels oder sogar noch einer Erhöhung, sank die Makrelenbiomasse langfristig immer auf die untere erlaubte Biomassegrenze (Bpa) ab und zog sich in ihre Kernbereiche zurück. Alle Flotten mit Ausnahme der dänischen Flotten wurden negativ beeinflusst und verzeichneten Verluste.

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18.10.2020

To whom it may concern.

I have examined the PhD thesis prepared by Sandra Rybicki titled 'Evaluating the spatio-temporal impacts of environmental, political and economic changes on the Northeast Atlantic mackerel and herring fisheries and stocks'. The thesis is written in English. As a native English speaker and a former Professor in the Department of Biology at the University of Hamburg, I can attest that the writing is of sufficient quality for the thesis to be submitted and reviewed.

If you have any questions or need additional information, please do not hesitate to contact me.

Sincerely,

Dr. Myron A. Peck

## *OUTLINE OF PUBLICATIONS*

The following overview outlines the three publications, which are included in this thesis. This outline serves as a clarification of each author's contribution to the respective Chapter.

## CHAPTER 1

**To fish or not to fish - Economic perspectives of the pelagic Northeast Atlantic mackerel and herring fishery**

*Sandra Rybicki, Katell G. Hamon, Sarah Simons, and Axel Temming*

Sandra Rybicki (SR) gathered the underlying data, performed the analyses, designed the graphics and wrote the text in close cooperation with Axel Temming (AT) and Katell Hamon (KH), who also critically reviewed the Chapter. Sarah Simons (SS) provided the scripts of the basic version of FishRent and reviewed the Chapter.

The Chapter is published in the peer reviewed *Frontiers in Marine Science* journal (2020).

Doi: 10.3389/fmars.2020.00625

## CHAPTER 2

**The more the merrier? Testing spatial resolution to simulate area closure effects on the pelagic North Sea autumn spawning herring stock and fishery**

*Sandra Rybicki, Katell G. Hamon, Sarah Simons, and Axel Temming*

Sandra Rybicki (SR) gathered the underlying data, performed the analyses, designed the graphics and wrote the text in close cooperation with Axel Temming (AT) and Katell Hamon (KH), who also critically reviewed the Chapter. The co-author Sarah Simons (SS) reviewed the Chapter.

The Chapter is submitted to the peer reviewed Journal *Regional Studies in Marine Science*.

## CHAPTER 3

**Less catch, more biomass? Simulating the future of Northeast Atlantic mackerel and its fishery**

*Sandra Rybicki, Katell G. Hamon, Sarah Simons, and Axel Temming*

Sandra Rybicki (SR) gathered the underlying data, performed the analyses, designed the graphics and wrote the text in close cooperation with Axel Temming (AT) and Katell Hamon (KH), who also critically reviewed the Chapter. The co-author Sarah Simons (SS) reviewed the Chapter.

The Chapter is submitted to the peer reviewed Journal *Marine Policy*.

## Further publications (not included in this thesis):

Pinnegar, J.K., Hamon, K.G., Kreiss, C.M., Tabeau, A., **Rybicki, S.**, Papathanasopoulou, E., Engelhard, G.H., et al. 2020. Future socio-political scenarios for aquatic resources in Europe: a common framework based on shared-socioeconomic-pathways (SSPs). *Accepted in Frontiers of Marine Science*.

Hamon, K.G., Kreiss, K., Pinnegar, J.K., Batsleer, J., Catalan, I., Damalas, D., Poos, J., **Rybicki, S.**, et al. 2020. Future socio-political scenarios for aquatic resources in Europe: an operationalized framework for marine fisheries projections. Frontiers to Marine Science. *Under revision in Frontiers of Marine Science*.

Kreiss, C.M., Papathanasopoulou, E., Hamon, K.G., Pinnegar, J.K., **Rybicki, S.**, Micallef, G., Tabeau, A., et al. 2020. Future socio-political scenarios for aquatic resources in Europe: an operationalised framework for aquaculture projections. Frontiers to Marine Science, 7: 568159. Doi:10.3389/fmars.2020.568159

Sulanke, E., **Rybicki, S.** 2020. Community Development Quotas and support of small-scale fisheries as two key concepts of the UKs post-Brexit fisheries Blue Growth strategy. For the ICYMare Book 2021. *Submitted.*

Hereby, I confirm the accuracy of the statements above

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## *GENERAL INTRODUCTION*

North Sea autumn spawning herring (*Clupea harengus*) and Northeast Atlantic (NEA) mackerel (*Scomber scombrus*) are economically the most important pelagic species within the European pelagic fishery sector. They are listed as the most important species in terms of landed weight and are within the top five species regarding landed value (STECF, 2018). In 2016, for example, 456 thousand tonnes of North Sea herring and 460 thousand tonnes of NEA mackerel were landed (STECF, 2018). Also in 2016, the main EU member states (MS) operating and earning the most in both the mackerel and herring fishery were the UK, Denmark and the Netherlands with vessels over 40m in size (STECF, 2018). Catches were almost exclusively exported as frozen products dominated by the Dutch fleet, which accommodates the largest EU freezer trawler company (EUMOFA, 2018). Main destinations are Nigeria, Egypt and Morocco, except for the Irish fleet where Japan represents an additional significant market (EUMOFA, 2018). After salmon, herring is the second most traded species within the EU, primarily sold as frozen and fresh (EUMOFA, 2018). European fleets targeting herring for human consumption operate primarily in ICES subareas 4 and 7d aiming for NSAS herring by using various types of trawls, such as pelagic trawlers, purse seines or lines and hooks (ICES, 2018a/b; STECF, 2018). This stock component, together with NEA mackerel, will therefore be the focus in this thesis. In order to determine the impacts of external factors on both the stocks and the fishery, it is crucial to understand the underlying ecology and economic structure first.

### North Sea autumn spawning herring

Several populations of Atlantic herring inhabit the NEA. However, one of the most important for the European pelagic fishery is the North Sea autumn spawning (NSAS) herring population (Bailey and Steele, 1992; STECF, 2018). It consists of four major components that are defined by their spawning locations, recruitment patterns and migration routes as well as growth rates: The Shetlands/Orkneys component, the Buchan, the Banks and the Downs component (Dickey-Collas et al., 2010; Figure 1). Yet, these components mix during part of the year, while being separated during the spawning season in the third and fourth quarter (Daan et al., 1990; Dickey-Collas et al., 2010). Mixing of NSAS herring with other stocks, such as small proportions of spring spawning herring, does occur and during certain times of a year both might be exploited together (Dickey-Collas et al., 2010). Within the North Sea, the NSAS herring stock size is, however, much larger and mixing effects are therefore thought to be minor (Simmonds, 2009).

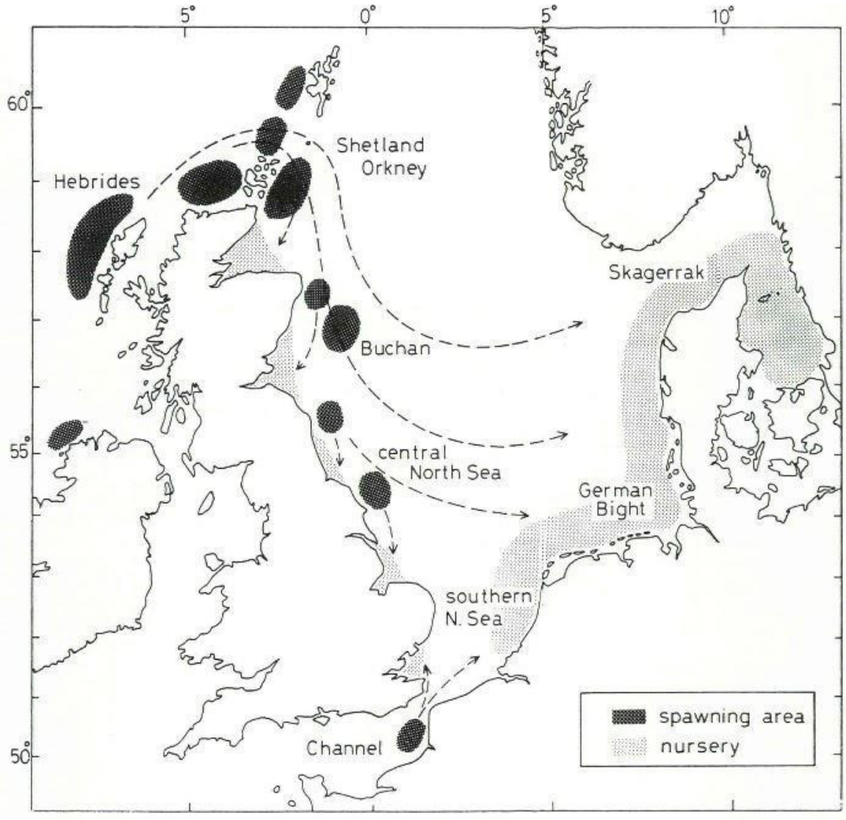


**Figure 1.** Spawning components of NSAS herring defined by the different spawning locations (marked in black; Corten and van de Kamp, 1992). Grey shades indicate nursery sites and arrows show the drift of herring larvae.

Spawning starts in the north during August and continues south until December (Hempel and Blaxter, 1967). When spawning, herring attach their eggs to specific substrates (coarse sand, gravel and small stones) of the seabed, hence being relatively dependent on suitable conditions (Daan et al., 1990). However, even when suitable conditions are given, spawning grounds can change over time, depending on the stock size. When the stock collapsed in the 1970s, the spawning ground on the Dogger Bank, for instance, was abandoned (Daan et al., 1990). After spawning, larvae hatch and drift towards the south-eastern North Sea (mainly Dutch, German and Danish waters) where the nursery grounds are situated. In recent years, recruitment continues to be low and highly variable despite high biomass levels (Corten and van de Kamp, 1992; Nash et al., 2009; Dickey-Collas et al., 2010). Multiple conditions are suspected to have caused these low recruitment values. First, bottom-water temperature around the spawning sites has increased, which has a negative impact on the metabolic rates and therefore on development times of larvae (Nash and Dickey-Collas, 2005; Corten, 2013). Second, a shift in the planktonic community occurred, induced by changes in the physical environment, affecting the survival of herring larvae due to a reduced food availability (Gröger et al., 2009; Payne et al., 2009).

With an age of approximately eighteen months, the young fish move to the central North Sea (Daan et al., 1990). The older they become the further north they move. Adult herring mainly migrate from the spawning grounds along the eastern Scottish and English coast in autumn to the north-western North Sea and Norwegian Trench to overwinter and continue north in spring and summer where they feed between the Shetlands and Norway (Corten, 2001; Figure 2).

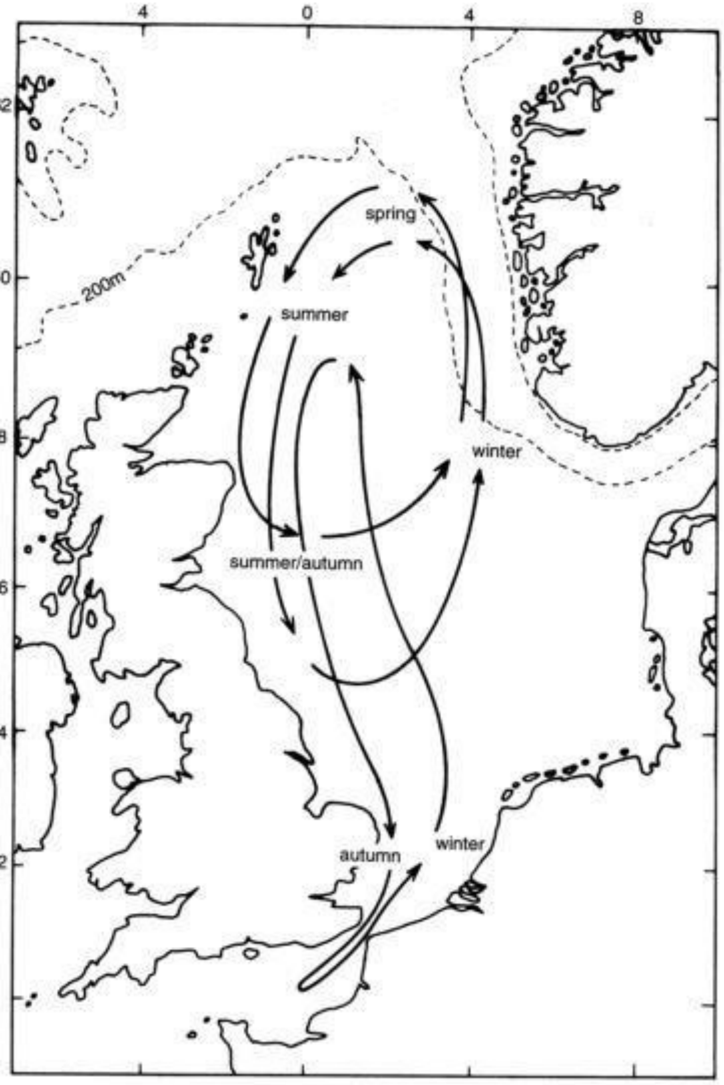


**Figure 2.** Spawning migrations of the different NSAS herring components (Corten, 2001).

*Fishery* – Over time, the NSAS herring stock has been heavily exploited and different components of the population have been targeted by different pressures (Cushing, 1992). Even though different components of the NSAS herring have been recognised, they are managed as one (Reiss et al., 2009; Simmonds, 2009). In the 1970s, the whole North Sea stock collapsed and the fishery had to be closed completely for five years (Figure 3). During this time period, the North Sea was still exploited by fourteen different nations being a free fishing area. Implementing a closure was problematic because the agreement of all nations was necessary

(Simmonds, 2007; Dickey-Collas et al., 2010). Moreover, there was no international inspection system active, hence many parties were afraid others might not implement catch restrictions. Other concerns were economic effects and the bankruptcy of a lot of companies (Dickey-Collas et al., 2010). After 1977, the introduction of 200 miles Exclusive Economic Zones (EEZs) restricted the fishing area and allowed national governments to implement management measures in their EEZ (Steel, 1977). The British were the first to close the herring fishery in the same year.

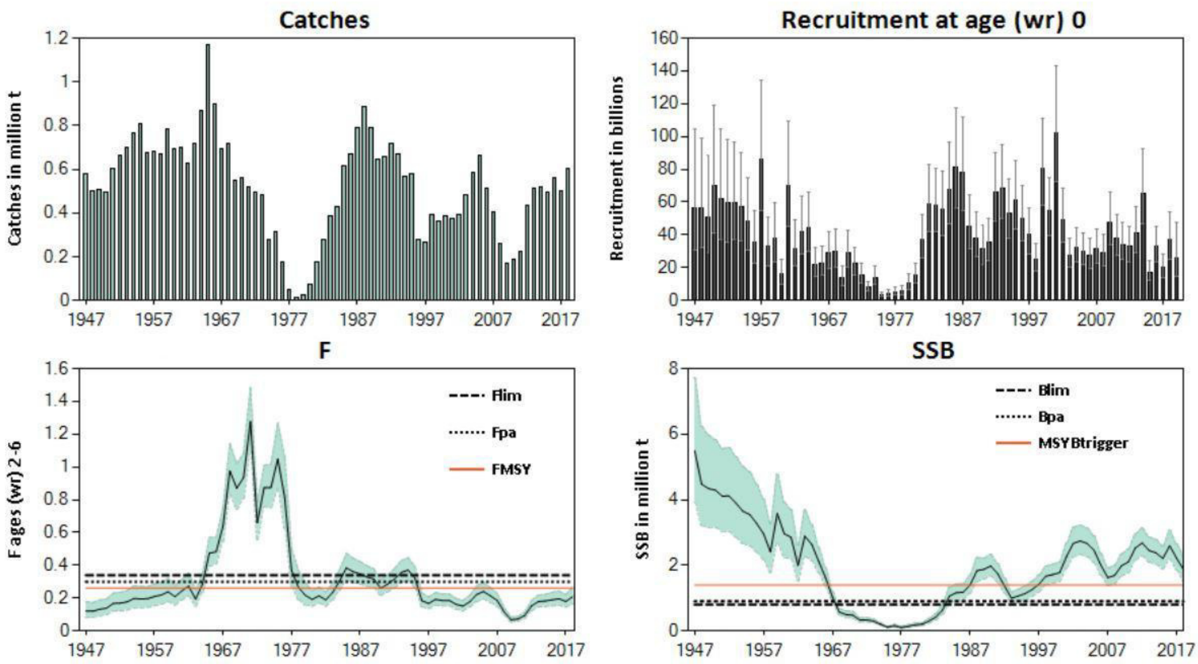


**Figure 3.** History of catch (in million t), recruitment (in billions), fishing mortality (F) and spawning stock biomass (SSB; in million t; ICES, 2019a). The solid red line indicate the level of F and SSB at MSY, the dotted line the precautionary level and the dashed line the level at the point of limit.

Other nations, however, continued to fish and illegally entered the British EEZ, almost resulting in a herring war (Dickey-Collas et al., 2010). It was stopped by the end of 1977 due to continued scientific advice to close the fishery, although small amounts of herring could still be landed as bycatch. At the same time, the Common Fisheries Policy was implemented (Steel, 1977). Yet, the different components of the NSAS herring did not have the same recovery trajectories, i.e. it took around 25 years to observe larger year-classes of the Downs component in the southern North Sea once again (Dickey-Collas et al., 2010). After reopening the fishery in 1983, for example, fishermen reported the absence of NSAS herring from the traditional western North Sea fishing grounds. Instead, they had to drive much further towards the north, where a very high abundance of herring was recorded (Corten et al., 1991), implying that the Orkney/Shetland component recovered much faster than the southern. Economic effects were significant, as expected: Many companies went bancrupt, fleets decreased in size (e.g. the Dutch had around 50 vessels targeting herring before the closure and only around 12 after), the UK even started to import herring products, the canning industry in Germany suffered massively and the consumer behaviour changed (Dickey-Collas et al., 2010). Moreover, prices decreased as the traditional market had disappeared and the first landings after the closure had to be used for fishemeal. Scandinavian fleets took over the Dutch market as they were still allowed to fish for spring spawners in the Kattegat and Skagerrak area (Nielsen and Olesen, 2008; Dickey-Collas et al., 2010). Due to the lack of local buyers, most of the UK catch was sold to processing vessels from eastern Europe in the 1980s (Wood and Hopper, 1984). This is when the Dutch fishery started to increase their mackerel and horse mackerel catch along the western British Isles. As these species could not be preserved in the same way as herring could (e.g. in brine), freezer trawler vessels were built. Later on, these were, and still are, also used for catching herring (Dickey-Collas et al., 2010). Currently, most NSAS herring is caught along the north-western Scottish coast and around the Orkneys and Shetland Islands during the third season. Additonally, an important herring roe fishery developed in the English Channel targeting the Downs component during the fourth season (Figure 4).

*Products* – As just mentioned, herring roe is an essential product that evolved after increasing catch again during the 1980s (Herrfurth, 1986; Bledsoe et al. 2003). The largest amount is exported to Japan, primarily relying on foreign herring roe products and hence promoting competition with the yet higher valued Pacific herring roe. NSAS herring caught for the purpose of roe sales is almost completely targeted in the English Channel in December, sometimes with Japanese customers onboard who assess the product quality. If it is good enough, the herring is shipped to Japan in frozen blocks and then thawed for sale and further processing (Herrfurth, 1986). For other products, NSAS herring is processed by curing (e.g. kipper, red herring or Bückling), salting, marinating (e.g. with mayonnaise or pickled) and canning (Tülsner and Koch, 2010). Herring is a very popular fish for which many different recipes exist all over Europe. For these products, size and fat content are of high importance during processing. If the fat content is too high, for example, the fish can be damaged more easily. “Matjes”, a very popular product in the Netherlands and Germany, needs a fat content around 12% without externally visible roe development. A thorough description of the different processing possibilities and necessities can be found in Tülsner and Koch (2010).

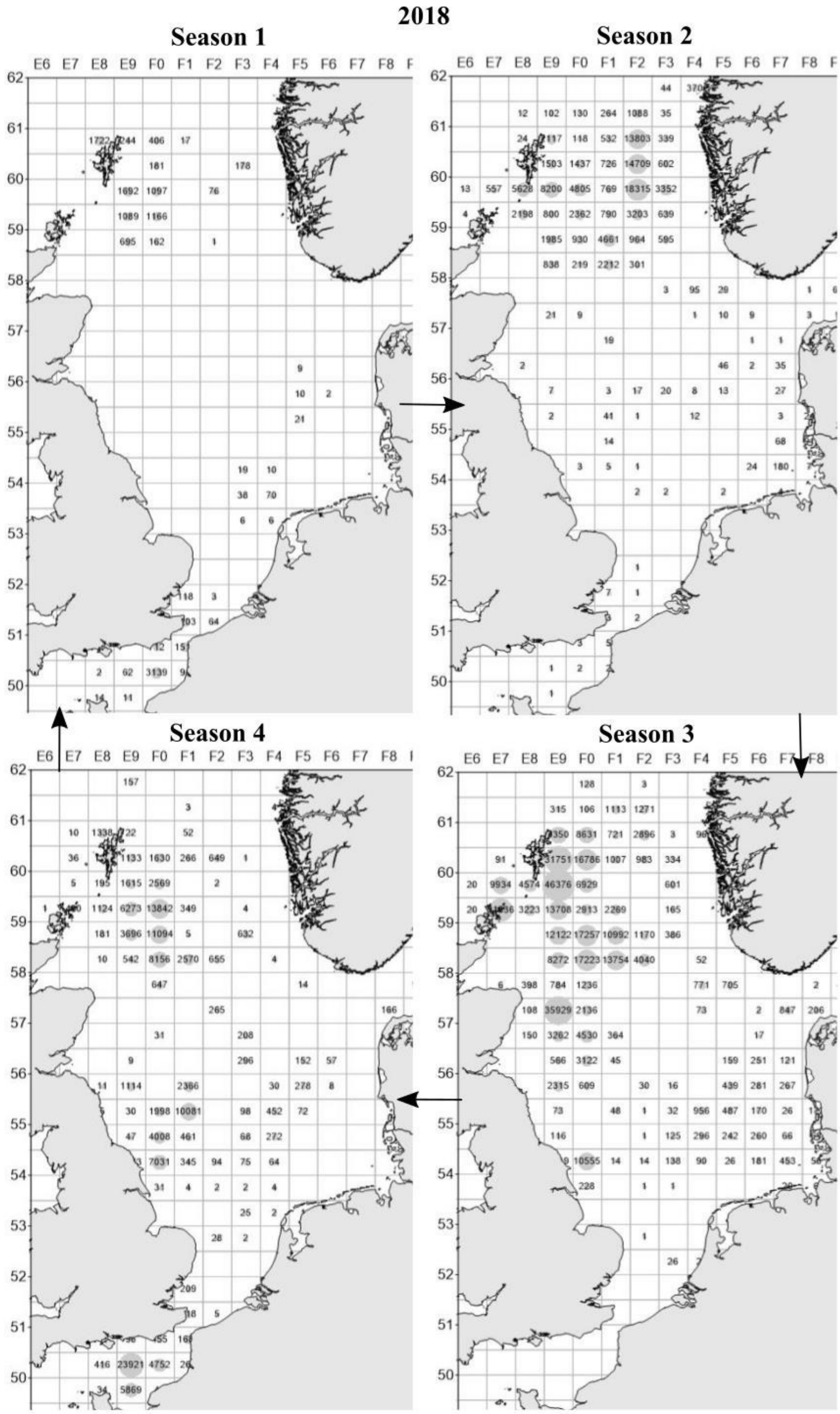


**Figure 4.** NSAS herring catch distribution in each season (i.e. quarter) of 2018 (ICES, 2019b).

*Management* – Assessments of NSAS herring have been conducted since the 1960s. In between 1990 and 1996, the total allowable catch (TAC) was set more or less according to advice. In 1996, a harvest control rule was also put in place, which is reviewed every three years. However, the stock biomass decreased again after the mid-2000s, caused by the already mentioned poor recruitment as well as the repeated disregard of advised TAC reductions (Dickey-Collas et al., 2010). Currently, the NSAS herring stock is thought to be managed well. Spawning stock biomass (SSB) is yet above $MSYB_{trigger}$ but recruitment continues to be low and SSB also shows a decreasing trend towards $MSYB_{trigger}$ (ICES, 2019a). In addition, no harvest control rule is currently active but the advice categorises NSAS herring as harvested sustainably (ICES, 2019a).

**Northeast Atlantic mackerel**

Northeast Atlantic mackerel (NEA mackerel) is a widely distributed stock, historically ranging from Morocco and the Mediterranean to the Faroe Islands, Norway and the Baltic Sea (Iversen, 2002). It is a stock crossing many EEZ boundaries as well as high seas, also called a straddling and transboundary stock (Bjørndal and Munro, 2020). The NEA mackerel stock is subdivided into three components according to their spawning areas, i.e. the North Sea, southern and western component, which is currently assessed to be the largest (Iversen, 2002; Jansen and Gislason, 2013). It migrates very far between its spawning and feeding grounds: Spawning starts in spring and early summer along the western British Isles and coast as well as western France. In summer, they migrate north towards the Orkneys and Shetland Islands as well as the Faroe Islands and Norway to feed (Figure 5; Iversen, 2002; Berge et al., 2014; Hughes et al., 2015; ICES, 2019c). During winter, migrations reverse towards the spawning grounds. Since 2007, NEA mackerel has been observed to expand its feeding activities up to Iceland, Greenland and northern Norway (up to Isfjorden, Svalbard; Berge et al., 2014), while the spawning area has also increased. Interestingly, the perspectives of historic NEA mackerel migration ranges vary greatly. As to Ehrenbaum (1914), a French admiral apparently noted the appearance of thousands of mackerel along the Greenland coast in spring during the 1750s, hibernating with their heads buried in mud. The more general view during the mid to late 1800s was, however, rejecting the theory of hibernating mackerel at the bottom during winter (Sars, 1869/1878; Allen, 1898). At the end of the 1800s and beginning of the 1900s, the different spawning components were already recognized (Garstang, 1898; Ehrenbaum, 1914) and new tagging experiments after 1950 further specified the components and migration routes (Figure 5; ICES, 1974; Iversen and Skagen, 1989). Already during the 1970s, a change in NEA mackerel stock distribution took place, which was noted by a shift of major fishing areas in the early 1980s towards the Norwegian Sea (Figure 5; Walsh and Martin, 1986). This change was thought to have occurred due to variations in oceanographic conditions, leading to an overfishing and collapse of the stock in 1970. Yet, it was only confirmed since 1988 and 1990 that NEA mackerel do not spawn along the coast but rather in open waters around the 200m depth line (ICES, 1988/1990). In the late 1990s, it was hypothesized that these migrations might be influenced by water temperature (Reid et al., 1997).

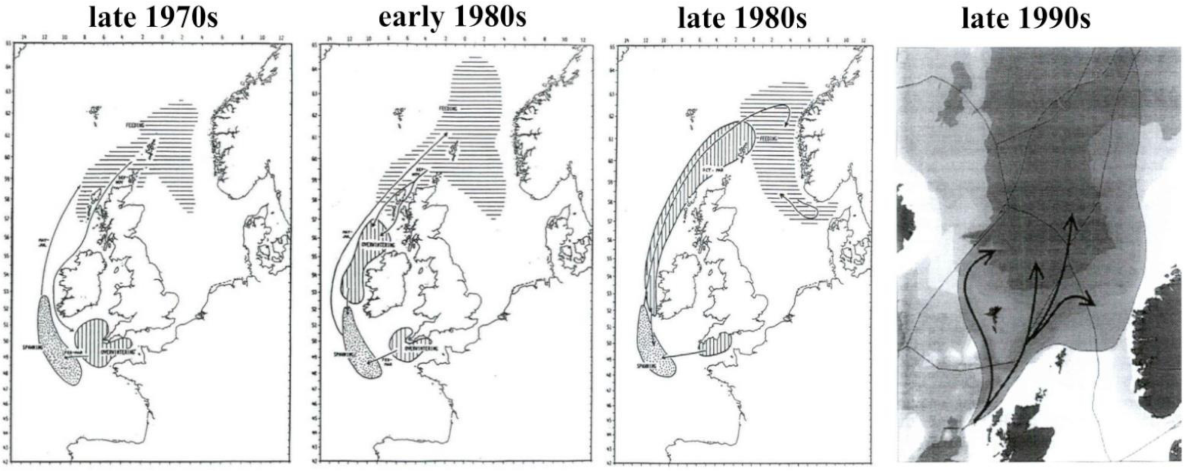


**Figure 5.** Migration pattern of the western NEA mackerel component in the late 1970s (left), early (middle) and late (right) 1980s as well as late 1990s (ICES, 1990; Belikov et al., 1998; Iversen, 2002). Horizontally lined patches represent the historical feeding areas, vertically lined patches the overwintering and dotted patches the spawning areas.

As to the currently observed expansion, several hypothesis exist. The most widely distributed one is that a larger stock size and changed environmental conditions, i.e. warmer waters around Iceland, have caused this phenomenon (e.g. Astthorsson et al., 2012; Berge et al., 2014). The question, however, remains if this is a long-term change also in terms of climate change or if this expansion only occurs temporarily during warmer periods.

*Fishery* – First, catch in the North Sea was not very high (<100ktons before 1965) but when the migration patterns of the Western component changed towards the North Sea and Norwegian Sea, catch increased substantially in the North Sea (up to nearly 1,000ktons) and a new fishery started in the Norwegian Sea after the 1980s (Figure 6; Iversen, 2002). Until the 1970s though, the NEA mackerel stock was unregulated and the fishery expanded rapidly resulting in a collapse of the North Sea component of the stock. Hence, quotas were introduced as well as closed areas and the focus of catch shifted towards the western and southern component (Iversen, 2002).

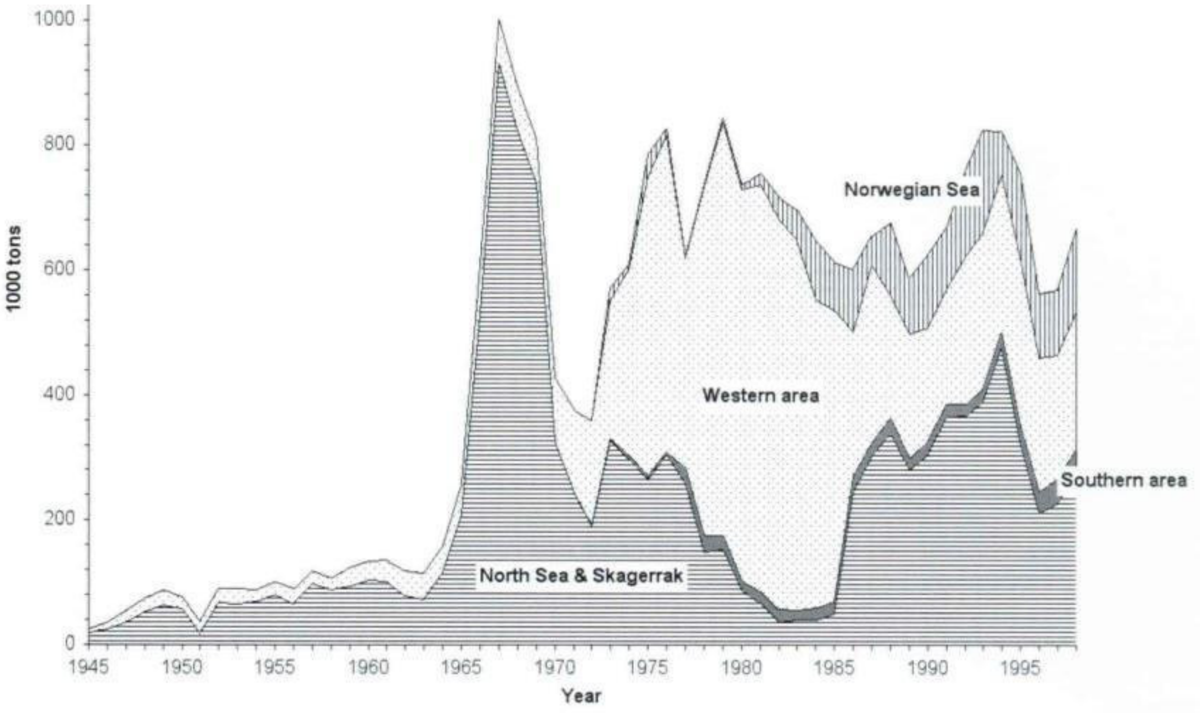


**Figure 6.** Catch of mackerel in different areas of the Northeast Atlantic from 1945-1998 (Iversen, 2002).

After a quota agreement in 1999, the stock was mainly fished by the European Union (EU), Norwegian and Faroese fleets (Østhagen et al., 2020). Since 2007, new players appeared when another change in migration patterns occurred towards the north-western Atlantic: The Faroe Islands and Iceland started to target NEA mackerel unilaterally, increasing their catch by 340% and 6500% respectively (Cendrowicz, 2010). Later on, Greenland also joined. The EU and Norway opposed this step and discussions about access rights to those fishing grounds started. Straddling and transboundary stocks, like NEA mackerel, and their fisheries are currently managed by the 1995 United Nations Fish Stocks Agreement (Bjørndal and Munro, 2020). This is done via Regional Fisheries Management Organisations (RFMOs), which include the EU, Iceland, the Faroe Islands, Greenland, Norway and Russia. In this region, the RFMO is called North East Atlantic Fisheries Commission (NEAFC; Østhagen et al., 2020). The United Kingdom (UK) might join as an additional member after the exit from the EU (Bjørndal and Munro, 2020). Unfortunately, the convention does not require the corresponding coastal states to reach an agreement over fishing rights. An attempt to settle the dispute and reach an agreement is proof enough to have acted. If this fails, each state is required to manage their share the best way they are able to (Bjørndal and Munro, 2020). Iceland claimed their right on a share of the stock, stating that the mackerel fishery has historically been important for their country (Fontaine, 2015). Iceland did not join any negotiations until 2010, when they officially received the Coastal State status now having a claim to a share of the TAC (Østhagen et al., 2020). This claim, based on historic catches, was primarily opposed by Norway and quota proposals varied between 5% by Norway and 16% by Iceland. Finally, Iceland received 0.31% instead of 16% of the TAC, which they did not accept and further negotiations have yet failed (Østhagen et al., 2020). The Faroe Islands, on the other hand, agreed to a long-term management plan receiving approximately 15% of the annual TAC (Østhagen et al., 2020). The still unresolved conflict gradually resulted in an overfishing of the NEA mackerel stock. Within 15 years (1998-2013), ICES advised quotas in between 300,000 and 700,000t. The actual catch, however, was at least 100,000t more than the advised annual TAC (Cendrowicz, 2010; Østhagen et al., 2020). A major problem during the negotiations was the interpretation of the current stock increase and shift/expansion: Iceland claimed this pattern would be long-term due to increasing water temperatures through climate change, whereas the EU and Norway thought it to appear rather irregularly (Gänsbauer et al., 2016). An important point to understand Iceland's position in these negotiations is their economic structure: It is heavily dependent on their fisheries, employing 7% of the Icelandic population and generating a revenue of approximately 22% of total exports (Hotvedt, 2010; Islandsbanki, 2016). Moreover, the Ministry works in close cooperation with the fishing industry. In 2016, the NEA mackerel fishery suddenly accounted for 8% of the total catch volume hence being increasingly important for the economic sector in Iceland (Win, 2017). On the Faroe Islands, the fishing sector employs double as many workers as in Iceland, i.e. 16% (Hotvedt, 2010). Again, the fishing sector is significant and cooperation between the industry and politics are very close (Østhagen et al., 2020). The same applies to Norway and as the NEA mackerel fishery is the second most valuable after cod, the influence of the fisheries sector during the negotiations was considerable (Statistics Norway, 2018). Within the EU, on the other hand, several member states are involved in targeting NEA mackerel, which primarily are Denmark, Germany, the Netherlands, Ireland and the UK. Currently, the EU fleets fish most of NEA mackerel during in season one (along the western Irish and UK coast) and season four (around the Orkney and Shetland Islands; Figure 7). Norway and Iceland catch most mackerel when it migrated towards its feeding grounds in the third season (Figure 7).

*Products* – Mackerel is highly suitable for hot and cold curing, either whole, as filet or gutted and split along the back (so-called "Fleckmakrele"; Tülsner and Koch, 2010). Mackerel filets are also sold fresh, in cans with different types of marinades, as surimi or salted. A thorough description of the different processing possibilities and necessities can be found in Tülsner and Koch (2010).

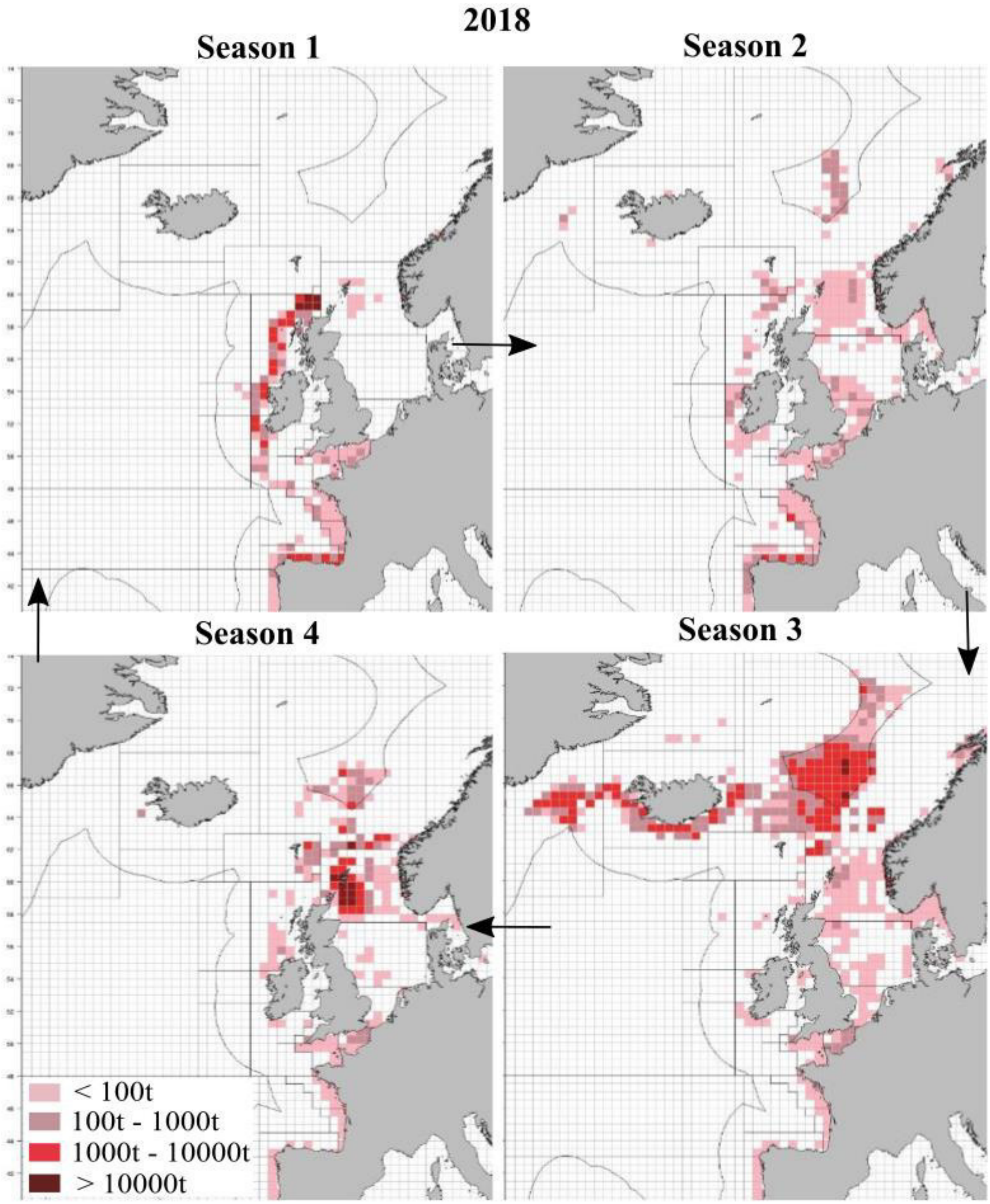


**Figure 7.** NEA mackerel catch distribution in each season of 2018 (ICES, 2019c).

*Management* – As already mentioned above, the current political situation and management of NEA mackerel is somewhat difficult. In addition, the ICES assessment varied to a great extend during the last couple of years (Figure 8). In 2017, SSB was estimated to be around 4 million t between 2011 and 2015, yet decreasing again to approximately 3.9 million t (Figure 8; ICES, 2017). During these years, fishing mortality was estimated to be close to the precautionary limit of 0.36, hence being well above $F_{msy}$. After an evaluation of methods at the beginning of 2019, SSB was estimated to have increased up to 5 million t in 2014, subsequently decreasing again to approximately 4.2 million t (less rapid though; Figure 8). Fishing mortality was now estimated to be around 0.29, hence in between $F_{msy}$ and $F_{pa}$ (ICES, 2019e). The estimates were even more positive during the assessment at the end of 2019, where SSB was expected to continue on a level around 4.2 million t in 2020 instead of further decreasing. A large change in fishing mortality could be noticed, which was estimated to continually decrease from 0.3 in 2007 to nearly $F_{msy}$ (0.23) in 2020 (Figure 8; ICES, 2019d).

In the age-based model of stock assessments, it is common to use commercial as well as scientific survey data. In case of NEA mackerel, data of three scientific surveys are utilized: the triannual mackerel egg survey, the International Bottom Trawl Survey (IBTS) in season one and three and Norwegian tagging data (ICES, 2019c/d/e). In the new assessment, a different data weighting procedure lead to an adjustment of the biological data, therefore increasing the influence of the tagging data on the assessment results (ICES, 2019c/d/e). Hence, a much more positive perception of the population was estimated, leading to an improved catch advice. Different future management strategies might need to be constructed to react to both developments of the stock, an increase as well as a decrease in stock size.

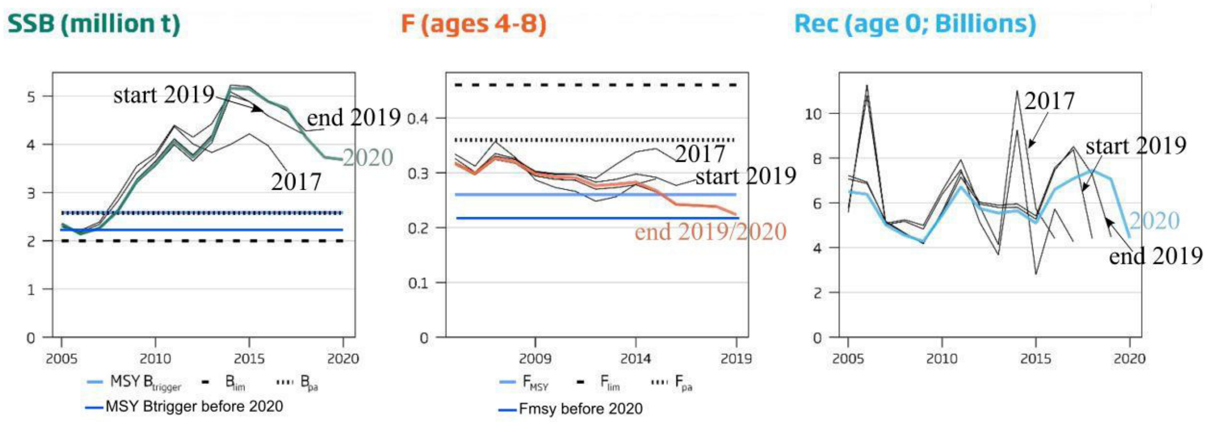


**Figure 8.** History of SSB (in million t), fishing mortality (F) and recruitment (in billions) from 2005 until 2020 (ICES, 2020). Shown are results from different assessments (2017, start 2019, end 2019 and 2020).

**Further Impacts**

Many factors can influence the stocks and the behaviour of fishermen. These can be of environmental origin (e.g. the recruitment problems concerning NSAS herring) as well as induced by changes in national/international management regulations (e.g. the NEA mackerel dispute). In case of NEA mackerel and NSAS herring, two other potential sources of influence should be named: Economic factors like fish and fuel prices variations can have significant effects as well as the current political debate about Brexit.

*Economy* – The strongest impact can result from extreme changes in fish and fuel prices, especially if these are large year-to-year changes (i.e. price shocks). These can be caused by a number of sources, such as natural disasters and political disputes or decisions. A decision by the European Commission (EC) to reduce the sulfur content in fuel by banning the usage of crude oil will lead to an estimated 30% increase in fuel costs after 2020 (stakeholder information; EC, 2018). Fuel price has a direct effect on fleet effort and a sudden increase in fuel costs can decrease the oil usage, also decreasing productivity and turning profits into losses (Lee and Ni, 2002; Frost, 2006). This is called the "input-cost effect". Additionally, higher oil costs can lead to a reduced income availability in households, also lowering the demand for seafood and affecting fish prices in turn (Lee and Ni, 2002). On the long-term, this can lead to a vicious circle as low profits lead to low investment, which then slows down productivity and again results in even lower profits (Frost, 2006).

*Political* - Another recent example particularly affecting the pelagic EU fisheries is the Brexit debate, where the question regarding access rights of EU fishing vessels to British waters and future quota allocation is of major importance in the discussions (Doering et al., 2017). Historically, EU member states received a fixed share of the EU quotas based on the stock-specific relative stability. Then quotas can be swapped within the EU in order to adjust or expand catch possibilities to the actual situation and need (Hoefnagel et al., 2015). Over time, an increased usage of quota swaps appeared, indicating that economic interests are not being entirely met by the historic quota share assignment (Hoefnagel et al., 2015; Penas Lado, 2016; Hoefnagel and de Vos, 2017). This is primarily thought to be caused due to the fact, that several conditions have changed over time: new fishing strategies, changes in demand, the evolution of fleets, and changes in stock productivity and their stock distribution (Sobrino and Sobrido, 2017). In the case of NEA mackerel and NSAS herring, most of the biomass occurs in the UKs EEZ during the main fishing seasons in autumn and winter (Corten, 2001). Yet, the UK fishermen have to share most of these stocks with other EU nations. The dissatisfaction with the relative stability principle as well as the implementation of the Common Fisheries Policy (CFP) are the primary causes driving the strong position of the UK fishermen to vote for an exit of the EU (Philipson and Symes, 2018). Depending on the EU's negotiation success, a hard Brexit could result in the closure of the entire UK EEZ for European fleets as well as the EU EEZs closure for the UK fleet in 2021. In such a case, the impacts on the pelagic fleet economy are thought to be serious (Doering et al., 2017; Turenhout et al., 2017; Bjørndal and Munro, 2020). Moreover, this can in turn have effects on prices and could already be noticed directly after the Brexit vote, leading to a significant drop in pound in 2016 and 2017 (STECF, 2018).

**Evaluating effects on stock biomass and fleet behaviour**

Different tools exist as an aid to estimate and evaluate trade-offs and feedback effects between resource, its management and user. Integrated Ecological-Economic Fisheries Models (IEEFMs) are such tools, combining natural/environmental and anthropogenic processes (Nielsen et al., 2017). The focus of the different modelling tools varies not only in terms of ecological or socio-economic aspects, but also in case of spatial and temporal resolution. Ecosystem models exist in many different forms, from conceptual over mass-balance to end-to-end models, and are usually applied in a long-term context (Fulton et al., 2015). They include detailed information about food webs, functional groups and different human uses, intending to display the complexity of a whole ecosystem. Examples of some of these models are Ecopath with Ecosim (EWE), Atlantis or SMART (Fulton et al., 2015; Wang et al., 2015; D'Andrea et al., 2020; Geary et al., 2020). To a certain extent, ecosystem models incorporate fishing activities. The focus, however, lies on ecological processes, such as changes in the predator-prey relationships, and fisheries (especially impacts on their economy) are usually not included in detail. Effects of any ecological changes on fleet activities and profitability can therefore not be illustrated and determined well. Some very complex general equilibrium models exist, also incorporating fisheries and aquaculture producers and processing (Pan et al., 2007; Fulton et al., 2011; World Bank, 2013; Da-Rocha et al., 2017). These are usually applied on a global scale and cannot be used in a regional context. Bio-economic simulation and optimisation models that incorporate both detailed stock and fleet dynamics are SimFish, FishRent and FcubEcon. They provide short to mid-term economic and biological outputs for a pre-defined set of scenarios and have previously been used to study the impact of management measures on demersal stocks and their European fleets (Hoff et al., 2010; Salz et al., 2011; Bartelings et al., 2015; Simons et al., 2014/2015). FishRent and SimFish exist in different versions that incorporate either a temporal scale only (Salz et al., 2011) or both spatial and temporal aspects

(Bartelings et al., 2015; Simons et al., 2014/2015). Different species can be included as well as different amounts of fleets ranging from single- to multi-species fisheries. The models can identify the equilibrium state that optimises a certain target variable, i.e. net profit, by identifying the optimal effort allocation under a set of constraints. Hence, in order to evaluate the spatio-temporal impacts of environmental, political and economic changes on the NEA mackerel and NSAS herring fisheries and stocks, FishRent is a well-suited tool and will be applied.

## *AIMS OF THE THESIS*

This thesis evaluates the impacts of current environmental, economic and political impacts on the highly valuable NEA mackerel and NSAS herring stocks and the corresponding fishery by applying and further developing the FishRent model. As previously described, these two pelagic species are the most valuable within the European region, employing numerous people not only directly as fishermen but also within the whole processing industry. Hence, the general political interest is usually to keep the resource on a sustainable level on the long-term. However, a number of changes occurred concerning recruitment success and species distribution, also being the reason for a number of current political disputes, which in turn influence economic factors such as prices.

Therefore, the first part of the thesis aimed to a) investigate the pelagic fleet structure in order to understand the underlying data and to illustrate possible differences between the fleets, b) adapt the demersal version of FishRent to pelagic fleets in order to c) test for following factors with regard to their impact on fleet profitability targeting NEA mackerel and NSAS herring: 1) changes in recruitment, 2) adapting the quota repartition key according to biomass distributions and 3) to test for variations in fish and fuel prices (**Chapter 1**).

The second part of the thesis will then investigate the necessary degree of spatial complexity in order to incorporate seasonal migration patterns and to test for the effectiveness and impacts of management measures. An area closure of the core spawning grounds is implemented at different spatial scales to determine whether this measure would aid in the NSAS herring stock recovery and what the effects of different resolutions would be on the stock biomass and fleet behaviour (**Chapter 2**).

The third part of the thesis will implement dynamic migration patterns into the spatial version, where the stock distribution changes depending on biomass level. This is very important when considering the NEA mackerel distribution changes and the resulting political conflicts.

Further, different total allowable catches (TAC) are implemented in order to simulate a) overfishing scenarios accompanied by a retreat of NEA mackerel to its core distribution areas, b) fishing at MSY as advised by ICES accompanied by a further expansion towards the north-west Atlantic. Again, the different effects on the stock biomass and fleet behaviour are finally investigated (**Chapter 3**).

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# CHAPTER 1 – To Fish or Not to Fish – Economic Perspectives of the Pelagic Northeast Atlantic Mackerel and Herring Fishery

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**Published in *Frontiers in Marine Science***

Rybicki S, Hamon KG, Simons S and Temming A (2020) To Fish or Not to Fish – Economic Perspectives of the Pelagic Northeast Atlantic Mackerel and Herring Fishery. Front. Mar. Sci. 7:625.

Doi: 10.3389/fmars.2020.00625

## Abstract

Environmental, political and economic conditions influence fishermen's decisions, which in turn have consequences on the profitability of fishing fleets. We applied the bio-economic model FishRent to understand the response of eight fleets operating in the Northeast Atlantic mackerel and North Sea autumn spawning herring fishery to a number of scenarios, including changes in recruitment, the quota allocation key, and disruptions in fish and fuel prices. In all scenarios, both the Irish and German fleets were close to the break-even point, making them more vulnerable to additional disturbances than other fleets. Yet, these events are expected to occur simultaneously and a larger margin between costs and revenue would enhance the fleets resilience. The replacement of the historical quota allocation key to countries by an allocation according to biomass distribution negatively affected the German fleet most (-450% profitable within one year from 2020 to 2021), followed by the Dutch and Danish fleets (-175% profitable on average among those fleets), while the UK and Ireland increased their profitability by more than 250%. The differences among fleets highlights the sensitivity of a historical allocation key revision. In case of a continued herring recruitment failure, the profitability of most fleets targeting herring decreased but none of the fleets had to disinvest. Declines in fish prices (16% for frozen mackerel and herring, 81% for fresh herring, and 105% for fresh mackerel on average) and increases in fuel prices (17% on average) forced the UK, Icelandic, and large-scale (>40m) Irish fleets to reduce their number of vessels by up to 40%.


**Keywords:** bio-economic model, Northeast Atlantic, pelagic fishery, mackerel, herring.

## 1. Introduction

It is well established that many aspects, such as changes in the environment, economy and political decisions, influence the behavior of fishermen and hence the profitability of fleets (e.g. Pascoe et al. 2008, Maynou et al. 2014, Hamon et al. 2014, Bartelings et al. 2015, Spijkers and Boonstra 2017). The pelagic fisheries for Northeast Atlantic (NEA) mackerel and North Sea autumn spawning (NSAS) herring have very high economic value in the European (EU) pelagic fishery sector, i.e. 21% (herring) and 32% (mackerel) of total value (pelagic EU fleets, average of 2013 to 2017; STECF 2019). Hence, they are listed as the most important species in terms of landed weight and are within the top five species regarding landed value (STECF 2018). Moreover, the EU pelagic sector employed 23% of fishermen on average from 2012 to 2016 (STECF 2019). For job security reasons as well as the growing demand for food with increasing human population, it is important to evaluate the magnitude of current environmental, economic and political changes.

In case of NSAS herring, for example, continued low recruitment is expected to have a large impact on the corresponding fisheries and their economic performance. Recent low recruitment has occurred, despite high biomass levels (e.g. Nash et al. 2009, ICES 2018b). Two main causes are suggested for this problem: a) A shift in the planktonic community of the North Sea due to oceanic climate changes, which results in less food availability and suitability impairing the survival of young NSAS herring larvae (Gröger et al. 2009, Payne et al. 2009), and b) Changes in the physical environment, such as increasing bottom-water temperatures close to the main spawning areas, affecting the development times and metabolic rates of herring larvae (e.g. Nash and Dickey-Collas 2005, Corten 2013).

In addition to low recruitment, recent changes in biomass distribution caused problems regarding access rights in the NEA. Currently, total allowable catches (TACs) are partitioned among EU countries by applying a fixed allocation key called the “relative stability”. It was defined based on three principles: 1) Traditional fishing activities between 1973 and 1978, 2) the establishment of Exclusive Economic Zones (EEZs) and the corresponding loss of potential fishing grounds in third countries’ waters, and 3) the enlargement of the EU, which involved prioritizing countries particularly dependent on fisheries (Hoefnagel et al. 2015, Penas Lado 2016, Sobrino and Sobrido 2017). Every year, EU countries receive a fixed share of the EU quotas based on the stock-specific relative stability, then quotas are swapped within the EU in order to match the expected catch. The increased usage of quota swaps is already a sign of economic interests not being entirely met (Hoefnagel et al. 2015, Penas Lado 2016, Hoefnagel and de Vos 2017). The growing problem is, however, that several conditions have changed over time: new fishing strategies, changes in demand, the evolution of fleets, and changes in stock productivity and their distribution (Sobrino and Sobrido 2017). In the case of NSAS herring, most of the biomass occurs in the UK EEZ during the main fishing season in autumn and winter. This causes questions regarding access rights and represents a major topic in discussions about Brexit (Doering et al. 2017). These factors do not only affect members of the EU. The NEA mackerel stock was noticed to shift and/or expand to the North-west since approximately 2007 (Astthorsson et al. 2012, Bruge et al. 2016, ICES 2018a). Since 2012, mackerel catch off Iceland and Greenland increased significantly (Hannesson 2013). In 2014, the EU, Norway, and the Faroe Islands agreed on a joint management strategy for 2015 and the subsequent five years, which Iceland and Greenland did not join yet (ICES 2018a). These are all indications that access rights and the relative stability principle might need to be reconsidered by, for example, matching the changing biological dynamics. For the respective pelagic fisheries, altering the relative stability principle might be substantial.

Furthermore, fish and fuel prices have a great impact on fleet profitability and large year-to-year differences are common. Influenced by a number of causes (e.g. natural disasters, political disputes, and overfishing) price shocks may be a result. In recent years, political decisions also had an impact on fish prices. After the Brexit vote, the pound dropped in 2016 and 2017 affecting the exchange rate and fish prices in general (STECF 2018). Currently, European fish prices increased, especially in case of herring (EUMOFA 2018). This trend started in 2014 and by 2017, they had reached 10% higher prices than in 2013. Between 2009 and 2014, during the NEA mackerel "war", Iceland joined into the mackerel fishery due to an increased abundance within their EEZ. This lead to a decrease in mackerel market prices as the catch volume increased drastically (STECF 2012, Jensen et al. 2015, EUMOFA 2018). Yet, these shocks can not only affect fish but also fuel prices, which in turn have one of the largest effects on fleet profitability as fuel cost account for 15-22% of total costs. Additionally, a strategy "for a climate neutral Europe by 2050" was released in 2018 by the European Commission (EC) seeking innovation techniques that significantly reduce the greenhouse gas emissions by 80% in the time frame of 1991 to 2050 (EC 2018). In case of the fishing industry a respective regulation is already in force since 2015, prohibiting fishing vessels to use crude oil in the Emission Control Areas (ECAs) and hence reducing the emission of sulphur oxides. This covers the EEZs of the North and Baltic Sea as well as of North America (Biermann et al. 2015). Additionally, a sulphur content reduction in marine fuels was enforced outside ECAs from

January 1st 2020, only leaving the more expensive marine gasoil as compliant fuel option for European fleets (Kazokoglu and Jakštas 2019).

Bio-economic models can be used to estimate the effects of the major sources of impacts to a fishery. Traditional bio-economic models are static and based on modelling fish populations solely as total biomass, disregarding reproductive success, age-specific growth, and catchability (Schaefer 1954, Doll 1988, Pan et al. 2007, Bjørndal and Munro 2012, Tahvonen et al. 2013). Recently, dynamic age-structured bio-economic models were used as tools for fisheries management. They incorporate and integrate anthropogenic as well as natural processes to generate a better understanding of feedback mechanisms between the two systems (Bastardie et al. 2013, Tahvonen et al. 2013, Maynou et al. 2014, Simons et al. 2015, Pascoe et al. 2016, Nielsen et al. 2017, Da-Rocha et al. 2017). Equilibrium or "end-to-end" models such as Atlantis, Ecosim with Ecopath (EWE) or SMART, usually have an increased focus on the complexity of the whole ecosystem, including food webs, detailed functional groups and different human uses (e.g. Fulton et al. 2015, Wang et al. 2015, D'Andrea et al. 2020). In this study, we however apply the simulation and optimization model, FishRent, which is more focussed on certain aspects of a system. It links an age-structured population model with highly resolved catch and effort data as well as the detailed cost structure of different fleets (Salz et al. 2011, Simons et al. 2015). It has been previously used to study the impact of different management measures on demersal European fleets (Bartelings et al. 2015, Simons et al. 2015). In this study, it was adopted and applied to the NEA mackerel and NSAS herring fishery concentrating on Danish, Dutch, German, Irish, UK, and Icelandic fleets. First, we compared the costs structure of those fleets in order to understand the underlying data and illustrate possible differences. With the support of the FishRent model, we then investigated the following factors with regard to their impact on the profitability of those eight fleets targeting the two focus species: 1) changes in recruitment, 2) a quota repartition key adaptation according to biomass distributions, and 3) variations in fish and fuel prices.

## 2. Materials and Methods

### 2.1. Model description

FishRent includes the economics of multiple fleets (basic agent), the impact of fishing on stock development, and the temporal interplay between fleets and fish stocks (Salz et al. 2011, Simons et al. 2015, Figure 1). The model is written in the General Algebraic Modeling System (GAMS) and uses the CONOPT solver (for a detailed description see Drud (1994)) to calculate effort, maximizing the annual profit of a fishery given the current ecological, regulatory and economic

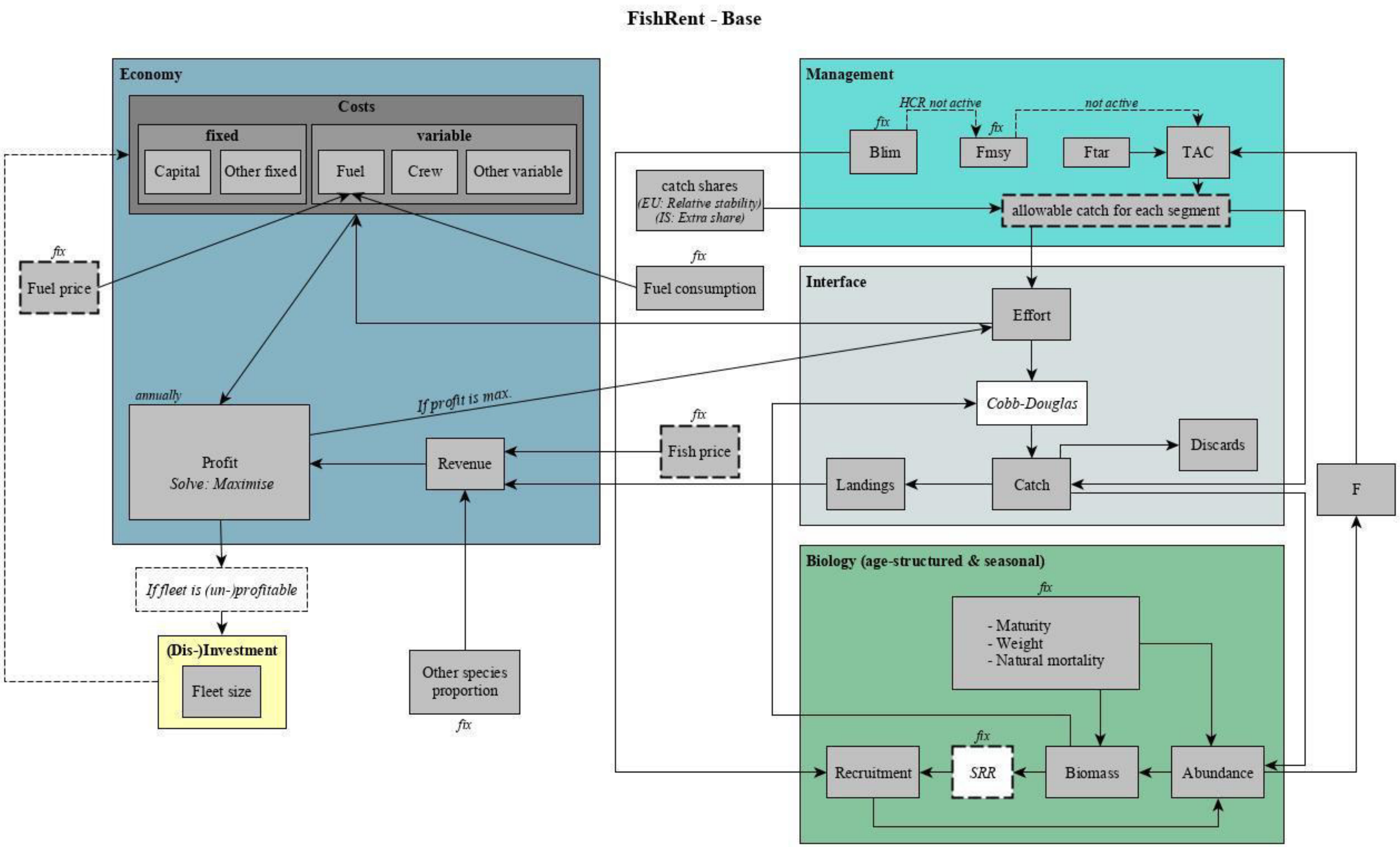


**Figure 1.** Schematic of the model process and the interaction between different sub-modules in FishRent. The effort is calculated until the maximum profit for all modelled fleet segments is estimated. This is used to calculate the catch by using the Cobb-Douglas production function, which has then an impact on the abundance, fishing mortality (*F*), biomass and, by applying and stock-recruitment relationship (SRR) function, recruitment calculation for the next time step. Boxes with bold dashed outlines signify parameters that were changed according to different scenarios.

conditions (Figure 1). To avoid unrealistic interannual variation of effort, future simulated effort of individual fleets may vary between a lower and upper limit set at 60% of historically observed total effort and historically observed maximal total effort per vessel (for more detail see Supplementary Table S.3).

### 2.1.1. Economy

The calculation of profitability includes: 1) revenue of fishing activities, 2) Capital and other fixed costs (e.g. insurance, administration, maintenance, accountancy costs, interest payments and annual depreciation costs), and 3) operating costs including fuel, crew, and other variable costs (e.g. income tax, expendables, landings, and sales costs) (Salz et al. 2011, Simons et al. 2015, Bartelings et al. 2015). Catch and fish prices determine revenue and effort, revenue and fuel price determine the operating costs (see Eq. S.1 to S.7 in Supplementary material), whereas the number of active vessels sets the level of fixed costs. Discarding was not considered in this study since reported discards by pelagic fleets are usually extremely low. More information concerning parameter estimations can be found in Supplementary material S.2.

### 2.1.2. (Dis-)investment

Depending on the profitability of each fleet, fleet size can increase or decrease (in terms of number of vessels) after the first modelled year. If fleets are profitable, reach their effort capacity, and are below their maximum investment limit, they can invest into new vessels. If fleets are unprofitable, they are allowed to disinvest to a maximum of 10% per year.

### 2.1.3. Interface

The fishing effort as well as the total stock biomass are used in the Cobb-Douglas catch production function, which assumes a non-linear relationship between catch and effort as well as between catch and stock size (Eq. 1; Frost et al. 2009).

$$C_{t,i,j} = c_{t,i,j} \times {E_{t,j}}^{\alpha_{1j}} \times {CB_{t,i}}^{\beta_{1j}} \tag{1}$$

where $C_{t,i,j}$ is catch, $c_{t,i,j}$ is the catchability coefficient of $i$th age, and $j$th fleet at time $t$. $E_{t,j}$ is the fishing effort of $j$th fleet at time $t$, $CB_{t,i}$ is the biomass at $i$th age at time $t$, and $\alpha_{1j}$ and $\beta_{1j}$ determine the degree of non-linearity in the relation of catch and effort for a given stock size (Salz et al. 2011, García et al. 2014). The application of the Cobb-Douglas function is of particular importance in case of pelagic fisheries, because fish usually form large schools and a non-linear relationship between effort and biomass levels in the catch is common (Frost et al. 2009, Cruz-Rivera et al. 2018). The settings of the two parameters $\alpha_1$ and $\beta_1$ have a significant influence on the estimation of maximum profitability and the remaining results, which is why a sensitivity analysis of those parameters was performed (see Supplementary material S.2).

### 2.1.4. Biology

With the calculated catch, the number of individuals $N_{t,i}$ is estimated using Pope's approximation (Pope 1972; Eq. 2).

$$N_{t,i} = N_{t-1,i-1} exp^{-M_i} - \frac{\sum_j C_{t-1,i-1,j}}{w_{t,i} \times \sum_j s_j} exp^{-\frac{M_i}{2}} \qquad (2)$$

where $w_{t,i}$ is weight at age and $s_j$ is the catch share. Catch share is a multiplier that determines total catch, hence accounting for the remaining fishing mortality by fleets not included in the model. It is the proportion of each fleets catch from the TAC, also including Iceland, i.e. representing their quota shares (see Supplementary Table S.4). The instantaneous natural mortality rate is represented by $M_i$. Both catch share and natural mortality are constant over time.

In addition, 1000 random stochastic iterations are computed while applying the stock-recruitment (SR) function in order to include a standard error for recruitment and SSB. Median recruitment and spawning stock biomass (SSB) values are then used for further calculations. For NEA mackerel the Beverton and Holt SR function was applied using all years available at the time of the study (1980-2016) (Beverton and Holt 1957; Eq. 3; Supplementary Table S.1, Figure S.2), because this showed the best fit to SR data (ICES 2019a). For herring a restricted ($B_{lim}$) hockey-stick SR function was chosen for years 2002-2016, following Payne et al. (2009) and ICES WKPELA (2018c; Eq. 4a and 4b; Supplementary Figure S.3).

$$R_t = \frac{\alpha_2 \times SSB_t}{\beta_2 + SSB_t} \times exp^{(D \times CV - 0.5 \times CV^2)} \qquad (3)$$

$$SSB < B_{\text{lim}} \qquad R_t = \alpha_2 \times SSB \times exp^{(D \times CV - 0.5 \times CV^2)} \qquad (4a)$$

Else

$$SSB \geq B_{lim} \qquad R_t = \alpha_2 \times B_{\text{lim}} \times exp^{(D \times CV - 0.5 \times CV^2)} \qquad (4b)$$

The parameters $\alpha_2$, $\beta_2$ and $B_{lim}$ are species specific (Table 1). $D$ is a standard normal deviate and $CV$ is the coefficient of variation ($CV$ = standard deviation/mean), which was estimated based on historical stock sizes for herring from 2012 to 2016 and for NEA mackerel from 2012 to 2014 (ICES 2018b, ICES 2019a). At the end of each year, all individuals within one age class are transferred to the next and those older than the maximum age are aggregated in the last age class.

Moreover, the age-specific fishing mortality $F_{t,i}$ is calculated using the estimated number of individuals from before (Eq. 5).

$$F_{t,i} = -log\left(\frac{N_{t,i}}{N_{t+1,i+1}}\right) - M_i \quad (5)$$

**2.1.5. Management**

Within the European Union, the TAC is now supposed to be set according to the MSY approach. Within the start years (average 2012-2014), fishing mortality ($F$) of mackerel was 32% higher than the advised $F_{msy}$ (ICES 2019a). This is mainly due to the fact, that no internationally agreed quotas existed as well as no harvest control rules being active at this time, which still has not changed. As to NSAS herring, fishing mortality was on average 44% below the advised $F_{msy}$ since 2007 (ICES 2018b). In the scenarios of this study, we decided to keep the level of the actual fishing mortalities by adding a multiplier (the average $F/F_{msy}$ ratio of the last eight years from 2008 onwards) to the advised $F_{msy}$ (Eq. 6).

$$F_{tar} = F_{MSY_{advice}} \times \frac{\overline{F}}{\overline{F}_{MSY}} \quad (6)$$

$F_{tar}$ is not age-class specific. Thus, in order to account for an age-structured stock, partial fishing mortalities at age ($Ftac_{t,i}$) are calculated by using the fishing mortality of the average age classes that are considered to be fully exploited in the assessments ($\overline{F_t}$; Eq. 7).

$$F_{tac_{t,i}} = \frac{F_{tar} \times F_{t-1,i}}{\overline{F_{t-1}}} \quad (7)$$

Together with the natural mortality ($M_i$) a total mortality rate, called $Ztac_{t,i}$ can be determined. These two parameters combined with the abundance and weight at age are used in the Baranov Catch equation in order to calculate a catch according to $F_{tar}$ (Baranov 1918; Supplementary Figure S.4; Eq. 8).

$$Catch_{tar_{t,i}} = \sum_i \left[\left(N_{t,i} \times \frac{F_{tac_{t,i}}}{Z_{tac_{t,i}}} \times (1 - exp^{(-Z_{tac_{t,i}})})\right) \times w_{t,i}\right] \quad (8)$$

This is used as the new TAC on a species level for the next year. $F_{tar}$ is not adjusted annually in any scenario, again due to the fact that for neither of the two species a harvest control rule is currently in place. In general, all fleets are not allowed to fish more than their quota, which is a fixed proportion (i.e. the previously introduced catch shares) of the TAC. This is an additional restriction to the effort limits wherein the model is allowed to operate. Moreover, total catch cannot be larger than 95% of the total biomass of the stock.

### 2.2. Data and Settings

FishRent was run for a period of 16 years (2014-2030) using five fleets (one Dutch, UK, and German as well as two Danish) targeting both NEA mackerel and NSAS herring directly and three fleets (one Icelandic and two Irish) exclusively targeting NEA mackerel (Figure 2).

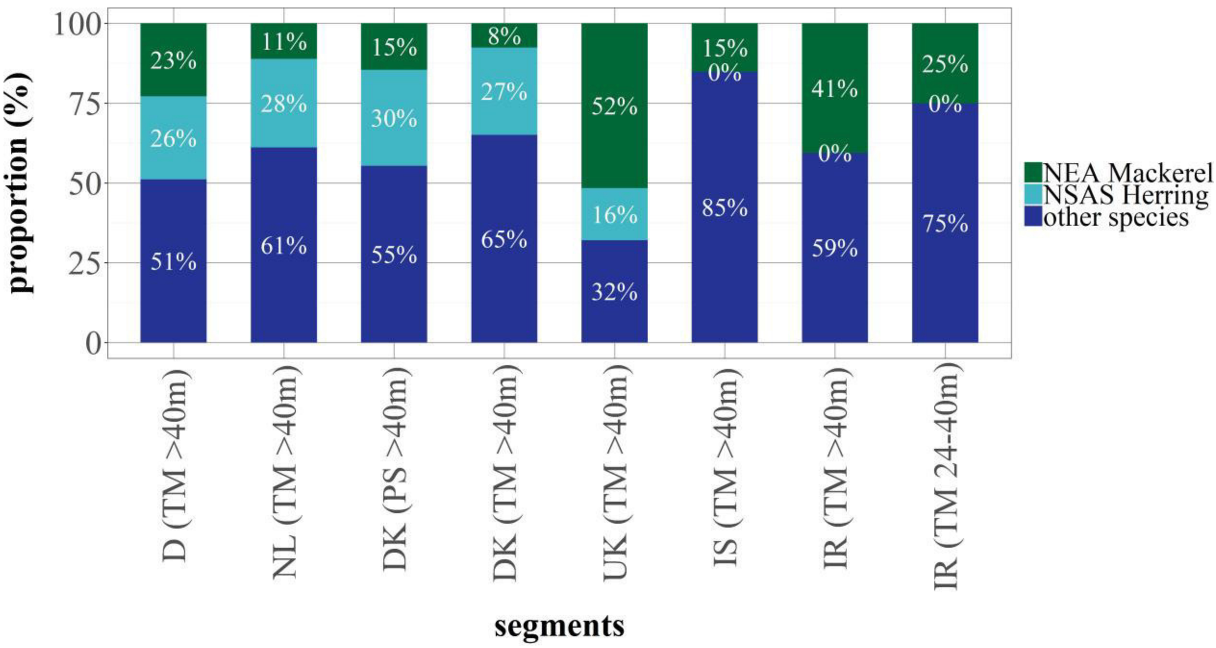


**Figure 2.** Catch composition of NSAS herring (%, light blue), NEA mackerel (%, green) and other species (%, dark blue) for the eight modelled fleets at the starting point (2014). The proportion of other species stays fixed throughout the model runs.

Only fleets where mackerel and herring constituted more than 25% of the total landings value for at least one of the two species were considered in the modelling approach. Fleets consist of multiple vessels and were classified by vessel length (vl in meters) using two categories ranging from 24-40m and over 40m as well as two predominant gear types (pelagic trawlers (TM) and purse seiners (PS)). This uses the classification of the European data collection framework as implemented by the Scientific, Technical and Economic Committee for Fisheries (STECF 2018). Detailed economic data (e.g. costs, effort, profit etc.) was received directly from national labs, also averaged over the years 2012 to 2014. Although Norway is also a major fishing nation targeting NEA mackerel and NSAS herring, we did unfortunately not receive any data in the detail and resolution needed for the model.

In order to set up the model, detailed biological data at age such as abundance, natural mortality and weight as well as spawning stock biomass (SSB) and recruitment was incorporated from the most recent stock assessments at the beginning of this study (ICES 2018b, ICES 2019a). Data for mackerel was however updated due a significant change in the scientific assessment at the beginning of 2019 (ICES 2019a). In the new assessment, biological data was adjusted due to a different weighting procedure of three scientific surveys, which lead to the tagging data having a larger influence on the assessment results than before (ICES 2019a). Hence, a much more positive perception of the population was estimated, also leading to an improved catch advice for the NEA mackerel stock. We used the default average of three years (2012-2014) as biological input for the starting year 2014. For NSAS herring, an average of five years (2012-2016) was chosen due to significant biological changes after 2014, especially in fishing mortality and weight at age (ICES 2018b).

### 2.3. Scenarios

#### 2.3.1. Scenario 1: The baseline

In the baseline scenario, FishRent projects the optimal behavior of fishermen in order to maximize the fleets profitability for 16 years using current conditions of $F$, the quota repartition key, fish and fuel prices, and the SR relationships. It is the basis for the other scenarios (Table 1).

#### 2.3.2. Scenario 2: Reduced recruitment of NSAS herring

As continued low recruitment of NSAS herring may have a large impact on the corresponding fisheries and their economic performance, different magnitudes of reduced recruitment were tested: 1) Extreme and 2) Medium. This was done by adjusting the density-independent parameter $\alpha_2$ (i.e. the amount of recruits per unit of biomass) in the SR relationship. For the extreme setting, the lowest historic recruitment-SSB-ratio observed since 2002 was determined, which occurred in 2003 (ICES 2018b; Table 1). This is also the period considered in the SR relationship of the NSAS herring assessment. The resulting value of $\alpha_2$=7.6 was then used as a target for the final modelling year 2030. For the second (medium) setting, the mean between the current ($\alpha_2$=41) and the extreme was applied to be attained until 2030, which was $\alpha_2$=24.3 (Table 1).

**Table 1.** Overview of the baseline scenario and the specific parameter changes for the three alternative scenarios. Fish and fuel price changes are in nominal terms. Country abbreviations: Germany (D), Denmark (DK), United Kingdom (UK), Netherlands (NL), Ireland (IR), Iceland (IS).

| | | Baseline (Scenario 1) | Scenario 2 | Scenario 3 | Scenario 4 | Sources |
|---|---|---|---|---|---|---|
| **Management Framework** | **Objective** | Current level of F cont. | | As in baseline | | ICES 2018b,<br>ICES 2019a |
| **Management Framework** | **Instruments** | Catch < Quota<br>Catch < 95% Biomass<br>RS principle | As in baseline | | Quota repartition key according to biomass distribution<br>*NSAS herring (%)*:<br>D (2.12), DK (2.38), UK (64.82), NL (8.27)<br>*NEA mackerel (%):*<br>D (0.005), DK (0.0031), UK (61.79), IR (21.32), NL (0.01), IS (14) | Hoefnagel et al. 2015,<br>ICES 2018b,<br>ICES 2019a |
| **Economic Framework** | **Fish Price** | Current situation cont. | As in baseline | Increase and decrease to historic first sale max. and min. (frozen: NL, D; fresh: IS, IR, UK, DK) | As in baseline | EUMOFA 2019a |
| **Economic Framework** | **Fuel Price** | Current situation cont. | As in baseline | Increase and decrease to historic max. and min. (marine gasoil) | As in baseline | EUMOFA 2019b |
| **Ecological Framework** | **Stock-Recruitment Relationship** | NSAS herring:<br>$\alpha_2 = 41$<br>$\beta_2/B_{lim} = 800{,}000$<br>NEA mackerel:<br>$\alpha_2 = 10{,}269{,}723$<br>$\beta_2 = 2{,}854{,}680$ | 1) NSAS herring:<br>$\alpha_2 = 24.3$<br>2) NSAS herring:<br>$\alpha_2 = 7.6$<br>Both: until 2030 | As in baseline | | ICES 2019a,<br>ICES 2018c |

### 2.3.3. Scenario 3: Fish and fuel price variations

Fish and fuel prices and their effect on the fleets are hard to predict. In this study, historic first sale fish and marine gasoil price time-series data (2008-2016) were obtained from the European Market Observatory for Fisheries and Aquaculture Products (EUMOFA) data portal (EUMOFA 2019a/b; Table 1 and 2).

**Table 2.** Model prices for each fleet (fish prices (€$kg^{-1}$): landings value divided by landings weight, fuel prices (€$l^{-1}$): fuel price divided by fuel consumption) Also shown are nominal historic prices (extremes) of first sale for fish (€$kg^{-1}$) and marine gasoil (€$l^{-1}$) in between 2008 and 2019. For all, except fresh mackerel, the mean price per country and year was used. In case of fresh mackerel, the unresolved price data per month, year and country was integrated (EUMOFA 2019a/b).

| segment | product | Model price | Minimum price | Maximum price |
|---|---|---|---|---|
| NL (TM > 40m) | Frozen Herring | 0.35 | 0.35 | 1 |
| D (TM > 40m) | Frozen Herring | 0.46 | | |
| UK (TM > 40m) | Fresh Herring | 0.43 | 0.25 | 1.55 |
| DK (TM > 40m) | Fresh Herring | 0.46 | | |
| DK (PS > 40m) | Fresh Herring | 0.47 | | |
| NL (TM > 40m) | Frozen Mackerel | 1.18 | 0.9 | 3 |
| D (TM > 40m) | Frozen Mackerel | 0.9 | | |
| UK (TM > 40m) | Fresh Mackerel | 1.05 | 0.5 | 10 |
| DK (TM > 40m) | Fresh Mackerel | 1.04 | | |
| DK (PS > 40m) | Fresh Mackerel | 1.02 | | |
| IR (TM > 40m) | Fresh Mackerel | 0.76 | | |
| IR (TM 24-40m) | Fresh Mackerel | 0.79 | | |
| IS (TM > 40m) | Fresh Mackerel | 1.49 | | |
| NL (TM > 40m) | Marine gasoil | 0.49 | 0.33 | 0.85 |
| D (TM > 40m) | Marine gasoil | 0.42 | | |
| UK (TM > 40m) | Marine gasoil | 0.66 | | |
| DK (TM > 40m) | Marine gasoil | 0.63 | | |
| DK (PS > 40m) | Marine gasoil | 0.63 | | |
| IR (TM > 40m) | Marine gasoil | 0.73 | | |
| IR (TM 24-40m) | Marine gasoil | 0.74 | | |
| IS (TM > 40m) | Marine gasoil | 0.66 | | |

First sale price for fish was available for either fresh or frozen products. For the German and Dutch fleets, herring and mackerel first sale prices for frozen products were used, whereas for the remaining six fleets (Ireland, Iceland, UK, and Denmark) fresh first sale prices were incorporated. The information about the main processing type (fresh or frozen) being used by each fleet was also obtained from national labs. The most rapid change in price over the mentioned time period was identified for each focus species and fleet. This was, on average, a year-to-year change (EUMOFA 2019a/b). Hence, historic price peaks and low points then replaced the original start values as a sudden, from year-to-year change from year 2020 onwards (Table 1 and 2). This year was chosen as a reference year, as it marks a point where historic biological effects are less predominant, hence showing actual effects of the price alterations. Fish and fuel price scenarios were run separately as well as in combinations (e.g. low fish, high fuel price and vice versa).

### 2.3.4. Scenario 4: Adapting the quota repartition key

An alternative approach other than the relative stability (RS) principle was employed, primarily reflecting political forcing such as Brexit or the "mackerel war" (Ørebech 2013, European Parliament 2017; Table 1). This was an attempt to adapt the quota repartition key to the current biomass distribution of both focus species. For this, two different approaches had to be used, one for each species. For NSAS herring, total biomass was calculated from abundance data in each ICES rectangle (mean 2012-2017) of the North Sea International Bottom Trawl Survey (NS-IBTS of the 3rd quarter; "CPUE per age and subarea" downloaded from DATRAS on the 10th of March 2019), which was standardized. Weight-at-age (kg) in the stock data (mean 2012-2017) from the HAWG Report (ICES 2018b) was then applied to the standardized abundance-at-age data in order to obtain a standardized biomass within the North Sea area. The proportions of NSAS herring biomass in each EEZ of the modelled fleets were then determined by using a geospatial intersect operation in ArcGIS (Version 10.5.1) and were finally used as each fleets new quota repartition key (Figure 3; Figure 4; Table 1).

For NEA mackerel, it was difficult to find standardized abundance or biomass data including not only the European EEZs but the whole NEA, i.e. also the entire Icelandic EEZ. However, as Iceland is included as a modelled fleet and as mackerel now keeps migrating into the Icelandic EEZ, this area is of high importance for future management strategies and should also be incorporated into the analysis. Therefore, catch- and effort-at-age data of the modelled fleets were used to calculate catch-per-unit-effort (CPUE), which was in turn standardized in order to account for the different gear techniques applied by the fleets.

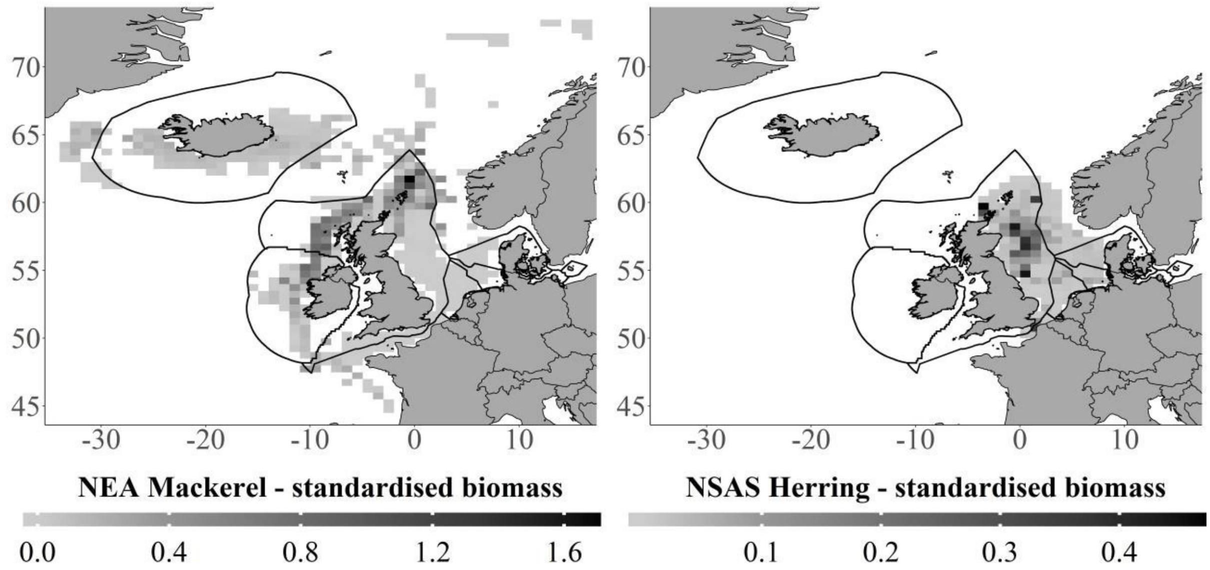


**Figure 3**. Standardized biomass: NSAS Herring (mean 2012-2017) calculated from the NS-IBTS (3rd quarter) standardized CPUE per age and subarea and NEA mackerel (mean 2012-2014) calculated from the standardized commercial CPUE of each modelled fleet segment. Shown are all age classes summarized (ICES 2018b, ICES 2019a).

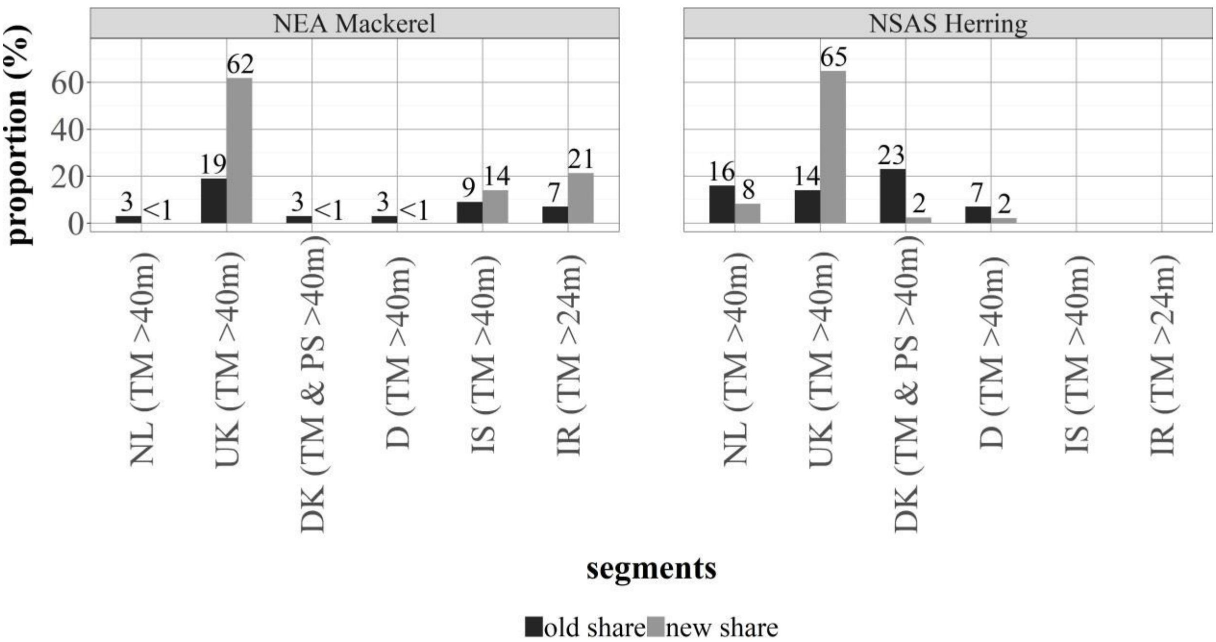


**Figure 4.** Old (for all fleets catching >25% of both species, black) and new (grey) quota partition keys (%) for NSAS herring and NEA mackerel.

This standardized CPUE was used as a proxy to calculate the standardized biomass (Figure 3; Figure 4; ICES 2019a). The approach assumes that fishermen would, through experience and sonar techniques, always know where schooling fish is located. In reality, this behavior can actually be observed when targeting pelagic species with well-developed sonar techniques. The approach should thus provide a rough estimate of mackerel proportions in each EEZ at the time when the modelled fleets target mackerel in order to see the main effects of implementing an adapted quota repartition key.

**3. Results**

All economic results presented in the following section are either given as percentage change over time or, in case of absolute numbers, aggregated into clusters of more than 10 vessels where appropriate.

**3.1. Cost structure of modelled fleets – The input**

The cost structure of the eight modelled fleets was investigated and showed unexpected differences (Figure 5). Capital costs, which also include annual depreciation costs, varied from 6% of total costs (Iceland) to 34% (Denmark). A similar observation could be made concerning fixed costs, which include insurances, administration and accountancy as well as fees such as harbor dues. The Danish fleets showed the smallest fixed costs share of only 4% per kg landed fish, whereas the UK fleet had the largest share of fixed costs (32%) (Figure 5).

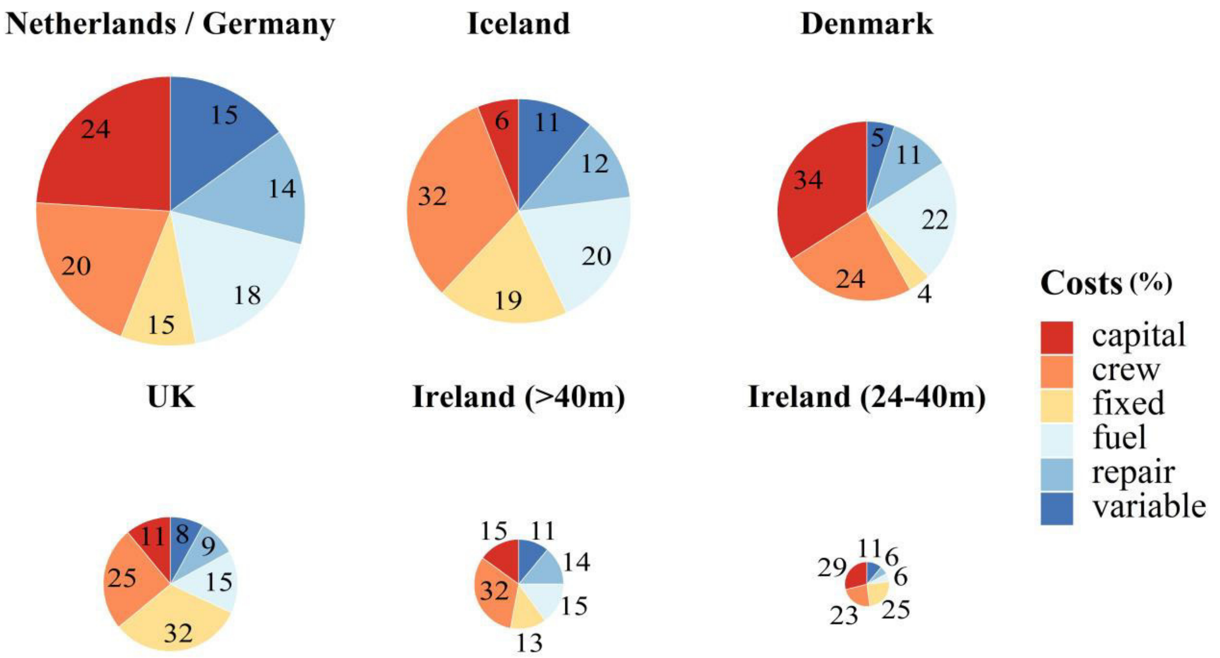


**Figure 5.** Cost structure (proportion (%) per kg landed) of the eight modelled fleets, average of years 2012 to 2014. The size of each pie chart shows the proportion of total costs per vessel in comparison to the other segments. Due to data privacy reasons the Dutch and German fleets as well as the two Danish fleets were aggregated (all segments shown here contain >10 vessels). The cost structure of the Icelandic fleet was estimated by using UK costs structure.

Crew costs share, on the other hand, were very similar among fleets (average: 26% per kg landed fish) and seemed to be independent from vessel sizes and fishing technique. The same applies to the fuel (18% on average of the fleets) and repair costs share (12% on average). The only exception was the Irish fleet (24-40m) with a fuel and repair costs share of only 6% per kg landed. Variable costs share, containing income tax, expandable material, landing and sales fees, subsistence and travel expenses as well as radio costs, was on average 10% per kg landed fish. Again, only the Danish fleets stood out with only 5% of variable costs share. In general, the Netherlands and Germany had the largest amount of costs compared to the other modelled fleets, followed by Iceland, the Danish, UK, and Irish fleets (Figure 5).

As to the relation of total costs and revenue per kg of landings, revenue of seven out of eight fleets was 57% higher on average than the total costs per kg landed (Figure 6). One exception was the large-scale Irish fleet (>40m) with only 13% difference between revenue and total costs.

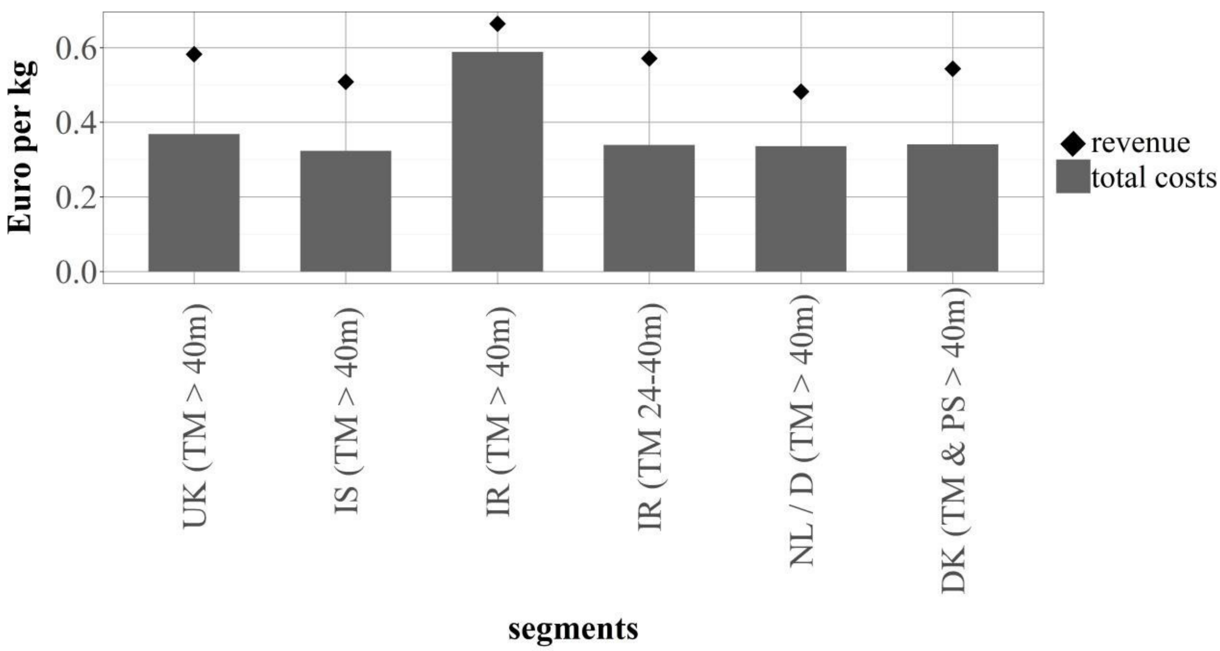


**Figure 6.** Total costs and revenue (Euro per kg landed) of the eight modelled fleets with an average of years 2012 to 2014. This also includes revenue from other species caught by those segments. Due to data privacy reasons the Dutch and German fleets as well as the two Danish fleets were aggregated (all segments shown here contain >10 vessels). The cost structure of the Icelandic fleet was estimated by using UK costs structure.

This fleet received 0.13 €$kg^{-1}$ more on average than the other seven fleets, but had a significantly higher proportion of total costs at the same time (0.25 €$kg^{-1}$ more on average). This made the large-scale Irish fleet more vulnerable to any negative effects implemented than the other modelled fleets. The two fleets with the largest difference between total costs and revenue (0.22

€kg$^{-1}$) and therefore being least vulnerable to harmful impacts were the smaller Irish (24-40m) and the UK fleets.

### 3.2. Scenario 1: The baseline

#### 3.2.1. Biology

When comparing the baseline scenario to data of the corresponding mackerel assessment reports, trends were similar and model results were also within the 95% CI (Figure 7). The trend of NSAS herring SSB output from the baseline scenario decreased from 3,000 ktons in 2014 to 2,500 ktons in 2018, similarly to the observed data from the assessment but remained 35% higher on average (Figure 7).

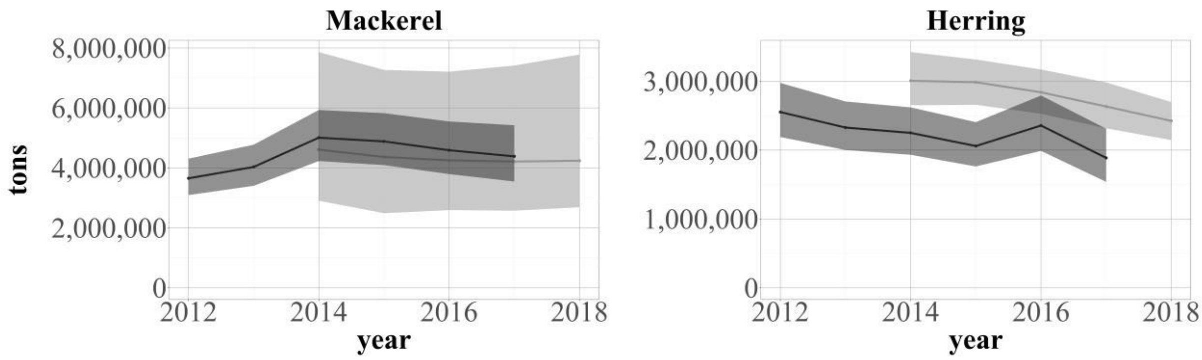


**Figure 7.** Comparison of the baseline scenarios SSB in tons (median of 1000 iterations; grey) with its 95% CI in comparison to the assessments SSB in tons (black). This was performed for NSAS herring with data from the 2018 assessment report (ICES 2018b) as well as for NEA mackerel with data from the updated assessment in 2019 (ICES 2019a).

Further, when examining the biological results of the baseline scenario until 2030, a decrease in SSB from nearly 5,000 ktons in 2014 to 4,000 ktons from 2017 on could be noticed for NEA mackerel (Figure 8). As to NSAS herring SSB decreased from 3,000 ktons to 2,000 ktons in 2020, after which year this level was maintained (Figure 8). This is a level that corresponds to the average historic trend between 1996 and 2013. Hence, the SSB peaks observed in historic data between 2012 and 2014 seemed to represent rather exceptional years caused by high recruitment in 2009 and 2013.

Moreover, as SSB decreased, the TAC of both NEA mackerel and NSAS herring also declined until after 2020 it became relatively stable (Figure 8). Both SSB and $F_{tar}$ influence the TAC level. Yet, the latter has less influence in all scenarios because it is kept on a similar level as the actually observed $F$ of the last few years.

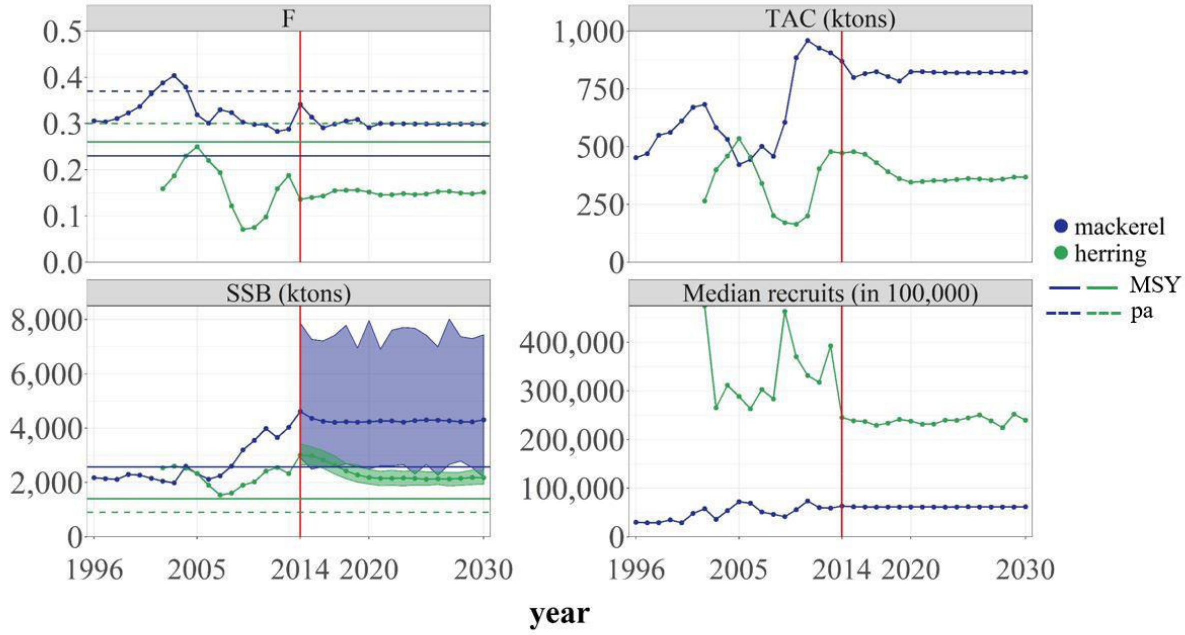


**Figure 8.** Biological output (SSB and median recruitment) as well as TAC and F from the baseline scenario for NSAS herring (green) and NEA mackerel (blue). The Beverton-Holt SR relationship was used for mackerel ($\alpha_2$=10,269,723, $\beta_2$=2,854,680) and the restricted hockey-stick relationship for herring ($\alpha_2$=41; $\beta_2$=$B_{lim}$=800,000t). SSB is shown with the 95% CI calculated from 1000 iterations; median recruitment is shown without the corresponding CI, because it displayed enormous variations from nearly none up to 2.5 trillion with some peaks even higher in case of herring. Note: After 2010, TAC values for mackerel represent the sum of unilateral quotas as no international agreed quotas exist. Start year of the model was 2014 (red line). Horizontal solid lines represent the MSY and dashed lines represent the precautionary limit of *F* and SSB for NSAS herring (green) and NEA mackerel (blue).

### 3.2.2. Economy

As a result of the biomass decline of NEA mackerel and NSAS herring in the baseline scenario, total catch of the modelled fleets decreased (Figure 9, grey bars). The fleets affected most within the first three years were the two Irish, the Icelandic, and the UK fleets. From the two focus species, the UK fleet catches mainly mackerel but the Irish and Icelandic fleets catch exclusively mackerel (Figure 2). Those four fleets caught between 15-25% less in 2017 compared to the start year 2014. Until 2030, the UK catch decreased by another 5%. The fleets targeting primarily NSAS herring were not affected as fast: The German fleet was impacted most, catching 10% less in 2017 and 19% less in 2030. Catch of the other three fleets was <10% less in 2017 and up to 20% less in 2030 compared to the start year in 2014. All fleets responded by decreasing their total and fishing effort. By 2017, the large-scale Irish fleet (>40m) was already up to 100% less profitable (Figure 9). The profitability of the two Danish fleets was affected least and only decreased by 25% in 2030, whereas most other fleets were 40% less profitable compared to the start year.

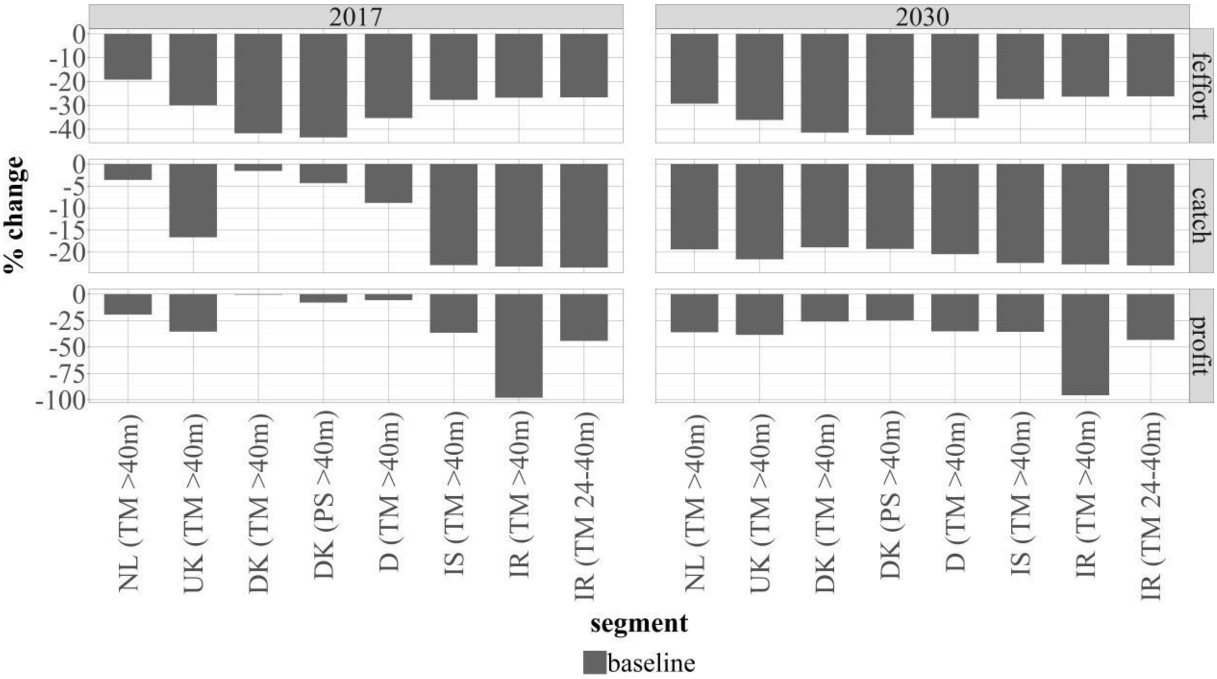


**Figure 9.** Economic output of each modelled fleet from the baseline scenario: fishing effort (feffort), catch, and profit in 2017 and 2030 relative to the start year 2014.

### 3.3. Scenario 2: Reduced NSAS herring recruitment

When reducing the parameter $\alpha_2$ (i.e. the amount of recruits per unit of biomass) in the SR relationship of NSAS herring, a 23% decrease in recruitment with the moderate setting of 24.3 could be observed in 2030 compared to the baseline scenario and a 58% decrease with the extremer setting of 7.6. This consequently led to a reduction in total abundance, SSB and total stock biomass, the extent depending on the degree of change (More information can be found in Supplementary Figure S.5/6). The $\alpha_2$=24.3 setting lead to 18% less SSB until 2030 compared to the baseline scenario, whereas in the $\alpha_2$=7.6 setting SSB decreased by 48%. Changes in $\alpha_2$ had by far the most influence on herring SSB compared to all other scenarios and affected catch and the related economic parameters of the fleets accordingly (Figure 10).

Fleets catching NSAS herring all decreased in profitability over time compared to the baseline scenario (Figure 10). The Icelandic and Irish fleets do not show large differences. As to the other five fleets, the influence of the $\alpha_2$=24.3 scenario on profitability was not as strong as in the $\alpha_2$=7.6 setting: Profit in the former only decreased in between 5-30%. The $\alpha_2$=7.6 setting had a larger effect on fleet profitability, where the Dutch and Danish fleets had a 45% reduction of profit on average and the German fleet even up to 80% (Figure 10).

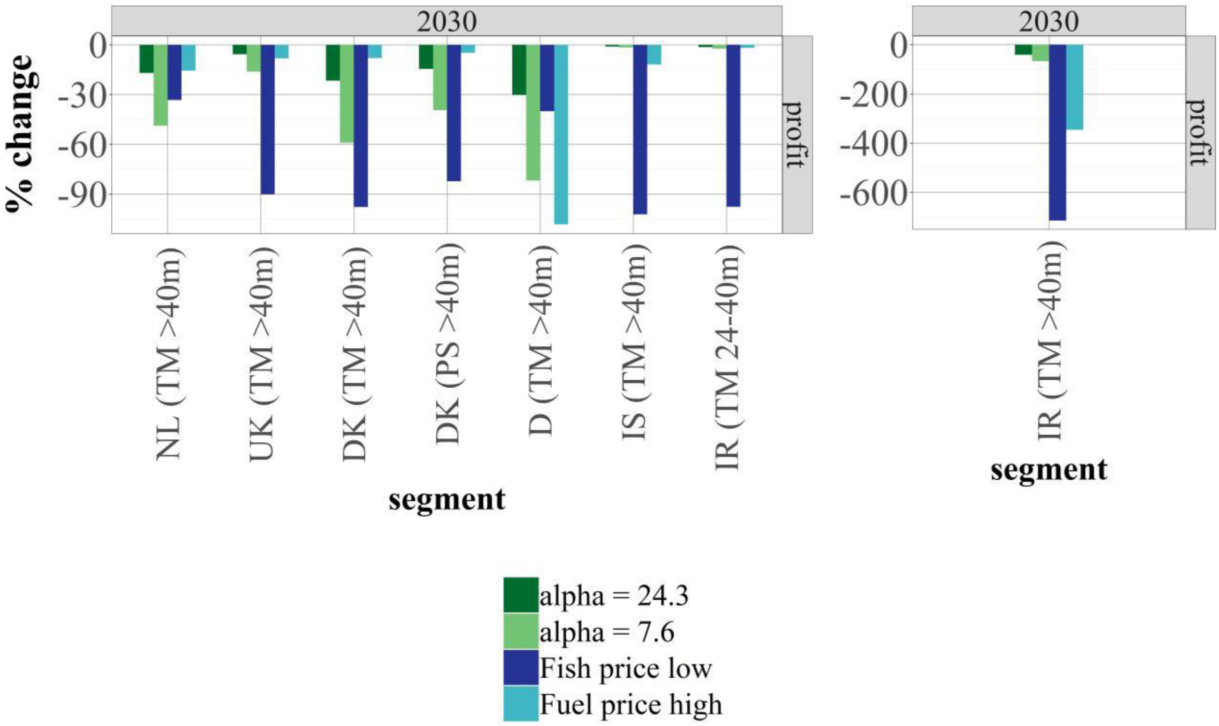


**Figure 10.** Change in profitability of eight modelled fleets compared to the baseline scenario when reducing recruitment (scenario 2 - green shades, here results of both settings of alpha are shown: alpha = 24.3 is the medium setting and alpha = 7.6 the extreme setting), lowering fish price (scenario 3 - dark blue), and increasing fuel price (scenario 3 - light blue). Note: A different scale was used for the large scale (>40m) Irish fleet in panel B.

### 3.4. Scenario 3: Fish price and fuel price variations

Alterations of fish and fuel prices had very large impacts on revenue and cost structure of all fleets, but not so much on the SSB of the stocks compared to baseline scenario. For simplification purposes, the following section will only address the two most threatening settings of low fish and high fuel price. Further detail concerning combinations of fish and fuel price can be found in Supplementary Figure S.8 and S.9.

In general, most fleets were much more affected by low fish prices than by high fuel prices, although fuel cost increased by at least 25% under the latter scenario (Figure 10A/B). Here, we focus on the change in profitability, for further detail see Supplementary Figure S.6. The large-scale (>40m) Irish fleet appeared to be the most sensitive to the fish and fuel price variations in general (Figure 10B). Their profit decreased from 11 million euros (MEUR) in 2014 to 0.5

MEUR in 2030 (-700% compared to the baseline scenario) with low fish prices. Therefore, they tried to be more profitable by reducing their total effort and fleet size by 30%. The UK and Icelandic fleets also reduced their fleet size by 38% and 60% respectively until 2030 in the low fish price setting. They however increased the days operating per vessel and therefore did not have to reduce their overall total effort as well as catch. Yet, their profitability decreased by 90% compared to the baseline scenario. By disinvesting, the large-scale Irish and the UK fleets could reach profitability again after five years, whereas the Icelandic fleet was not able to achieve profitability until 2030 and continued to disinvest. All other fleets decreased in profitability and, to increase catch and receive more revenue, increased their effort in comparison to the baseline scenario until they were limited by their quota. This in turn increased operating costs and significantly reduced their margin between total costs and revenue to the point of break-even. In the end, especially the Danish fleets were very close to unprofitability, just managing to maintain themselves. The Dutch fleet was the least affected when reducing fish price. Their profitability only decreased by 30% until 2030 compared to the baseline scenario (Figure 10A).

The German fleet, however, seemed to be much more sensitive to fuel price changes. Increasing fuel price dissipated all profit (-100%) compared to the baseline scenario than just reducing fish price (-40%; Figure 10A). Fuel costs also increased by 100% compared to the baseline scenario in 2030, which was 70% more than for the other fleets.

### 3.5. Scenario 4: Adapting the quota repartition key

The analysis of the spatial biomass distributions showed the largest proportions of NEA mackerel and NSAS herring situated in the UK EEZ, followed by Ireland and Iceland. Since the biomass proportion of both species was very low in the Danish, German, and Dutch EEZs, the share for those countries was also very low (<1% for mackerel, <3% for herring; Table 1). Fleets from Denmark, Germany, and the Netherlands were immediately unprofitable when implementing the reallocated quotas (Figure 11A). Consequently, they tried to catch a larger amount of herring and mackerel than their allowed quota limit in order to stay profitable, which is why the model could not find an optimal or feasible solution for this scenario. Further results concerning profitability should therefore be considered with care.

The Danish and Dutch fleets were already up to 250% less profitable within the first year of reallocated catch shares (i.e. 2021; Figure 11A). The German fleet was affected the most with profit decreasing by 450% in 2021 compared to 2020. Interestingly, the Icelandic fleet was also almost 100% less profitable within one year although gaining a 5% higher catch share.

However, they increased fishing effort massively (by 120%) at the same time, which affected fuel costs accordingly (for further detail see Supplementary Figure S.7).

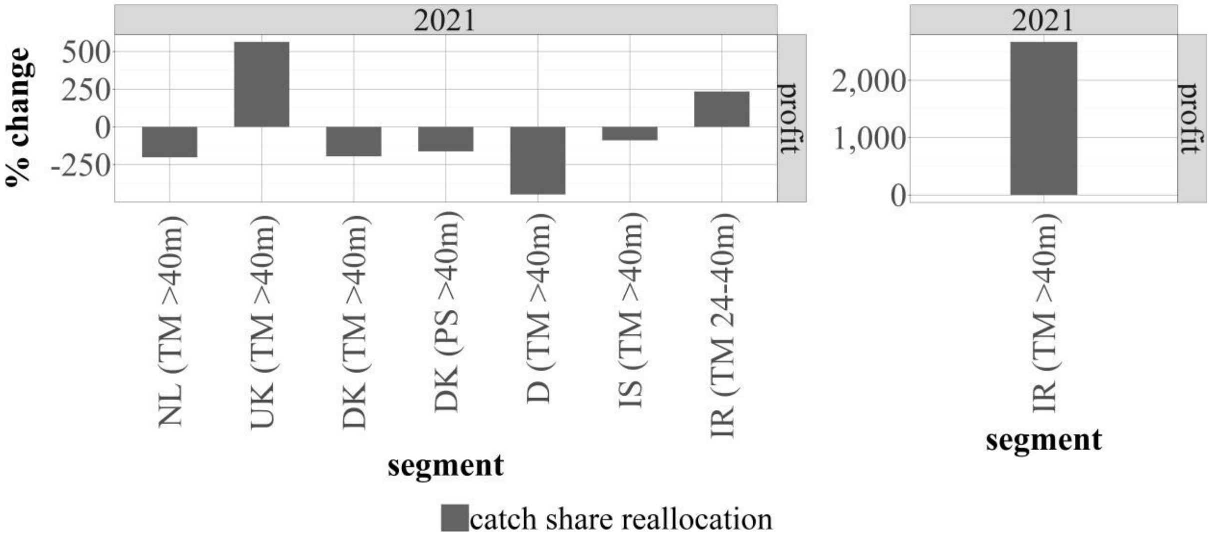


**Figure 11.** Change in profitability of eight modelled fleets compared to 2020 (A and B) when implementing new catch shares in 2021. In 2020, the old catch shares were still intact. Note: A different scale was used for the large scale (>40m) Irish fleet in panel B.

The Irish, especially the large-scale, and UK fleets on the other hand, had the most advantages by far and turned out to be more than 250% more profitable within one year (Figure 11A/B). The modelled large-scale Irish fleet and the UK fleet received most of the mackerel share. The former, for example, had 6% in 2020 and received three times the share in 2021. Catching more than double the amount in 2021 than in 2020, they increased their profitability from approximately -1.2 to 31.6 MEUR (+2500% compared to 2020) within one year. Compared to the large-scale Irish fleet, the effect was not as large when examining the UK fleets profitability but still considerable: They also received 3-4 times the share of NEA mackerel and NSAS herring and caught more than triple the amount of both species together. Yet, they were six times more profitable in 2021 than in 2020, increasing profit from approximately 59 MEUR to 392 MEUR (+500%) (Figure 11A). Neither the Irish nor the UK fleets caught the full amount of newly available quota as they were limited by the maximum allowable effort.

In general, when comparing the five scenarios, alterations of the quota repartition key had the largest impacts on all fleets. For the Dutch, Danish, and German fleet, this was substantial causing these fleets to be unprofitable immediately. For the Irish and UK fleets this scenario was most profitable on the other hand. The second strongest effects on the Danish, UK, Icelandic, and Irish fleets were variations in fish price. The second largest impact on the Dutch fleet, on the other hand, had the low recruitment scenario and on the German fleet the reduced fuel price scenario. In contrast, the lowest effects on profitability of the Icelandic and Irish fleets had the NSAS herring recruitment reduction scenarios. Changing fuel price, however, had least impacts on the Danish, UK, and Dutch fleets.

## 4. Discussion

### 4.1. Pre-analysis: Cost structure of modelled fleets

In order to be able to interpret the model outcomes from the different scenarios a data pre-analysis was conducted. Although all vessels were >24m in length the cost structure differed in some cases.

#### 4.1.1. Fixed costs

One example were fixed costs (incl. insurances, administration, accounting and harbor dues): The UK and Irish fleets as well as the Icelandic fleet had a very high share in fixed costs (15% of revenue on average) compared to the German, Dutch, and Danish fleets (4% of revenue on average). This difference can be explained by the various fishing techniques used. The German and Dutch fleets, for example, use pelagic freezer trawlers that can actively trawl for a longer period of time while processing the catch directly on board. Refrigerated Seawater (RSW) trawlers as used by the UK, Irish, Danish and Icelandic fleets, on the other hand, apply tanks filled with water in order to cool the fish caught and need to return to the harbor more often as the storage capacity is smaller (Knarr 2019a/b). They might therefore have a higher share of fixed costs due to more frequent discharges in the harbor. The difference is also reflected in vessel sizes: The freezer trawler, with a much larger storage capacity, are around 110m in size, whereas the RSW trawler tend to be around 50-60m.

#### 4.1.2. Fuel and repair costs

The storage capacity and technique, on the other hand, does not seem to affect fuel and repair costs share. Usually freezer trawler cover a much larger area in contrast to the RSW trawler, which need to stay closer to the harbor. Hence, one might expect the former to have a larger amount of fuel costs share compared to the latter; however, both were in between 10-13% of revenue. Hence, the large area covered by freezer-trawler and the effort of more frequent returning trips to the fishing grounds by the RSW trawler seem to outweigh each other, generating this similarity. One exception was the smaller Irish fleet (24-40m), which had a fuel cost share of 3% of revenue. This is due to the smaller number of sea days compared to the

>40m fleets (approx. 13% less), which might in turn be a reason why their fixed costs share was the second largest of all fleets (25% of revenue).

### 4.1.3. Crew costs

The crew costs share was also surprisingly similar amongst all fleets (av.: 16% of revenue), independent of vessel size. Freezer trawler were expected to have a lower share of crew costs compared to RSW vessels, being floating factories and using automated processing machines that substitute labor to some extent (Knarr 2019a/b). Onboard freezer trawler, labor costs are not entirely fishing but also processing labor and enables corresponding companies to reduce their labor costs on land. Findings of Tietze et al. (2001, 2005), suggest a decline in labor cost share between 1995 and 2003 with increasing technological advances: For example, between 1995 and 1997, labor costs share of the German pelagic trawler fleet (90-120m in length) made up 44% of total costs (Tietze et al. 2001). In 2002 and 2003, it was only 36% (Tietze et al. 2005) and in this study even less (18% of total costs as an average of 2012-2014 combined with the Dutch fleet). Concerning the Dutch fleet only, crew costs in general seemed to decrease by 22% from 2008 until 2016 (STECF 2017). At the same time number of vessels were half in 2016 compared to 2008, but the total number of crew members also decreased by 27%. Crew costs can, however, also be influenced by other parameters than just technological advances. These are usually fish prices as well as the amount of fish caught. This is mainly because the major proportion of the salary depends on the amount of fish caught. Crew members receive a certain proportion of the catch value, depending on the position they hold.

### 4.1.4. Capital costs

The share of capital costs, which include depreciation and interest, was similar amongst six out of eight fleets ranging from 14-21% of revenue. Two fleets, Iceland and the UK, however, only had a capital cost share between 4-7% of revenue. This can occur due to four possibilities: 1) High proportion of self-financing, 2) cost transfers within companies operating pan-European, 3) better terms of credit, and 4) high vessel ages that are maintained with the company's own holdings. In case of the UK, average vessel age increased over time, but this is also valid for all other fleets (STECF 2017). Additionally, the average UK vessel age is the lowest: 13 years between 2008 and 2016, which indicates a larger capital cost share due to newer vessels and a larger amount of depreciation. For most other fleets, on the other hand, average vessel age was more than 19 years in the same time-period (STECF 2017). Therefore, the first two possibilities mentioned before may be the most likely concerning the UK. First, a high proportion of financing from own resources is possible if vessels are mainly owned by large-scale, pan-

European operating companies through a process called “quota hopping”. It is usually defined as the process where companies buy vessels and flag them in other countries. Second, profit and cost transfers within those large-scale companies are also common. In Germany, depreciations (included in capital costs) as well as subsidiary profits can be transferred to the parent company through a so-called profit transfer agreement (Gelder and Spaargaren 2011). This can be a reason why the German fleet had a smaller capital costs share and was close to the break-even point in all scenarios, whereas the Dutch fleet was far more profitable with a much larger share of capital costs.

In case of Iceland, the actual cost data was lacking. From all modelled fleets, the UK fleet had most similarities to the Icelandic fleet especially in terms of the amount of fishing days per vessel and vessel age. Moreover, both fleets use primarily RSW trawlers to catch mackerel. Hence, the UK costs structure was used to estimate capital, other fixed, crew, repair, fuel, and variable costs for the Icelandic fleet. This might therefore generate a relatively small share of capital costs for Iceland as well as the UK.

A more detailed discussion of capital costs and problems concerning their estimation can be found in Supplementary S.1.

### 4.2. Robustness of the biology module

FishRent is an age-structured profit maximization model, not a stock assessment model, and the baseline scenario does not represent a status quo. Hence, modelled fleets will always aspire to be as profitable as possible under the given circumstances. How fleets actually behaved in reality does, however, not always have to represent the most profitable decision. Other external factors may have occurred which could not be influenced by fishermen (i.e. storms, vessel break-down). Moreover, the assumptions in the model do not always correspond with the knowledge of the fishermen, who rather fish according to past experience. This might have then affected fishing mortality in another way than estimated by the model, in turn also affecting the biomass differently.

In the biological output from the baseline model recruitment, abundance, and biomass of both NEA mackerel and NSAS herring decreased and stayed stable after 2020. This stable pattern occurs due to the amount of 1000 random iterations for recruitment and SSB and the consequent usage of the median. The calculated confidence intervals (CI’s) show how large the error might actually be, which is extremely high especially for herring from nearly none up to 2.5 trillion. Yet, this is still in line with the 95% CI from assessment reports (ICES 2018b, ICES 2019a).

Moreover, the SSB trend of the baseline scenario was similar for both species compared to the assessment. Some differences could still be noticed, particularly concerning herring SSB. A reason for differences between the baseline scenario and assessment values is the usage of an optimization routine in FishRent. This is not included in assessments, as these try to describe the actual condition of the population in order to recommend a sustainable management advice, not what would be most profitable for the fleets. Unfortunately, it was not possible to incorporate any data prior to 2012 in this study, which is why baseline model outputs to assessment values could not be compared to a longer time-period. To get a clearer picture of how well the model results reflect the observed trend of assessments it would be recommendable to include a larger number of years. Yet, for the years that could be used, the differences are only small and fit well to what has been observed. This indicates that the decisions made by the model of what is most optimal in terms of profitability also fits roughly to decisions made by fishermen in reality.

**4.3. (Dis-)investment**

In the decrease in fish price setting from the price variation scenario, three fleets disinvested and therefore reduced their vessel numbers because they were unprofitable, i.e. the costs were higher than the revenue. In reality, fishermen or companies would not directly sell their vessels in case a fishery turns unprofitable. The system is very inertial, which is partly due to the fact that licensing for quotas is needed, making it particularly difficult to sell large vessels in Europe. In the model, also several conditions control fleet size changes: First, (dis-)investment can only occur after the first modelled year. Second, if fleets are profitable, reached their effort capacity and are below their maximum investment limit, they can invest into new vessels. Third, if fleets are unprofitable, they are allowed to disinvest a maximum of 10% per year. The investment limits in this model version were determined by the maximal change of investment and disinvestment observed within the last 10 years (STECF 2016). This approach was also used by Simons et al. (2015) and Bartelings et al. (2015). Yet, Frost et al. (2013) note the sparseness of empirical evidence for the investment behavior of fleets, but also emphasize the importance of such module in economic models that display long-term resource rent developments. Disinvestment in these model runs are therefore interpreted as a sign of overcapacity within a fleet.

**4.4. Scenarios**

In this study, the scenario affecting the profitability of all fleets the most was the adaptation of the quota repartition key scenario according to the biomass distribution of NEA mackerel and

NSAS herring. The degree of profitability largely depended on the newly calculated shares and hence the amount of mackerel and herring each fleet was allowed to catch. Not many other studies have been conducted in a similar way. Léopold et al. (2013) evaluated the biological and economical success of spatial collective quotas concerning an artisanal sea cucumber fishery in New Caledonia. Their results showed a higher stock resilience, buffering effects of market fluctuations and periodic overfishing. Holland already stated in 2004, that costs (e.g. for monitoring and enforcement) may be higher when implementing spatial fishery quotas, although such management may provide a more optimal usage of resources. In the case of the NEA mackerel and NSAS herring fishery, the German, Dutch, and Danish fleets would however lose two highly important fisheries. The UK and Irish fleets, on the other hand, would gain a significant amount of both species also increasing their value massively.

Moreover, in a real quota repartition key adaptation process the fixed proportion of other species included in the revenue calculation might also change and therefore have a different effect on the revenue of the pelagic fleets. Actually, this might worsen the situation for the Dutch, German, and Danish fleets since other pelagic species caught by those fleets (e.g. blue whiting, horse mackerel, and sprat) also primarily occur in Irish, Faroese, and UK waters (Doering et al. 2017). Another possibility to provide more flexibility to the relative stability principle, would be the more widespread use of individual transferrable quotas (ITQs), shifting more responsibilities back towards the industry. However, this system is controversial, raising concerns about the concentration of fishing rights in larger companies (Hoefnagel et al. 2015). Implementing an ITQ system and determining its effects on the pelagic fleets as a more flexible application of the relative stability principle might be another scenario worth considering for future modelling work.

The second strongest effects were associated with the fish and fuel price alteration scenario. One fleet that stood out, because it was the only one showing more extreme reactions when altering fuel price than fish price, was the German fleet. This was because the share of fuel costs was 6% higher than for the others. Moreover, the starting fish price (an average of the years 2012-2014) was already at 0.46 €$kg^{-1}$ for frozen herring and 0.90 €$kg^{-1}$ for frozen mackerel. Therefore, the difference between frozen herring start price and the low-level historic price (herring: 0.35€$kg^{-1}$, mackerel: 0.90 €$kg^{-1}$; Table 2) was only 31% and none in case of mackerel. For all other fleets, fish prices were reduced by at least 70% to reach the low historic price of our scenario. The effect of reducing fish prices thus did not have a very large effect on the German fleet compared to altering fuel price. Additionally, the German as well as the large-scale Irish fleets were close to the break-even point from the beginning, making them more vulnerable to further disturbances than other fleets in all scenarios. The large-scale Irish fleet additionally received the smallest value per kg fresh mackerel (0.76 €$kg^{-1}$). Hence, the difference to the low fish price scenario was by 52%. Furthermore, their margin between revenue and total costs per kg was only 0.10 €$kg^{-1}$, whereas for the others it was on average double (0.21 €$kg^{-1}$). These are all reasons for the extreme sensitivity of the large-scale Irish fleet to any alteration induced by the scenarios tested, most of all lowering the fish price.

Both, fish and fuel prices alterations, where implemented as a sudden event. In our results, the Dutch fleet was affected least by any changes implemented into the model. The quota concentration and enterprise enlargement imply profit and costs transfers, as already discussed earlier. This could be a reason for their larger revenue-costs margin compared to the other fleets, which nearly reached their break-even point until 2030. This enhances their resilience to any additional impacts that may occur and often these events do not appear one at a time. Yet, one shock where a massive disinvestment in the Dutch fleet due to high fuel prices coinciding with low fish prices was actually observed, occurred after the latest financial crisis. While cutter companies were still resilient during other economic crises, many could not overcome this one (Hoefnagel and de Vos 2017). Especially, the larger pelagic companies had the resources to buy quotas of the insolvent cutter companies because they either merged with a quota holding enterprise, bought the whole enterprise or held already quotas themselves (Hoefnagel and de Vos 2017). This situation further increased quota concentration within the Netherlands.

Additionally, fuel prices increased since the mid-90s, reducing economic benefits of the fleets. Jones et al. (2015) found fuel prices to have increased from 0.65 £$l^{-1}$ in 1992 to 1.20£$l^{-1}$ (1.76 €$l^{-1}$) in 2007 when using global cost of fishing database for the UK. This is more than the upper fuel price of 0.85 €$l^{-1}$ that we used in our scenarios, indicating that a longer time-series might be worth considering to test for the effects of potential fuel price shocks on the profitability of the pelagic fishery. Cheilari et al. (2013), on the other hand, identified a fuel cost increase from 0.25 €$l^{-1}$ in 2002 to 0.63 €$l^{-1}$ in 2008 using data from data of the Annual Economic Report in 2010. This is more in accordance to our assumptions. They estimated the effects of the fuel price crises on the economic performance on 54 European fishing fleets and found the number of vessels as well as landings decreasing over time because of increasing fuel prices. The situation of fuel prices is likely to worsen from 2020 on, which is when marine crude oil will be prohibited, and companies have to buy the much more expensive marine gasoil (Kazokoglu and Jakštas 2019). In this case, stakeholders expect a fuel price increase of up to 30%. This is

14% more than what we tested for in the fuel price increase scenario. As to our results, this will mainly affect the large-scale Irish and German fleets than others, as these are also the fleets with the smallest revenue-costs margin.

Compared to the other scenarios, the recruitment scenarios had the least impact on the fleets. Yet, the current level of NSAS herring recruitment is already relatively low and can still become a serious problem for the fleets mainly targeting this species, i.e. the Dutch, German, and the Danish fleets. The medium recruitment reduction setting would decrease profitability of these fleets compared to the baseline scenario but not to a substantial level. However, the low recruitment reduction setting did have drastic consequences, especially for the German fleet. A further reduction of NSAS herring recruitment in future is possible in context with warming oceans. Lynam et al. (2005), for example, suggest the existence of a negative correlation between climate variations, jellyfish abundance and herring survival. In 2007, a special ICES working group concluded that poor recruitment is likely to be linked to increased water temperatures at the spawning sites that raise metabolic rates and therefore food demand. At the same time, less food was available (ICES 2007). Studies of Hufnagl and Peck (2011) as well as Fässler et al. (2011) also indicate an increased larval mortality due to elevated water temperatures in the central and northern North Sea after 2002. Finally, results of the European Horizon 2020 project “Climate change and European aquatic RESources” already showed a further decrease of NSAS herring biomass and a reduced habitat suitability in the whole North Sea area, which is even more pronounced in the south due to increasing water temperatures until 2050 (CERES D2.3 2019).

Although the recruitment scenarios were primarily applied to NSAS herring, the decrease in NEA mackerel SSB should also be considered. It is not a major decrease (from 4800 ktons to 4100 ktons) but has an impact on the fleets nevertheless. It occurs due to the current overfishing of the stock due to a much larger TAC (approximately 35% (mean 2012-2014)) than advised by ICES (ICES 2019a). Additionally, Iceland continues to set their own unilateral quota, therefore adding more fishing pressure onto the stock (ICES 2019a/b).

## 5. Conclusion

We adapted a dynamic and integrated age-structured bio-economic model, FishRent, to the economically valuable pelagic fishery targeting NEA mackerel and NSAS herring. Those fleets are currently exposed to many changes in the environment, policy and economics. In order for them to be able to adapt in time, it is important to determine the magnitudes of those changes. This study showed the continued decrease of recruitment and the associated effects on fleet profitability. We further demonstrated the magnitude of possible price shocks on pelagic European fleets illustrating the potential behavior of fishermen in order to cope with these impacts.

One lesson learned from the application of these scenarios is the relevance of the relative stability revision not only in terms of recent political questions concerning access rights as seen in the Brexit debate, but also regarding climate change. For several pelagic fisheries, a spatial quota reallocation according to biomass distributions would be a severe problem. Other management options, such as ITQ systems embedded into co-management, that introduce higher flexibility to the relative stability principle might be worth considering. The effects of such measures should, however, be tested first.

In this regard, it would be necessary to introduce spatial scales into the current model version. The NEA region could be further divided into the northern NEA, southern NEA and the North Sea area. Again, NEA mackerel is a highly migratory species and has been observed to expand further to the North-west since 2007 (ICES 2019b). With such a regional split of the model, one could simulate the observed expansion of mackerel towards the North-west and the subsequent effects on the fleet behavior. This provides possibilities to test for changes in management and alternative strategies concerning the international disagreement of quotas in the context of climate change spatial dynamics.

**Author Contributions**

All authors contributed to the conception and design of the study; SR wrote and designed the first draft of the Chapter. All authors also contributed to Chapter revision, read and approved the submitted version.

**Funding**

This project received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No 678193 (CERES – Climate change and European Aquatic Resources). This document reflects only the authors' view. The European Commission is not responsible for the dissemination of CERES project results and for any use that may be made of the information.

**Conflict of Interest**

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

**Data Availability Statements**

Detailed economic, catch and effort data analyzed in this study was obtained from EU national labs as well as the Marine and Freshwater Institute in Reykjavík (Iceland). Requests to access these datasets should be directed to Anna Ólafsdóttir (MRI), Matt Elliott (MMO), Arina Motova (Seafish), Josefine Egekvist (DTU Aqua), Kim Normark Andersen (DST), Emmet Jackson (BIM), Hans Gerritsen (Marine Institute IR), Katell Hamon (WUR), Jörg Berkenhagen (TI-SF) and Torsten Schulze (TI-SF). More data can be accessed from the STECF (open source). Biological data was obtained from ICES assessments and is open access.

**Acknowledgements**

First, many thanks are given to the numerous researchers of the national labs for providing catch, effort and economic data as well as their expert knowledge (in no particular order): MMO, MRI, Seafish, DTU Aqua, DST, TI-SF, Marine Institute IR and BIM. Also, acknowledgements are given to Anna Ólafsdóttir (MRI), Jens Ulleweit and Norbert Rohlf for plenty of information concerning the biology of NEA mackerel and herring as well as Marc Taylor and Alexander Kempf for their modelling expertise (all TI-SF, no specific order). Last but not least, many thanks for a lot of feedback and new ideas are given to Martin Pastoors (PFA), Dr. Uwe Richter (Doggerbank Seefischerei GmbH), Miriam Püts, Bernhard Kühn and the Thünen Journal Club.

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# Supplementary material

## S.1. Profit calculation

### Eq. S.1: Profit

Catch determines revenue. Together with a fixed proportion of revenue earned from other species not included in this study and fuel, crew, variable, fixed, and capital costs, profit is defined.

$$PrF_{j,t} = Rev_{j,t} - FuC_{j,t} - CrC_{j,t} - VaC_{j,t} - FxC_{j,t} - \mathrm{CaC}_{j,t}$$

$PrF_{j,t}$ is the profit for *j*th fleet at time *t*, $Rev_{j,t}$ is revenue, $CrC_{j,t}$ are crew costs, $VaC_{j,t}$ are variable costs, $FxC_{j,t}$ are fixed costs and $CaC_{j,t}$ are capital costs.

### Eq. S.2: Revenue

$$Rev_{j,t} = \frac{Catch_{j,t} \times fish\ price_j}{proportion\ other\ species_j}$$

### Eq. S. 3: Fuel costs

$$FuC_{j,t} = \frac{fuel\ usage_j * fuel\ price_j \ \times (E_{j,t} + \left(beta_j * E_{j,t}\right))}{1 - Dasoth_j}$$

$E_{j,t}$ is fishing effort, $beta_j$ is a fishing effort multiplier, and $dasoth_j$ are the total days at sea observed proportion of other species fished by each fleet.

### Eq. S. 4: Crew costs

$CrC_{j,t} = Rev_{j,t} \times CrCO_j$ ; $CrC0_j$ (crew costs share)

### Eq. S. 5: Variable costs

$VaC_{j,t} = Rev_{j,t} \times VaCO_j$ ; $VaCO_j$ (variable costs share)

### Eq. S. 6: Fixed costs

$$FxC_{j,t} = FxCO_j \times FLE_{j,t}$$

$FxCO_j$ is the fixed costs share for *j*th fleet and $FLE_{j,t}$ is the number of vessels operating for *j*th fleet at time *t*.

**Eq. S. 7: Capital costs**

$CaC_{j,t} = CaCO_j \times FLE_{j,t}$ ; $CaCO_j$ (capital costs share)

The share of capital costs, which include depreciation and interest, was similar amongst six out of eight fleets ranging from 14-21% of revenue. Two fleets, Iceland and the UK, however, only had a capital cost share between 4-7% of revenue. This can occur due to four possibilities: 1) High proportion of self-financing, 2) cost transfers within companies operating pan-European, 3) better terms of credit, and 4) high vessel ages that are maintained with the company's own holdings. In case of the UK, average vessel age increased over time, but this is also valid for all other fleets (STECF 2017). Additionally, the average UK vessel age is the lowest: 13 years between 2008 and 2016, which indicates a larger capital cost share due to newer vessels and a larger amount of depreciation. For most other fleets, on the other hand, average vessel age was more than 19 years in the same time-period (STECF 2017). Therefore, the first two possibilities mentioned before may be the most likely concerning the UK. First, a high proportion of financing from own resources is possible if vessels are mainly owned by large-scale, pan-European operating companies through a process called "quota hopping". It is usually defined as the process where companies buy vessels and flag them in other countries. Consequently, they are able to buy and fish a quota in this foreign country but usually also employ a foreign crew and land their catch in the main port where the company is situated (Coelho et al. 2011). An example is the situation in the UK: It is one of the countries where most foreign investment has been made, especially from Spain and the Netherlands. At the end of the 90's about 25% of the UK quotas were owned by vessels belonging to foreign companies (Coelho et al. 2011). Especially large companies have a higher capital surplus and are therefore more flexible with financing and the coverage of costs. Another known example is the ownership of the few large-scale pelagic freezer-trawler of the German fleet by a Dutch company. A consequence is a concentration of quotas, which are only owned by a few companies. Unfortunately, it is hard to identify the actual level of quota ownership concentration because the registration occurs at the firm level not at the level of proprietary companies (Hoefnagel and de Vos 2017).

The second possibility, profit and cost transfers within those large-scale companies, is also common. In Germany, depreciations (included in capital costs) as well as subsidiary profits can be transferred to the parent company through a so-called profit transfer agreement (Gelder and Spaargaren 2011). Parent company and subsidiary are then registered as a "fiscal unity", also allowing them to reduce taxes. Consequently, it is hard to relate to actual depreciations costs as well as profitability and the official numbers might therefore be an under-/overestimation

(Hoefnagel and de Vos 2017). This could also be a reason why the German fleet had a smaller capital costs share and was close to the break-even point in all scenarios, whereas the Dutch fleet was far more profitable with a much larger share of capital costs.

When comparing the capital cost share relative to total costs, Tietze et al. (2005) determined it to be 19% for the German pelagic trawler fleet (90-120m in length) in 2002 to 2003. This is the same as the average capital costs share of the fleets in this study. Especially, the smaller Irish (24-40m), Danish and Dutch fleets had a capital costs share >25% of total costs. Interestingly, these are also the fleets with the highest average vessel age (i.e. 18-25 years). The remaining fleets had an average vessel age of 13-15 years. This would suggest a smaller capital costs share for the Irish, Danish and Dutch than for the others due to less depreciation costs. Yet, these fleets invested into new vessels at the same time or just before 2012, probably causing the capital costs share to be this high in years we used as model input (STECF 2017). The input years should thus be considered with care, as the state of the fleets in the chosen years will also influence the behavior of the fleets during scenarios. In this study, three years were taken as an average in order to account for some of the variation, but a larger number of years might be worth considering.

A last point that should be mentioned concerning capital costs of European fleets in general relates to the annual determination within the Data Collection Framework (DCF). This is done by using the Perceptual Inventory Method established by the Organization for Economic Co-operation and Development (IREPA Onlus 2006). It contains different functions of which each includes certain assumptions about how much (in %) various parts of a vessel account for an annual depreciation rate. These assumptions can however vary between countries and ownerships (individual enterprises versus pan-European enterprises with many subsidiaries), therefore representing rough estimates only. This can make it difficult to compare capital costs between the modelled fleets and it should be remembered that capital costs used in this study represent an estimation only.

## S.2. Parameter estimation

**Table S.1.** Parameter estimation, definition and data sources for Northeast Atlantic mackerel (NEA MAC) and North Sea autumn spawning herring (NSAS HER).

| Parameter | Definition | Value | Estimation | Source |
|---|---|---|---|---|
| $\alpha_{2;MAC}$ | Species-specific Beverton and Holt for NEA mackerel in 2019; Time frame: 1990-2016 | 10,245,580 | Values self-estimated by using the Solver function in Excel and values from the assessment | Excel (2016), ICES 2019 |
| $\beta_{2;MAC}$ | | 2,668,788 | | |
| $\alpha_{2;HER}$ | Fleeted regression parameter for NSAS herring; Time frame: 2002-2016 | 41 | Estimated by using the R Script, EqSim function, and values from the Benchmark Report 2018 | ICES 2018b |
| $\beta_{2;HER}/B_{lim}$ | | 800,000 | | |
| $\alpha_1$ | Cobb-Douglas production function coefficients | 0.8 | Taken from literature | Frost et al. 2009 |
| $\beta_1$ | | 0.2 | | |
| $s_{i,j}$ | Catch share of ith age and jth fleet | See Table S.3 | Average catch share of 2012-2014 | National labs |
| $F_{MSY;\,MAC}$ | Fishing mortality at MSY level for NEA mackerel in 2019 | 0.23 | Taken from Inter-Benchmark Report | ICES 2019 |
| $F_{MSY;\,HER}$ | Fishing mortality at MSY level for NSAS herring | 0.26 | Taken from assessment | ICES 2018a |
| $F_{multiplier;\,MAC}$ | | 1.26 | $F/F_{MSY}$ ratio from 2012-2014 | ICES 2019 |
| $F_{multiplier;\,HER}$ | | 0.53 | $F/F_{MSY}$ ratio from 2008-2015 | ICES 2018a |

**Sensitivity Analysis for Cobb-Douglas production function coefficients**

The settings of the two parameters $\alpha_1$ and $\beta_1$, that represent degrees of non-linearity in the Cobb-Douglas catch production function, can have a significant influence on the estimation of maximum profitability and therefore the remaining results. As to Frost et al. (2009) and Cruz-Rivera et al. (2018), the stock abundance effect on the fishing effort is very low concerning pelagic species ($\beta_1$=0.1-0.2). Due to highly developed sonar techniques, it is easy to locate and catch schooling fish with relatively low effort compared to non-schooling fish. This relationship will not change as the general number of schools may decrease during a period of declining abundances, but not the average size (Cruz-Rivera et al. 2018). Accordingly, they suggest that the Catch per Unit Effort (CPUE) may be almost constant anytime, resulting in larger $\alpha_1$ value (close to 1) for pelagic species. Consequently, fishing effort would have a larger impact on yield than biomass. To evaluate the magnitude and sensitivity of the model on changes in $\alpha_1$ and $\beta_1$, different levels of the two parameters were tested as was also performed by Thøgersen et al. (2012) (Table S.2).

**Table S.2.** Testing for parameter sensitivity: Levels of change of the Cobb-Douglas parameters $\alpha_1$ and $\beta_1$. Note: Values marked as bold were used in all scenarios.

| | **Levels of $\alpha_1$ change** | | | | |
|---|---|---|---|---|---|
| **Parameters** | **1.** | **2.** | **3.** | **4.** | **5.** |
| 1) $\beta_1$ = **0.2** | 0.2 | 0.4 | 0.6 | **0.8** | 1 |
| 2) $\beta_1$ = 0.6 | 0.2 | 0.4 | 0.6 | 0.8 | 1 |
| 3) $\beta_1$ = 0.8 | 0.2 | 0.4 | 0.6 | 0.8 | 1 |

The relationship between total profit from all modelled fleets and the two parameters $\alpha_1$ and $\beta_1$ from the Cobb-Douglas catch production function was determined by altering both parameters (Figure S.1). In general, the profitability decreased with increasing $\alpha_1$ and $\beta_1$. A large effect of increasing the $\alpha_1$ from 0.2 to 0.4 could be seen when combining it with $\beta_1$ = 0.2. This is when total profit increased from 40 to 120 million Euros. After this point profit increased but more steadily and much less extreme with higher $\alpha_1$.

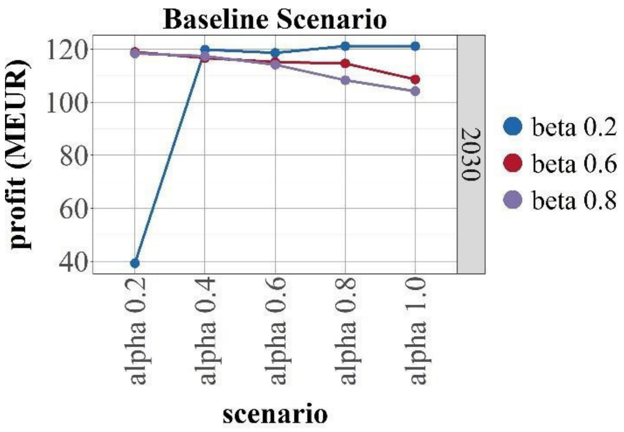


**Figure S.1.** Profit (total of all modelled fleets) in million Euros (MEUR) as a function of the effort-catch parameter alpha ($\alpha_1$) for different stock-catch parameters ($\beta_1$) in 2030.

The influence of both parameters was shown, where altering the parameter $\beta_1$ had a large influence on the profitability of the fleets: The lower the beta, the larger the profitability. Hence, changes in effort had a large impact on the catchability and thus the amount of catch per fleet in contrast to changes in biomass. This is thought to be true for pelagic fisheries but can result in the known problem of “hyperstability” ($0 > \beta_1 > 1$), i.e. the slower decrease of catch rates regardless of declining biomass (Harley et al. 2001; Frost et al. 2009). Yet, the two coefficients of the Cobb-Douglas production function can vary largely amongst fleets and fishing techniques and it is uncertain how these coefficients should be defined correctly. Many studies that tried estimating alpha and beta focused on demersal fisheries (Garza-Gil et al. 2003, Eide et al. 2003, Kronbak 2004, Thøgersen et al. 2012, Frost et al. 2013). In this case, it is often assumed that the parameter $\beta_1$, related to the biomass, has a larger influence on yield than effort. Therefore, Frost et al. (2009) advise the implementation of a large $\beta_1$ (e.g. 0.6) and a small $\alpha_1$ (e.g. 0.4). These values were also used by Simons et al. (2015), who tested the impact of different management strategies on the North Sea saithe fishery. Kronbak (2004), however, used $\alpha_1$=0.75 and $\beta_1$=0.64 in case of bottom trawlers in the Baltic Sea. Thøgersen et al. (2012) applied linear and non-linear functions to estimate catch in context of a demersal fishery in the North Sea including nineteen fleets. The coefficients they used were $\alpha_1$= 0.59 and $\beta_1$= 0.24, but they also conducted a sensitivity analysis where they varied the two parameters from 0.2 to 1. They found that gross profits decreased by approximately 1 MEUR with increasing alpha and beta in an optimizing joint fishery scenario. In our study, profitability also decreased with increasing alpha and beta but effects of changing $\beta_1$ were much smaller. At the same time, both NSAS herring and the NEA mackerel stocks decrease over time, which is why profit will also decrease the higher the beta. Yet, the reaction of the FishRent model to those changes was unexpectedly small. Apparently, the variations in effort and biomass are too small to show any large effects, which means that the results are robust to the assumptions.

**Table S.3.** Proportion of other species caught by the modelled fleets (P_other), fuel usage per day (Ufuel), and maximum effort that was allowed for fleets to fish (Maxeff). Country abbreviations: Germany (D), Denmark (DK), United Kingdom (UK), Netherlands (NL), Ireland (IR), Iceland (IS). Pelagic trawler are represented by TM and pelagic purse seiner by PS.

| Fleet | P_other (%) | Ufuel ($Lday^{-1}$) | Maxeff (days) |
|---|---|---|---|
| NL (TM > 40m) | 47 | 69 | 943 |
| UK (TM > 40m) | 81 | 72 | 1921 |
| NL & D (TM > 40m) | 57 | 74 | 868 |
| DK (TM & PS > 40m) | 47 | 36.5 | 1477 |
| IS (TM > 40m) | 45 | 197 | 1004 |
| IR (TM > 40m) | 45 | 248 | 500 |
| IR (TM 24-40m) | 34 | 21 | 177 |

**Table S.4** Overview of the original catch share according to relative stability (RS) (% of the modelled fleets of TAC), the reallocated catch share (proportion of NEA mackerel and NSAS herring in each fleet fleets EEZ), the share of total catch, and fish prices (landings value divided by landings weight) for all modelled fleets and species. Note: After 2010, TAC values for mackerel represent the sum of unilateral quotas, as no international agreed quotas exist.

| Species | Fleet | Catch share original (%) | Catch share reallocated (%) | Share of total catch (%) | Fish prices (€$kg^{-1}$) |
|---|---|---|---|---|---|
| Mackerel | NL (TM > 40m) | 3 | 0.01 | 2.3 | 1.18 |
| | UK (TM > 40m) | 19 | 61.79 | 2.3 | 1.05 |
| | DK (TM > 40m) | 2 | 0.002 | 2.3 | 1.04 |
| | DK (PS > 40m) | 1 | 0.001 | 2.3 | 1.02 |
| | D (TM > 40m) | 3 | 0.005 | 2.3 | 0.90 |
| | IS (TM > 40m) | 9 | 14 | 2.3 | 1.49 |
| | IR (TM > 40m) | 6 | 18.5 | 2.3 | 0.76 |
| | IR (TM 24-40m) | 1 | 0.28 | 2.3 | 0.79 |
| Herring | NL (TM > 40m) | 16 | 8.27 | 1.6 | 0.35 |
| | UK (TM > 40m) | 14 | 64.82 | 1.6 | 0.43 |
| | DK (TM > 40m) | 16 | 1.7 | 1.6 | 0.46 |
| | DK (PS > 40m) | 7 | 0.7 | 1.6 | 0.47 |
| | D (TM > 40m) | 7 | 2.12 | 1.6 | 0.46 |

## S.3. Stock-recruitment relationships of NEA mackerel and NSAS herring

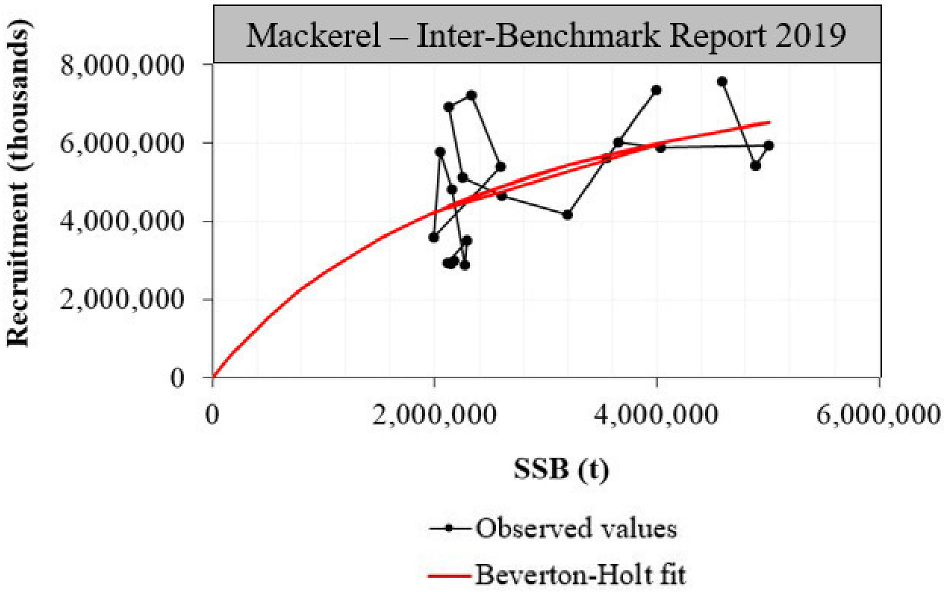


**Figure S.2.1** The self-estimated Beverton-Holt stock-recruitment relationship of NEA mackerel. Black points represent observations from the Inter-Benchmark report 2019 (ICES 2019). The red line represents the corresponding predicted recruitment, which was estimated by using the solver function in Excel.

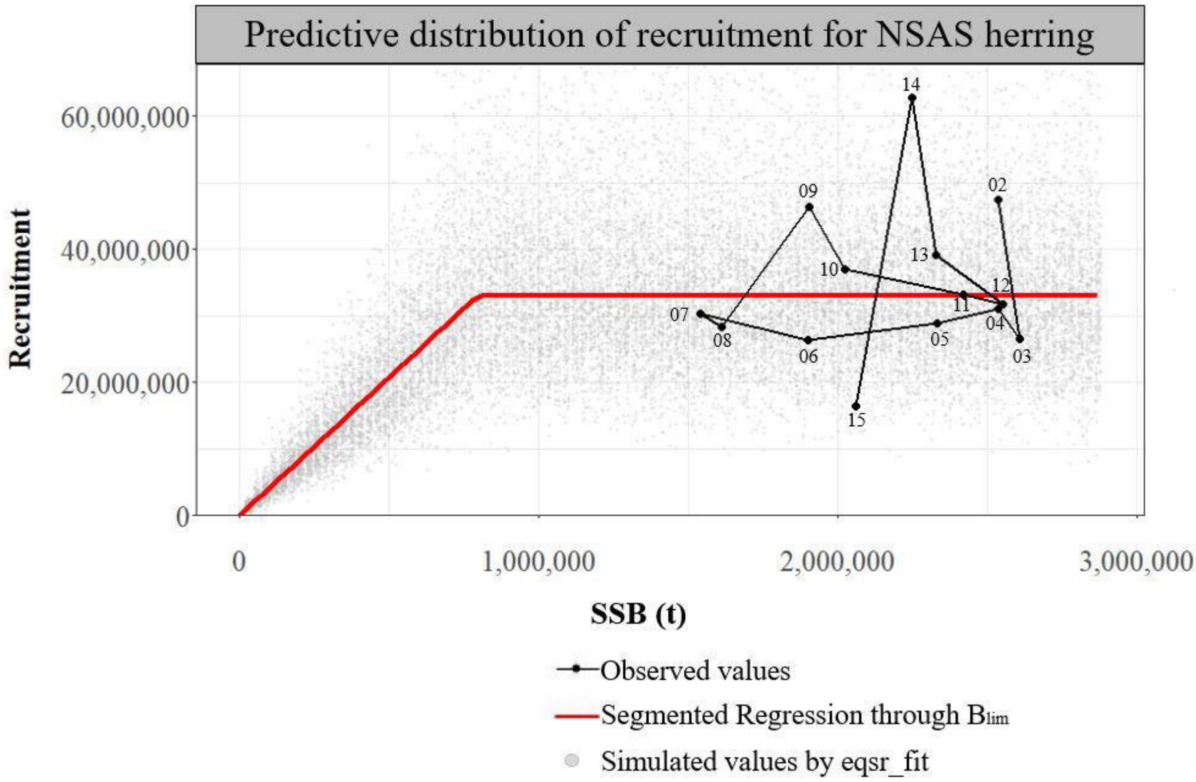


**Figure S.3.2** The estimated restricted hockey-stick stock-recruitment relationship of NSAS herring (through $B_{lim}$: 800,000 t). Black points represent observations from the assessment report 2018 (ICES 2018a). The red line represents the corresponding predicted recruitment, which was estimated by using the eqsr_fit function with 1001 simulations in R (Version 3.5.2).

### S.4. Detailed schematic of the management module

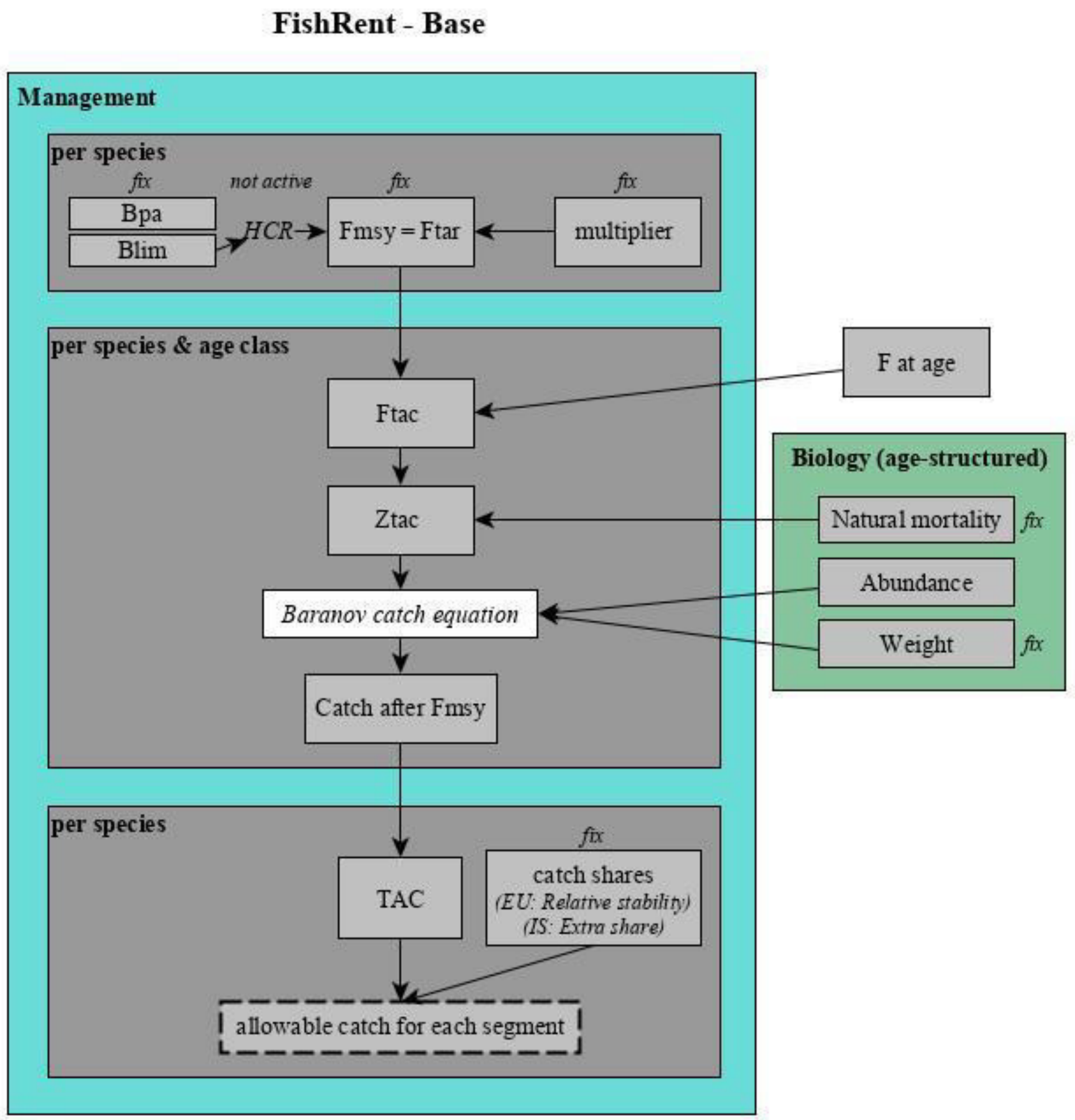


**Figure S.4.3** Detailed schematic of the management module in FishRent. Note: No harvest control rule (HCR) is currently active for NEA mackerel and NSAS herring. A multiplier has been used on $F_{msy}$ (here then referred to as target $F$ "$F_{tar}$") in order to keep the level of fishing from the last years. In the case of mackerel, for example, no unilaterally agreed TAC exists and $F$ has been and still is much higher than $F_{msy}$ for at least the last 10 years.

## S.5. Additional results (more details)

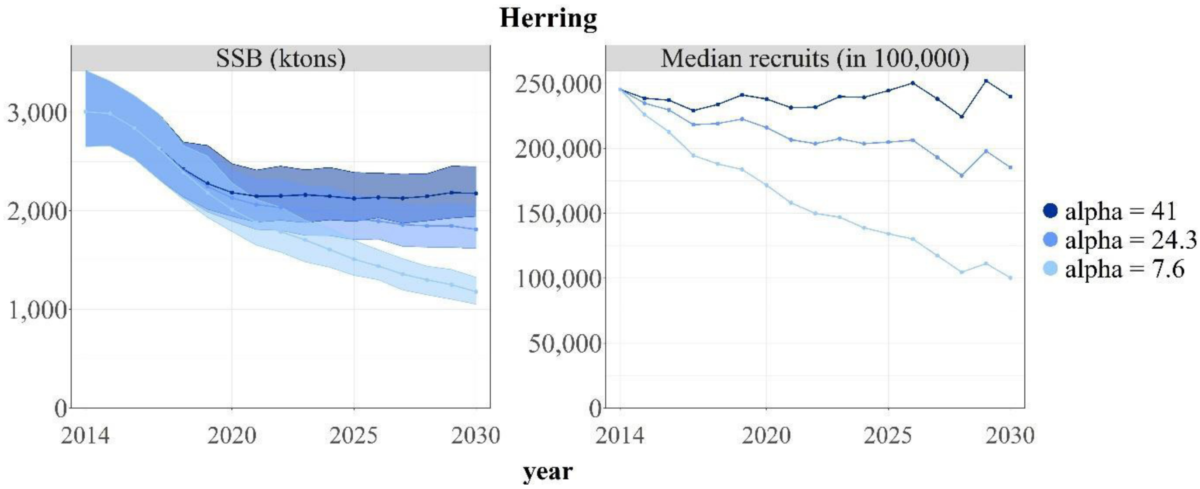


**Figure S.5**. The influence of $\alpha_2$ changes in the SR relationship of NSAS herring on different recruitment (in 100,000), and SSB (in ktons). The dark blue line ($\alpha_2 = 41$) represents the original setting of the baseline scenario when using the restricted hockey-stick SR relationship. The medium blue line shows the decrease in $\alpha_2$ to 24.3 and light blue line to 7.6 in 2030. SSB is shown with the 95% CI calculated from 1000 iterations, median recruitment is however shown without the confidence interval because of extremely large ranges.

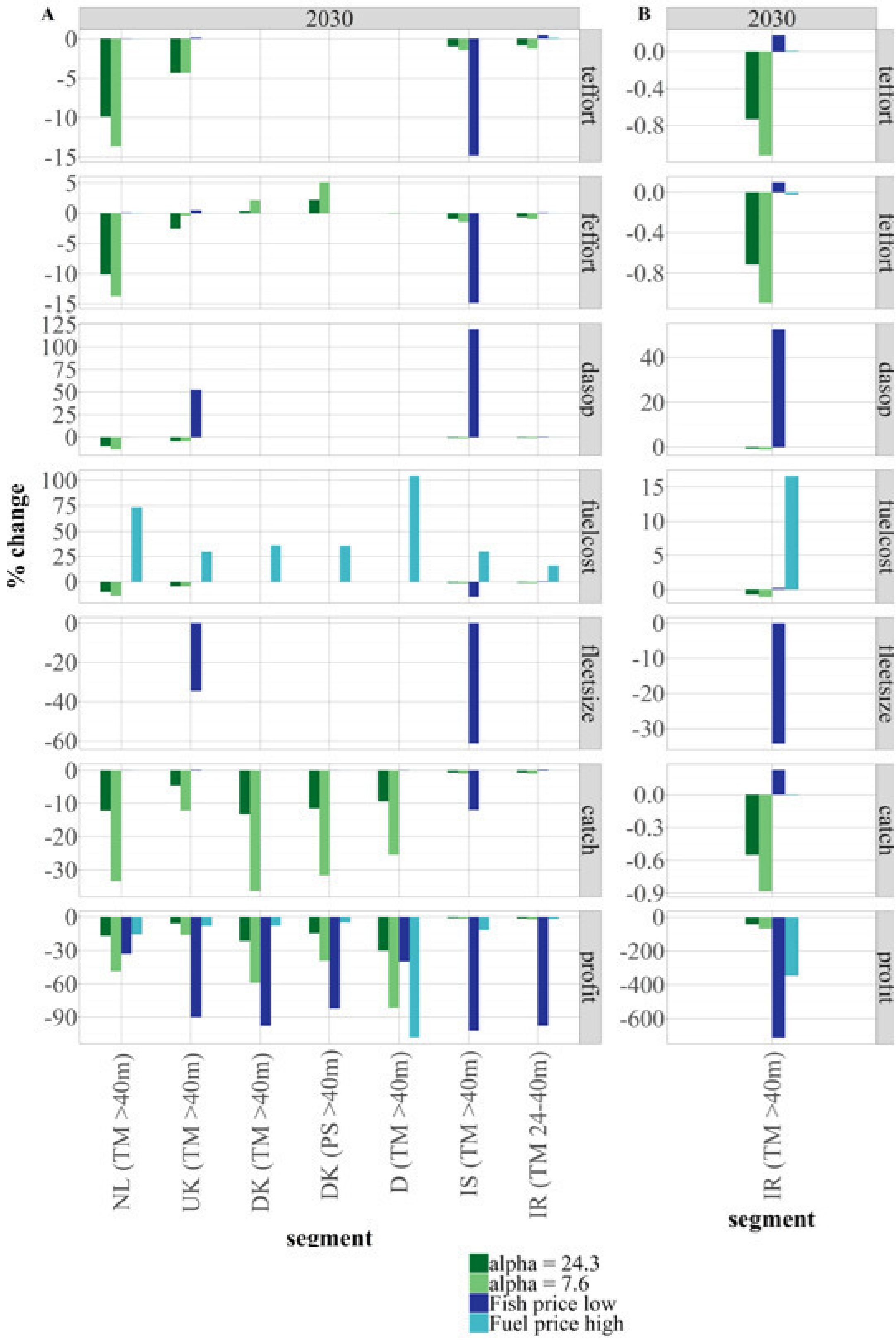


**Figure S.6.** Total effort (teffort), fishing effort (feffort), days operating per vessel (dasop), fuel cost, fleet size, catch as well as profit of all eight modelled fleets (A and B) when reducing recruitment (green shades), lowering fish price (dark blue), and increasing fuel price (light blue) Note: A different scale was used for the large scale (>40m) Irish fleet (B).

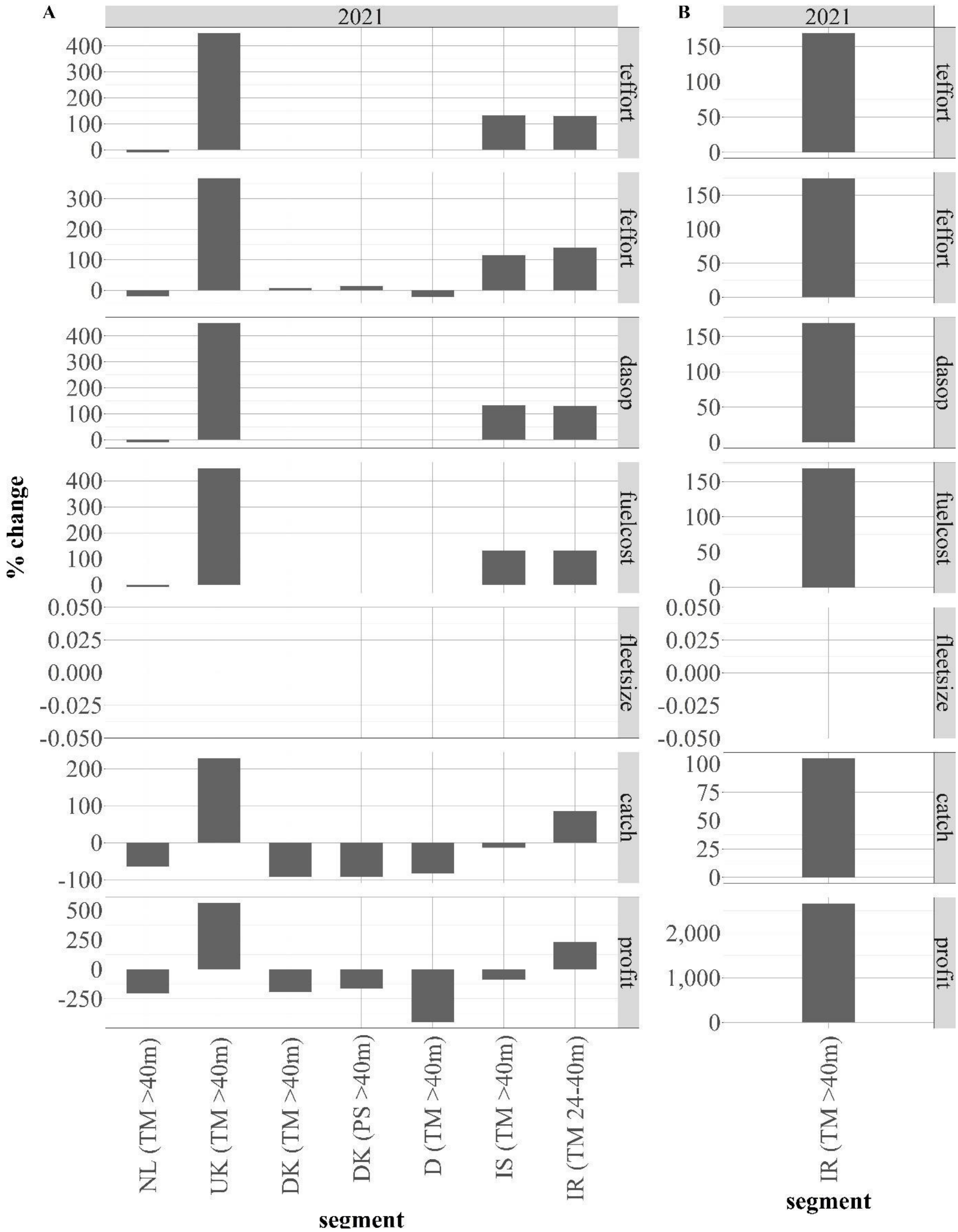


**Figure S.7.** Total effort (teffort), fishing effort (feffort), days operating per vessel (dasop), fuel cost, fleet size, catch as well as profit of the modelled fleets (A and B) when adapting the quota repartition key in 2021 compared to 2020 (the year old catch shares were still intact). Note: A different scale was used for the large scale (>40m) Irish fleet (B).

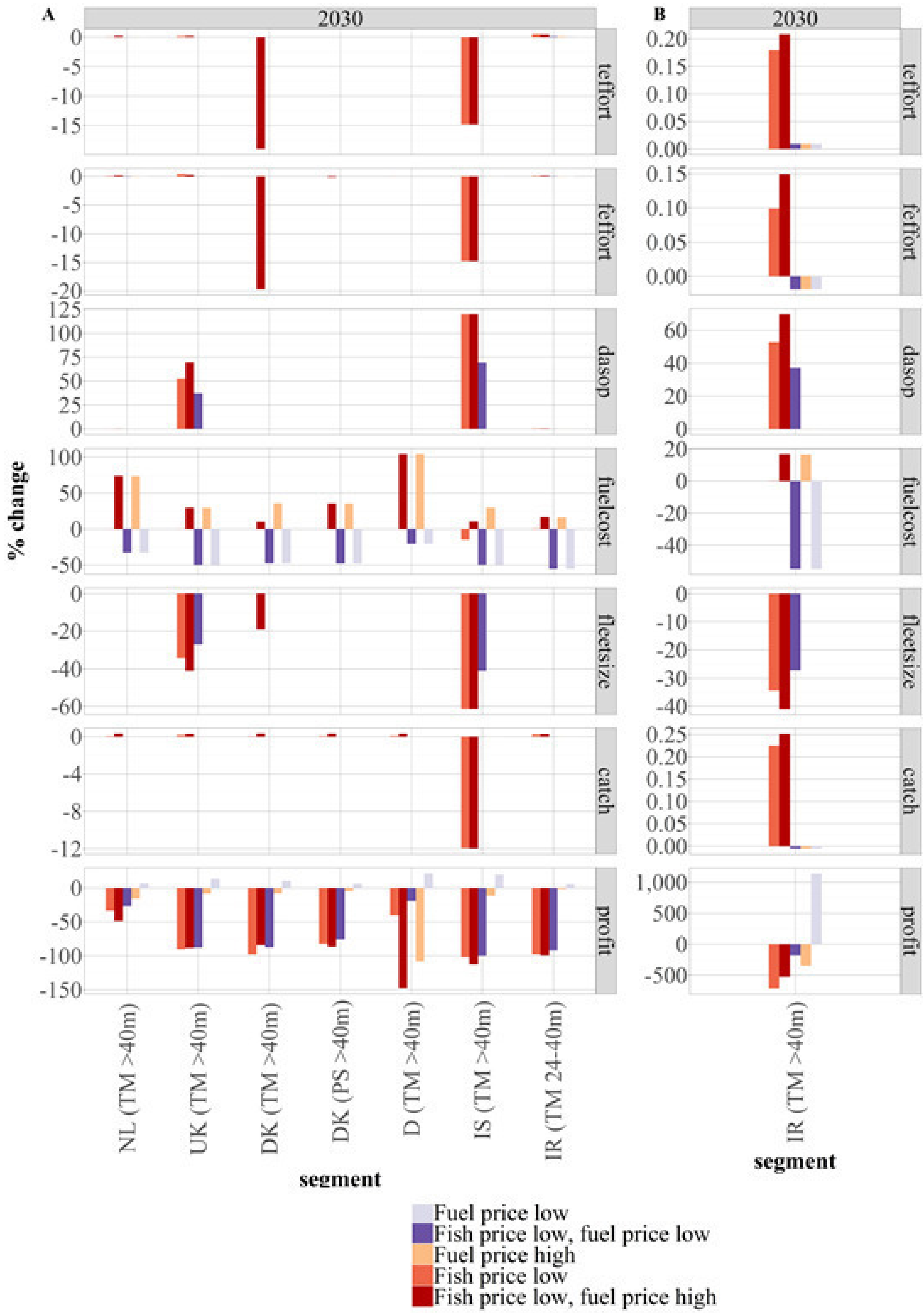


**Figure S.8.** Detailed economic output of each fleet in 2030 relative to the baseline scenario in 2030 for the combination of fish and fuel price (orange, red, light dark purple; A and B). Shown are: total effort (teffort), fishing effort (feffort), days operating per vessel (dasop), fuel cost, fleet size, catch as well as profit. Note: A different scale was used for the large scale (>40m) Irish fleet (B).

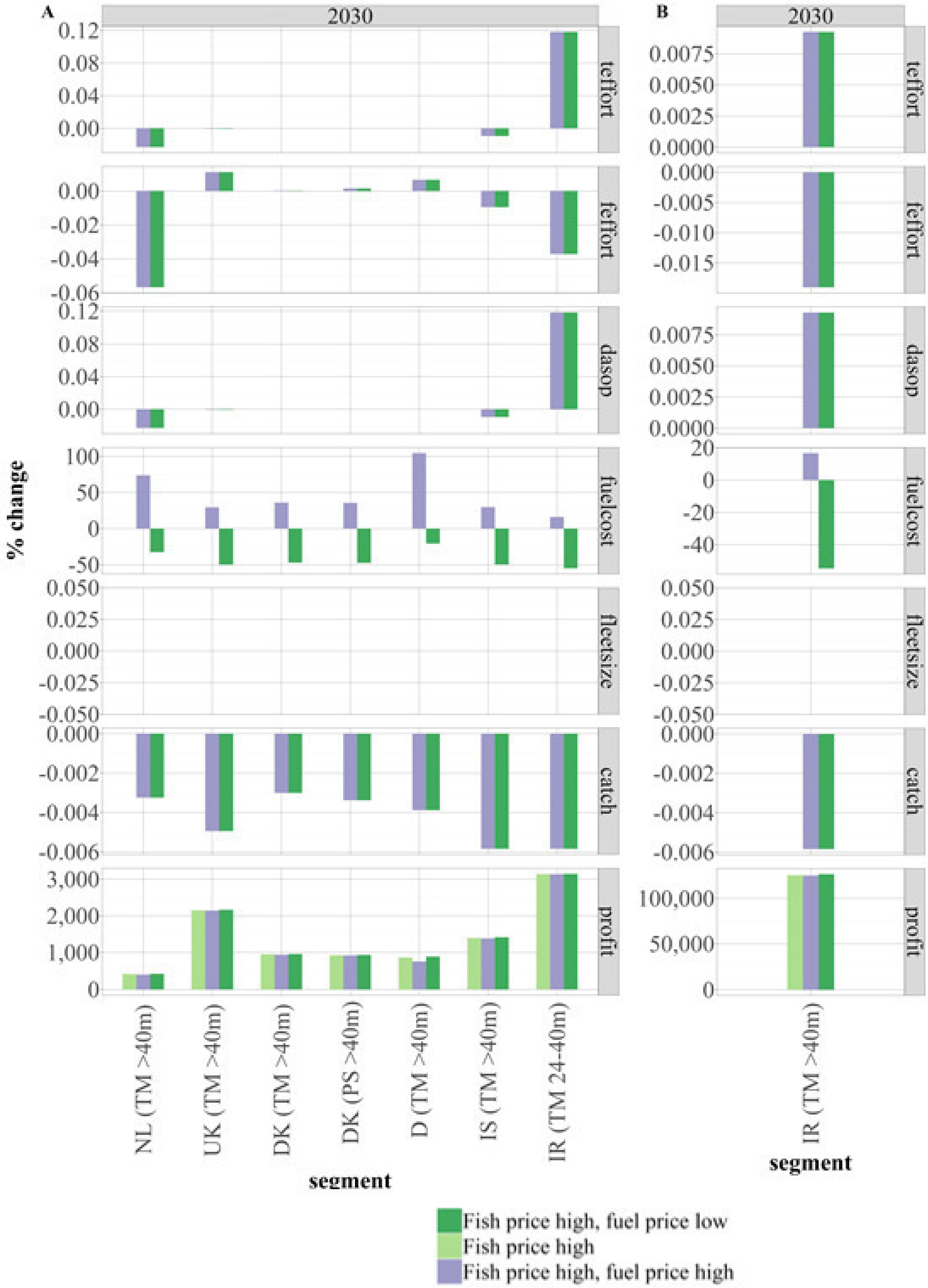


**Figure S.9.** Detailed economic output of each fleet in 2030 relative to the baseline scenario in 2030 for the high fish price scenarios (dark, light green and purple; A and B). Shown are: total effort (teffort), fishing effort (feffort), days operating per vessel (dasop), fuel cost, fleet size, catch as well as profit. Note: A different scale was used for the large scale (>40m) Irish fleet (B).

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# CHAPTER 2 – The more the merrier? Testing spatial resolution to simulate area closure effects on the pelagic North Sea autumn spawning herring stock and fishery

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**Submitted to *Regional Studies in Marine Science***

**Abstract**

Spatially explicit bio-economic models that are age-structured and dynamic become increasingly important, being used for different purposes including spatial management measure evaluation. One of the reasons why those complex models are still rare is the extensive data need. We adapted the temporal version of the pelagic FishRent model to be spatially explicit and incorporated seasonal migration patterns of North Sea herring. During this process, we showed the effects of different resolutions on stock biomass and simulated fleet behaviour. For effects over time, a relatively low resolution might suffice, whereas spatial effects are better captured with a higher resolution. Further, we closed the major spawning grounds at different resolutions. By doing so, we illustrated the need to incorporate a dynamic behaviour of fishing fleets and to increase fleets' flexibility by increasing the amount of accessible areas for each fleet was substantial.

**Keywords: spatial information, closure, fleet dynamics, herring, North Sea.**

## 1. Introduction

During the last decades, the need for tools that can estimate and evaluate trade-offs and feedback effects between the sustainable, long-term supply of resources, their management and socio-economic impacts is increasing. For this reason, Integrated Ecological-Economic Fisheries Models (IEEFMs) are becoming increasingly popular (Nielsen *et al.*, 2017). They mathematically combine anthropogenic and natural processes addressing several disciplines from socio-economics to oceanography (Bastardie *et al.*, 2013; Tahvonen *et al.*, 2013; Maynou *et al.*, 2014; Bartelings *et al.*, 2015; Simons *et al.*, 2015; Pascoe *et al.*, 2016; Nielsen *et al.*, 2017; Da-Rocha *et al.*, 2017). Different types exist, ranging from conceptual/descriptive over strategic to tactical models with various details and resolutions. The application often depends on the research question and data availability (Fulton *et al*., 2015; Nielsen *et al.*, 2017). Equilibrium or "end-to-end" models usually have an increased focus on the complexity of the whole ecosystem, including food webs, detailed functional groups and different human uses. Fulton *et al*. (2015) define these to have a rather strategic, long-term purpose. In this study, we however apply a tactical model, which is more focussed on certain aspects of a system. FishRent is an optimisation and simulation model integrating a dynamic age-structured population model with highly resolved catch-effort data and the detailed cost structure of different fleets (Salz *et al*., 2011; Bartelings *et al*., 2015; Simons *et al*., 2014/2015; Rybicki *et al.*, 2020). It provides short to mid-term economic and biological outputs for a pre-defined set of scenarios (Guillen *et al*., 2004). FishRent identifies the effort allocation that maximises a certain target variable, i.e. net profit, under a set of constraints such as management measures. The model has mainly been used to study the impact of management measures on demersal European fleets (STECF, 2015) but has recently been adapted as a temporal model to pelagic fleets targeting Northeast Atlantic mackerel and North Sea autumn spawning (NSAS) herring (Rybicki *et al.*, 2020).

A relatively recent step towards more complex IEEFMs that increase fishery dynamics is spatial explicitness. This aspect is necessary for spatial management measure evaluation, such as the requirements and effectiveness of marine reserves or marine protected areas (MPAs) (Pelletier and Mahévas, 2005). Marine reserves are often related to no-take zones, permanently prohibiting any anthropogenic activities, whereas MPAs are usually referred to when implementing areas where certain activities or types of fisheries are restricted (Pelletier and Mahévas, 2005; Lester *et al.*, 2009). Employing either of the two can be important to buffer any impact on reproduction and recruitment (Lester *et al.*, 2009). Low recruitment despite high biomass levels is currently a significant problem concerning the NSAS herring stock (Nash and

Dickey-Collas, 2005; Gröger *et al.*, 2009; Payne *et al.*, 2009; Nash *et al.*, 2009; Corten, 2013; ICES, 2018a). Although overfishing is not thought to be the main problem for the currently observed low NSAS herring recruitment, implementing a marine reserve or MPA for the core spawning grounds could reduce the general pressure on the spawning component of the stock. Effects of such a closure can be tested by applying a spatio-temporal version of FishRent. The data needed to test for temporal scenarios only is already demanding, but for spatio-temporal closure scenarios it is extensive and the error as well as uncertainty of results increases. This is also why assessment models are often neither spatially explicit nor consider seasonality (ICES, 2020d). Especially regarding pelagic, transboundary and straddling stocks, the stock behaviour is, however, an important characteristic to consider and occurs over both, space and time (Corten, 2001; Bjørndal and Munro, 2020). The accuracy of the patterns used in models is highly significant. If the model is only spatially and not seasonally resolved, for example, a constant biomass distribution throughout the year and therefore also annual catch rates would be assumed. This can lead to a higher simulated fishing intensity than observed in reality, in which fleets are actually limited by time and may also change fishing areas within a season. Thus, spatio-temporal models should be used for management strategy evaluation.

However, the greater the model complexity, the more assumptions and decisions between desired analysis and actual data availability have to be made as the need for data to parameterise the model appropriately increases immensely. In respect to modelling effort, time and accuracy, a balance between a high spatio-temporal resolution and data necessity should occur. It is therefore important to know the limits of the underlying data in terms of time and space. Nielsen *et al*. (2017) provide a good overview of different IEEFMs worldwide and compare capabilities amongst those, but they still compare models that use different spatial resolutions, study areas, species and fleets. Not many studies have yet been published that investigate trade-offs between increasing complexity and prediction accuracy of bio-economic models, mostly occurring due to the quality and availability of underlying data. Moreover, the issue of how much complexity is actually necessary to evaluate the impacts of spatial management measure on fleet profitability as well as stock viability has not been addressed often.

FishRent, is a well-suited tool when it comes to dealing with multiple fleets at the same time. This is useful as different fleets from different countries often operate from various harbours and have differing seasonal preferences when fishing for specific species. This can be especially important when trying to estimate impacts of management objectives involving straddling and transboundary stocks, which are mostly pelagic species. Hence, this study uses FishRent to investigate the necessary degree of spatial complexity to study natural and political changes to fishing grounds by answering following questions: 1) How detailed should the spatial resolution be when incorporating seasonal migration patterns for pelagic fish? 2) What is the effect on the simulated effort distribution and net profit of key European pelagic fleets targeting NSAS herring when increasing fleets' flexibility? 3) What are the impacts on the stock biomass and net profit of those fleets when implementing a marine reserve for the core spawning grounds and which spatial scale is necessary?

## 2. Materials and Methods

### 2.1. Model description

The optimisation and simulation model FishRent includes the economics of multiple fleets and the temporal and spatial interplay between fleets and fish stocks (Salz *et al.,* 2011; Bartelings *et al*., 2015; Simons *et al.,* 2015). It is written in the General Algebraic Modeling System (GAMS) and uses the CONOPT solver (for a detailed description see Drud (1994)) to determine effort, maximising the total annual net profit of a fishery given the current ecological, regulatory and economic conditions. The model tries to find the most optimal solution within a set of constraints. Those include a bounded vessel utilisation (i.e. minimum and maximum number of days at sea per vessel and per year), management constraints such as TAC, quotas, catch limited by biomass availability (for more details see management section for how those are implemented). To avoid an unrealistic interannual variation of effort, future simulated effort of individual fleets may vary between a lower and upper limit set at 60% of historically observed total effort and historically observed maximal total effort per vessel (for more detail concerning the effort calculation see Supplementary S.1 and for a model overview see Supplementary Figures S.4.1/2).

#### 2.1.1. Economy

The calculation of net profit includes: 1) revenue of fishing activities, 2) capital and other fixed costs (e.g. administration, insurance, accountancy, maintenance costs, interest payments, and annual depreciation costs) and 3) operating costs including fuel, crew and other variable costs (e.g. expendables, income tax, landings, and sales costs) (Salz *et al.,* 2011; Simons *et al.,* 2015; Bartelings *et al.,* 2015; Rybicki *et al.,* 2020). Fish prices and catch determine effort allocation and revenue, fuel price, and revenue influence operating costs (see Eq. S.1 to S.13 in Supplementary material), and the fixed costs are proportional to the number of active vessels. Discarding was not considered since reported discards by the NSAS herring fishery are usually extremely low or not present. More information concerning parameter estimations in general can be found in Supplementary material S.1/2.

### 2.1.2. (Dis-)investment

After the first modelled year, fleet size can decrease or increase (in terms of vessel numbers), depending on fleet profitability: 1) If fleets are profitable, reach their effort capacity, and are below their maximum investment limit, they are allowed to invest into new vessels by 4% at most. 2) If fleets are unprofitable (i.e. make losses), they can disinvest by a maximum of 10% per year.

### 2.1.3. Interface

By using the Cobb-Douglas catch production function, fishing effort as well as total stock biomass are considered, assuming a non-linear relationship between catch and effort as well as between catch and stock size (Frost *et al.,* 2009; Supplementary material S.1/2). In this study, the application of the Cobb-Douglas function is of particular importance since pelagic fish usually form large schools and a non-linear relationship between effort and amount of catch is common (Frost *et al.,* 2009; Cruz-Rivera *et al.,* 2018). A sensitivity analysis concerning the two parameters representing the degree of non-linearity in the relation of catch and effort for a given stock size was already performed in Rybicki *et al*. (2020).

### 2.1.4. Biology

The NSAS herring stock consists of three sub-populations (northern, central and southern), which are managed as one. The number of individuals $N_{t,i,k}$ is estimated for each season (i.e. quarter of a year), age class and area by using the determined catch within Pope's approximation (Pope, 1972; Supplementary material S.3) and the initial abundance from the latest stock assessment when starting this study (ICES, 2018a). For further detail see Simons *et al.* (2014), Bartelings *et al.* (2015), or Rybicki *et al.* (2020). The three sub-populations are then spatially distributed in each season via a migration matrix according to known NSAS herring migration routes (Corten, 2001/2013; Dickey-Collas *et al*., 2010; Figure 1; Eq. 1): NSAS herring migrations start in August-September with the northern and central population migrating from their feeding grounds (April-July) in the central and northern North Sea to their spawning grounds along the UK east coast and Shetland (Corten, 2001). This is the most important time for targeting NSAS herring. Afterwards, they continue to migrate to their overwintering areas in the eastern part of the North Sea along the Norwegian Trench. The southern population, however, spawns in the fourth season of the year, mostly December (Corten, 2001).

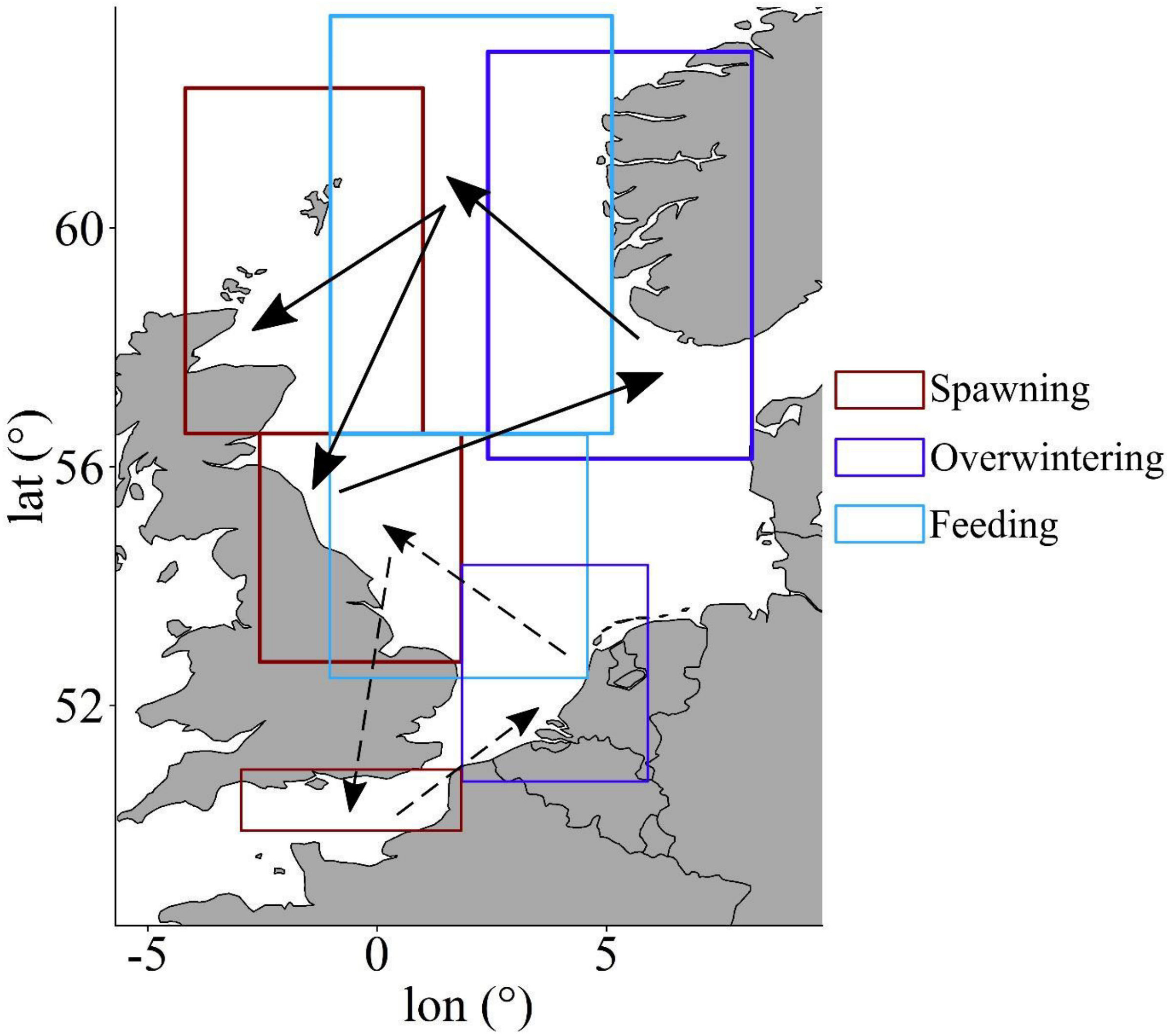


**Figure 1.** Schematic of the migration routes for the different NSAS herring components (solid lined arrow: main component, striped arrow: Downs component). Red marks the area where spawning takes place between August and December, dark blue where NSAS herring is thought to overwinter between January and March and light blue where feeding occurs between April and July (after Corten, 2001/2013; Dickey-Collas, *et al*. 2010).

This takes place in the English Channel. Overwintering occurs in the southern North Sea and feeding is, similar to the central population, typically in the central North Sea (Corten, 2001).

$$Nmig_{t,i,k} = N_{t,i,k} * \mathrm{sum}(kt, N_{t,i,k} * fmc_{t,i,k,kt}) - \mathrm{sum}(kf, N_{t,i,kf} * fmc_{t,i,kf,k}) \qquad (1)$$

where $Nmig_{t,i,k}$ is the new number of individuals at time $t$, $i$th age class and $k$th area, and $fmc_{t,i,kf,kt}$ is the migration matrix where $kf$ (from) and $kt$ (to) define the direction of movement between areas. This matrix can also include diffusion between areas. The proportion of migrating fish is an input to the model and can vary between 0 (no migration occurring) and 1 (100% migration occurring).

The recruitment is simulated using a restricted ($B_{lim}$) hockey-stick stock-recruitment function (Payne *et al.*, 2009; ICES, 2018b; Supplementary Eq. 15 / Figure S.3), with 1000 random stochastic iterations to include a standard error for recruitment and SSB. Median recruitment and spawning stock biomass (SSB) values are then used to calculate survival, fishing mortality and next year's TAC (see management section). At the end of each year, all individuals within one age class are transferred to the next and those older than the maximum age are aggregated in the last age class.

### 2.1.5. Management

Within the European Union, the TAC is now supposed to be set according to the MSY approach. The fishing mortality of NSAS herring has been 44% below the advised $F_{msy}$ on average since 2007, due to relatively low TAC settings (ICES, 2018a). Rybicki *et al.* (2020) used a fixed level of the averaged fishing mortality (2007-2017) by adding a multiplier to the advised $F_{msy}$ in order to simulate a more realistic fishing mortality. This approach was also applied in this study. The Baranov catch equation was finally used in order to calculate a catch according to the target fishing mortality (0.14) (Baranov, 1918; for further detail see Simons *et al.* (2014), Bartelings *et al.* (2015), or Rybicki *et al.* (2020)). This catch is finally used as the new TAC for the following year. No harvest control rule is currently active. Moreover, all fleets are limited by their quota, which is a fixed proportion of the TAC, as well as total catch, which has to be below 95% of the total stock biomass. This limit was introduced to guarantee that some biomass remains the water. In some scenarios, area restrictions or closures are active. This was implemented according to Bartelings *et al.* (2015; Eq. 2).

$$\lambda^* \, CB_{i,k,t} >= sum_j[C_{j,i,k,t} \,/\, (1\text{-}clos_{j,k,t})\,] \qquad (2)$$

where $\lambda$ is set to 0.95, $CB_{j,k,t}$ is the total biomass for $i$th age class, $k$th area at time $t$ and $C$ is catch for $j$th fleet. The parameter $clos_{j,k,t}$ has to be previously defined by the model user and lies between 0.001 (no closure) and 0.99 (full closure).

## 2.2. Data and Settings

FishRent was run for a period of 16 years (2014-2030) using five fleets (Table 1) targeting NSAS herring. Only fleets where herring constituted more than 25% of the total landings value were considered in the modelling approach. Fleets are classified by vessel length categories

(>40m) and their predominant gear types (pelagic trawlers (TM) or purse seiners (PS)), following the classification of the European data collection framework as implemented by the Scientific, Technical and Economic Committee for Fisheries (STECF, 2018). Detailed economic data (e.g. costs, effort, profit etc.) was received directly from national labs and averaged over the years 2012 to 2014. Here it should be highlighted, that data was not freely available in such detail when this study began, especially the economic data. Unfortunately, data from Norway could not be obtained.

For the calibration process, detailed biological data at age (i.e. abundance, natural mortality, weight, SSB and recruitment) was used from the most recent stock assessment at the beginning of this study (ICES, 2018a). Due to significant biological changes after 2014, especially in fishing mortality and weight at age, an average of five years (2012-2016) was chosen for the biological input instead of only three (ICES, 2018a).

**Table 1.** Overview of the five fleets included into the model, their vessel sizes (in metres), primary fishing and cooling technique and the name used within this study. Note: RSW means refrigerated seawater.

| Fleet | Size | Technique | Cooling technique | Name |
|---|---|---|---|---|
| Denmark | >40m | Pelagic Trawler | RSW | DK (TM >40m) |
| Denmark | >40m | Purse Seine | RSW | DK (PS >40m) |
| Netherlands | >40m | Pelagic Freezer Trawler | Freezing | NL (TM >40m) |
| Germany | >40m | Pelagic Freezer Trawler | Freezing | D (TM >40m) |
| United Kingdom | >40m | Pelagic Trawler | RSW | UK (TM >40m) |

### 2.2.1. Scenario 1: Incorporating seasonal biomass patterns in different spatial resolutions

We employed four spatial resolution scenarios and distributed the seasonal biomass accordingly (Figure 2 and 3; Supplementary Figures S.5-7). The first resolution covers only one area, i.e. the Greater North Sea (including eastern Channel), and does not include any seasonal migration patterns (Figure 2.A). Hence, the dynamics of this scenario are limited to re-distributing the effort over time. The second resolution covers four-areas (4A), already introducing more dynamics in space (Figure 2.B), whereas the third incorporates eight-areas (8A; Figure 2.C; Table 2). The fourth resolution contains eighteen-areas (18A) where the western part of the North Sea is further subdivided to capture the spatial migration patterns and the core spawning grounds more accurately than in the other three scenarios (Figure 2.D). In all resolutions, we assume that seasonal migration patterns stay constant among modelling years and that the biomass is homogenously distributed within an area (e.g. Figure 3 for the eighteen areas resolution and Supplementary S.5-7 for the other resolutions).

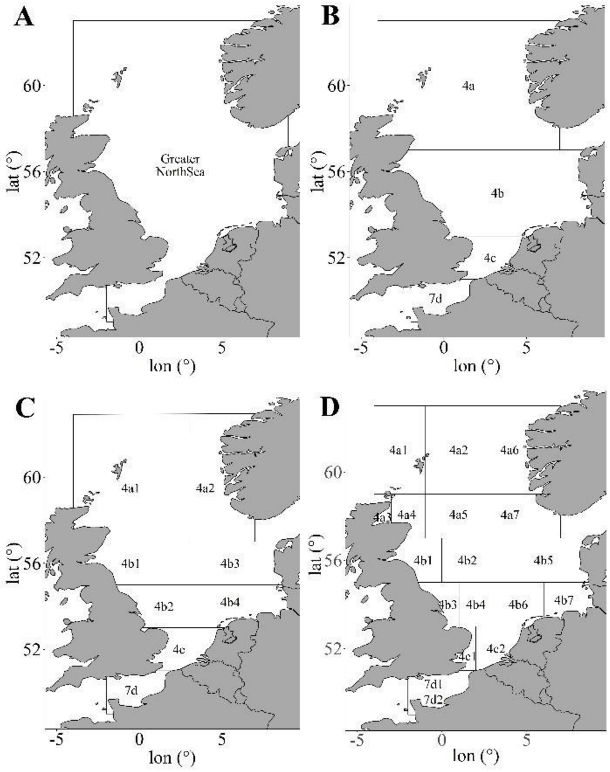


**Figure 2.** Four different spatial resolutions. A: one area, B: four areas, C: eight areas and D: eighteen areas.

### 2.2.2. Scenario 2: Increasing fleets' flexibility

During the process of scenario implementation, the inflexibility of the fleets appeared to be a major problem as the fleet behaviour appeared to be very static and the area closure scenarios were thus difficult to implement. Hence, the access to areas was increased in order to enhance the spatial flexibility of all fleets, because many fleets only fished in two or three areas in the underlying data (Table 2; Supplementary Tables S.5/6). For this, the average catchability of an area where at least one fleet fished for herring was assigned to those fleets that did not fish in this area according to the input data. This was done depending on the fishing technique because catchability is likely to be much higher for large (>100m) freezer trawler than for smaller (24-80m) refrigerated seawater (RSW) operated vessels, which need to return to the harbour more often. In the end the two freezer trawler fleets, the Dutch and the German, were allowed to fish within the same areas primarily increasing the areas available for the German fleet. The same approach was applied to the RSW trawler (two Danish and the UK fleet). As the differences were very small between the 4A and 8A resolution, we continued by using 8A and 18A for any other scenario.

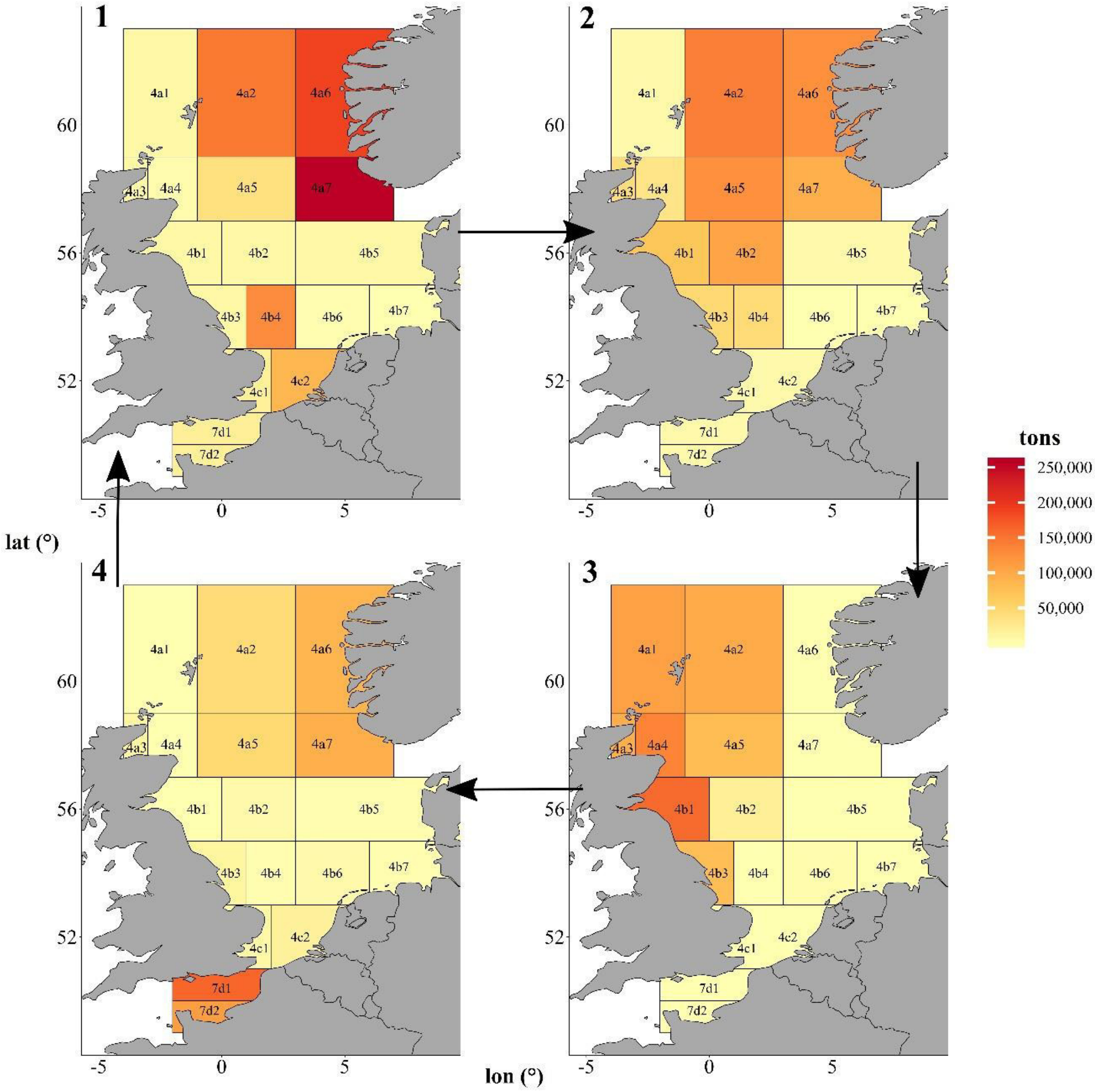


**Figure 3.** Initial total stock biomass distribution within the fourth resolution (eighteen areas) in each season according to Corten (2001, 2013a) and Dickey-Collas *et al*. (2010). A similar overview of the other resolutions can be seen in Supplementary Figures S.5-7.

**Table 2**. Overview of changes implemented step by step for each of the scenarios.

| | Changes | Scenarios<br>1) Resolution increase | <br>2) Increase flexibility | <br>3) Spawning closure |
|---|---|---|---|---|
| 1 | Resolution | 1 (1A)<br>4 (4A)<br>8 (8A)<br>18 (18A) | 8 (8A_flex)<br>18 (18A_flex) | 8 (8A_clos / 8A_flex_clos)<br>18 (18A_clos / 18A_flex_clos) |
| 2 | Additional access to areas | no | yes | yes |
| 3 | Area closures | no | no | yes<br>8: partial closure of<br>Q3: 4a1 (34%), 4b2 (56%), 4b1 (32%)<br>Q4: 7d (65%)<br>18: full closure of<br>Q3: 4a1, 4a3.1, 4b1, 4b3<br>Q4: 7d |

### 2.2.3. Scenario 3: Closing the main spawning grounds

To show how the spatial version of the pelagic FishRent model can be used to address questions regarding spatial closures, we applied a closure scenario: the protection of the spawning stock by implementing a marine reserve for the core spawning grounds. Moreover, to show how different spatial resolutions effect outcomes, we applied this closure to the 8A and 18A resolution scenario (Table 2). For this, the areas covering the central spawning grounds along the UK coast were closed to any fishing activities during the third and fourth season (Figure 4). Since the available areas for a spawning grounds closure with an 8A resolution were very large, covering much more than the core spawning grounds, we implemented partial closures: In the third season, areas 4a1 and 4b2 were half closed (i.e. 50%), area 4b1 was closed to a third (33%) and in the fourth season, area 7d was half closed (50%). As for the eighteen area resolution it was possible to completely close the particular areas (Figure 4). Proportions were determined via spatial analysis in R (packages rgeos, maps, maptools, Version 3.5.2), in which the feature size of each area from the eight area resolution as well as the size of each area from the eighteen area resolution was estimated.

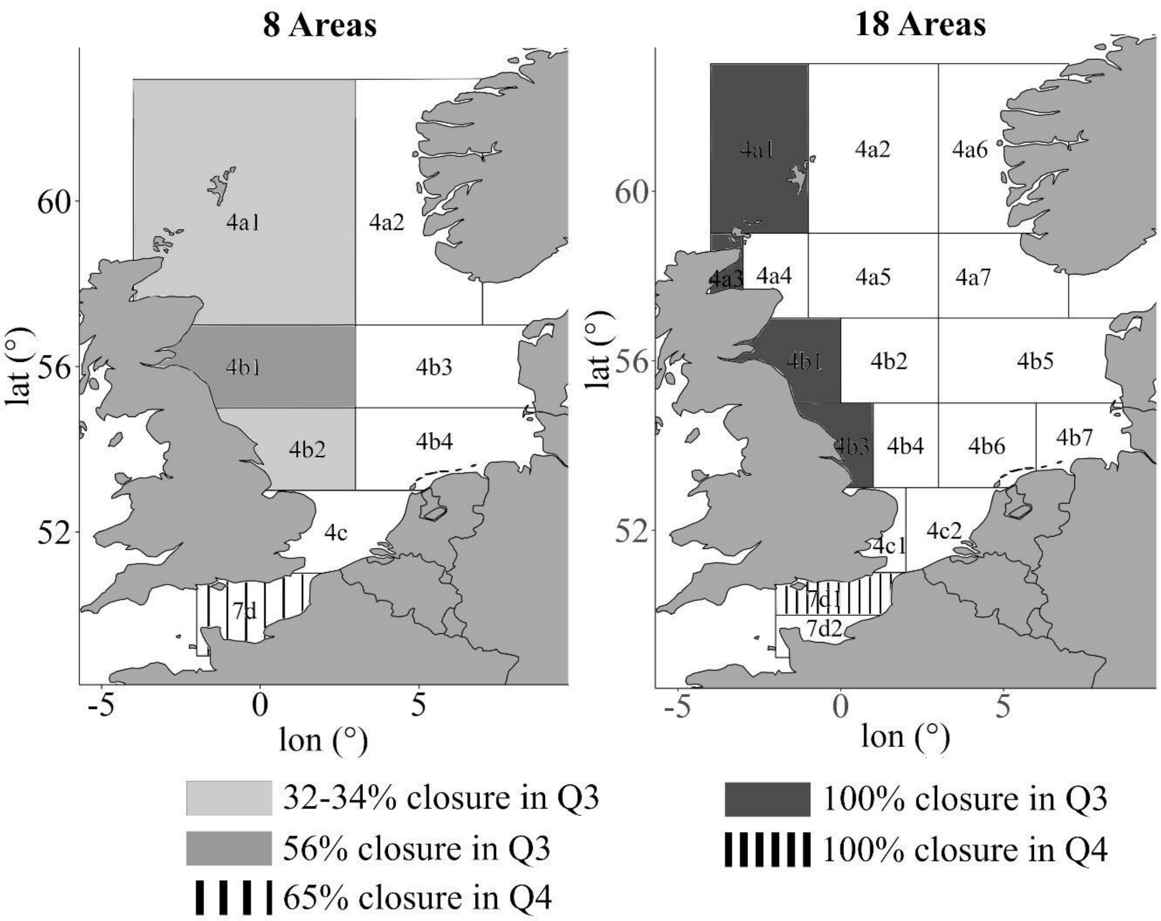


**Figure 4.** Closures due to a marine reserve implementation, covering the core spawning grounds during spawning season in the third and fourth season with 8A (left) and 18A (right).

## 3. Results

### 3.1. Scenario 1: Increasing spatial resolution

Under all spatial resolution scenarios, SSB decreased gradually. Differences between one area and eighteen areas were very small (<0.5%) and the general trend was a decrease from 3000 ktons in 2014 to 2240 ktons in 2030 (Figures 5; Supplementary S.8). This decrease also occurred uniformly in space. The spatial resolution did not have a large impact on effort, catch and profit over time (Figure 6). When comparing catch over time, differences were very small between the 1A to 18A resolution (<0.5%, Figure 6). Results of the 4A and 8A resolution were especially similar, with a difference in catch of 0.2% in 2030 (Figure 6). In 2030, catch was slightly lower (+0.3-0.5%) for the four and eight are resolution than for the 18A resolution (-0.1%).

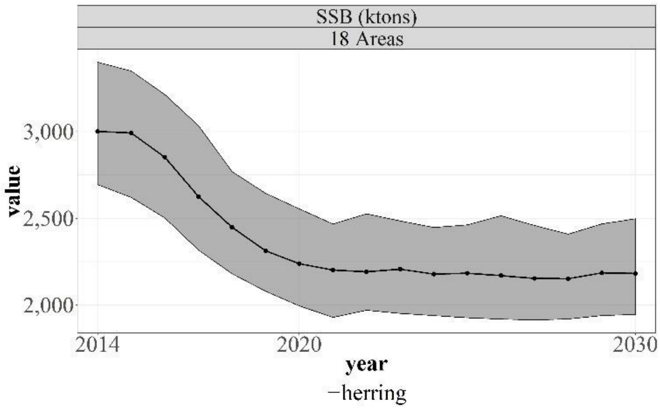


**Figure 5**. SSB trend (ktons) of NSAS herring from 2014 to 2030 of the 18A resolution.

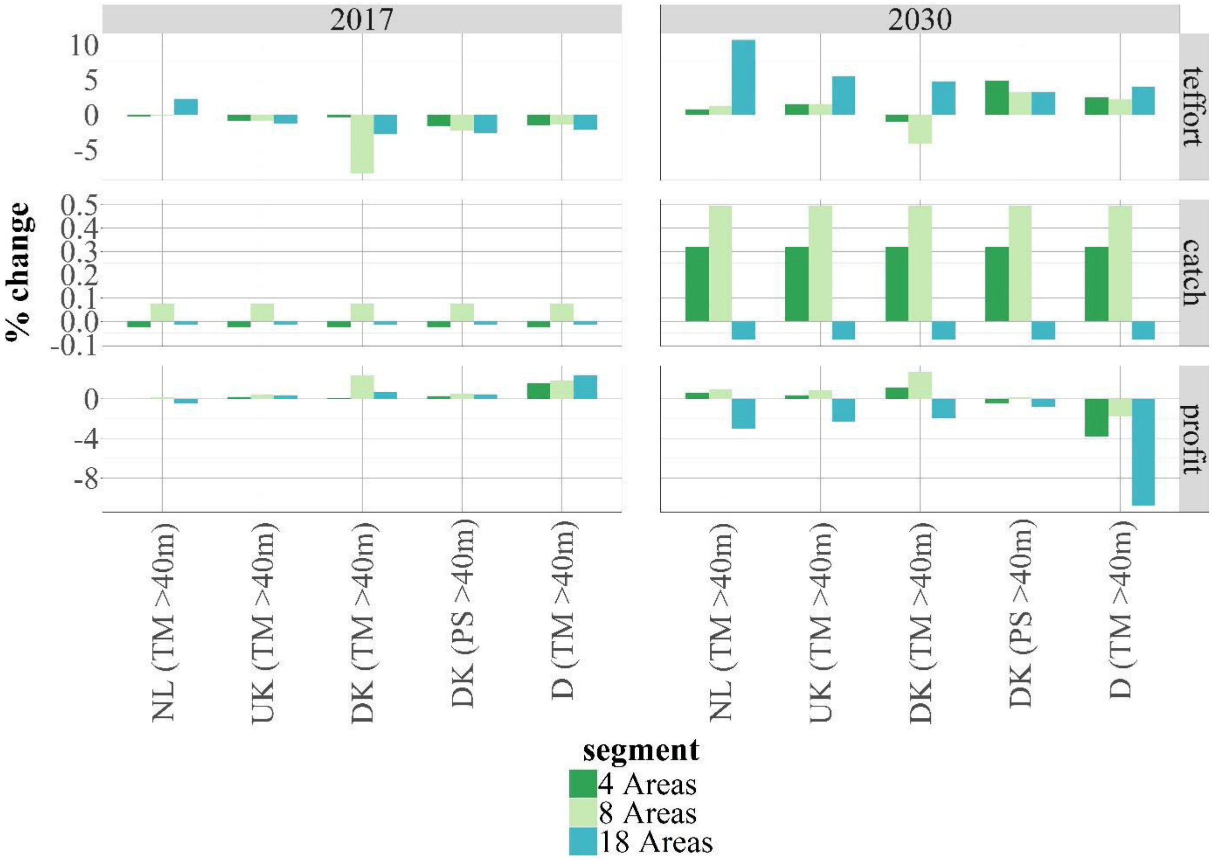


**Figure 6.** Total effort (teffort), fuel costs and profit changes (%) of all five fleets in 2017 and 2030 compared to the 1A resolution. Medium green for the 4A, light green for the 8A and blue for the 18A resolution.

The variations in effort, and correspondingly fuel costs, were slightly larger: After four years (in 2017), total effort decreased by up to 7% (Danish Pelagic Trawler fleet) under the 8A resolution compared to 1A (Figure 6, left). The remaining fleets varied between -2% and +2%. On the long-term (until 2030), total effort of all fleets increased by up to 10% (Dutch fleet) under all spatial resolutions (Figure 6, right). Again, the difference between 4A and 8A compared to 1A was small. When increasing from 8A to 18A, on the other hand, most fleets increased total effort, especially the Dutch UK and Danish Pelagic Trawler fleet (Figure 6, right). One exception was the Danish Purse Seine fleet, which slightly decreased their total effort from +5% (4A) to +3% (18A) with increasing resolution compared to 1A.

Within the first four years, changes in profit were also very small compared to the 1A resolution, but on the long-term varied to a slightly larger extent (Figure 6, right). Especially the German fleet was 11% less profitable on the long-term compared to the 1A resolution with increasing spatial resolution. The Dutch, UK and Danish Purse Seine fleets showed the least variations in profit over time compared to the other fleets, but all were slightly less profitable under the 18A resolution than under the 1A resolution scenario (-2% on average; Figure 6). No fleet had to reduce their numbers of vessels, hence still being profitable over time in general.

Alterations occurred in both space and time. Seasonal effects could also be noticed when increasing the number of areas (Figure 7). For the 8A resolution, for instance, fleets reduced their effort and catch in season four rather than in the main fishing season three, whereas with the 18A resolution they were able to maintain the catch level in season four (Figure 7).

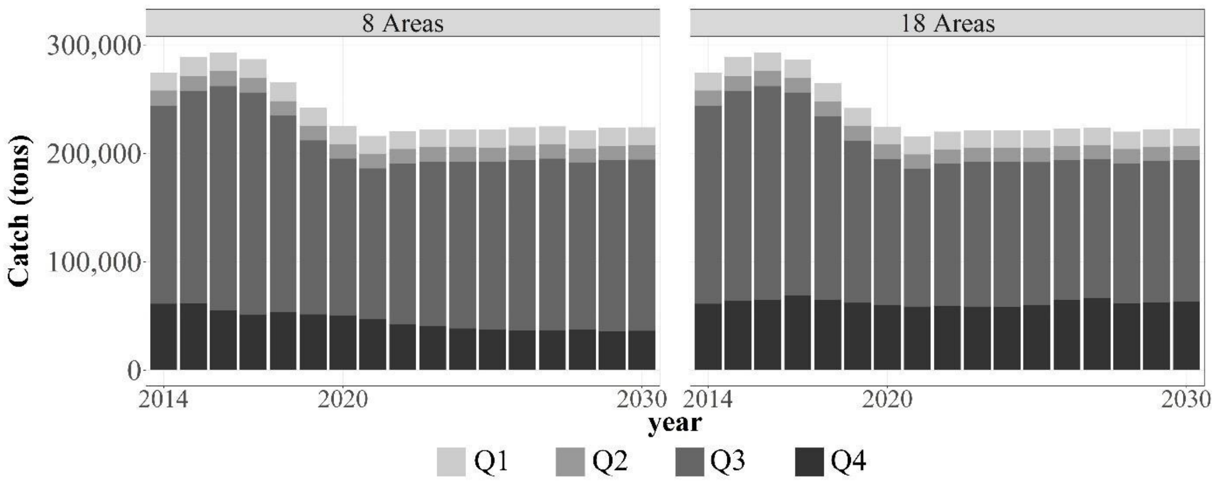


**Figure 7**. Seasonal changes in catch (tons) for the 8A and 18A resolution from 2014 to 2030. Light grey (top) represents season one, medium grey is for season two, dark grey for season three and black (bottom) for season four.

As an example for fishing effort changes in space, we will present season three and four from the 8A and 18A resolution for the German and UK fleet as these were the seasons with the largest changes (Figures 8 and 9). Again it can be noticed what was already described before: for the 8A resolution, the German fleet increased their fishing effort by approximately 15%

(2030) around Scotland (4a1 and 4b1) in season three and remained unchanged compared to the initial year 2014 in area 4b2, east of England. In season four, fishing effort remained unchanged in 4a1 but decreased by up to 60% in the southern North Sea (7d; Figure 9 A/B). In the 18A resolution, however, the German fleet already decreased its fishing effort by 30% in season three in area 4a5 but could sustain their catch level in all other areas and even increase their effort (and catch) by 10% in area 4b1.

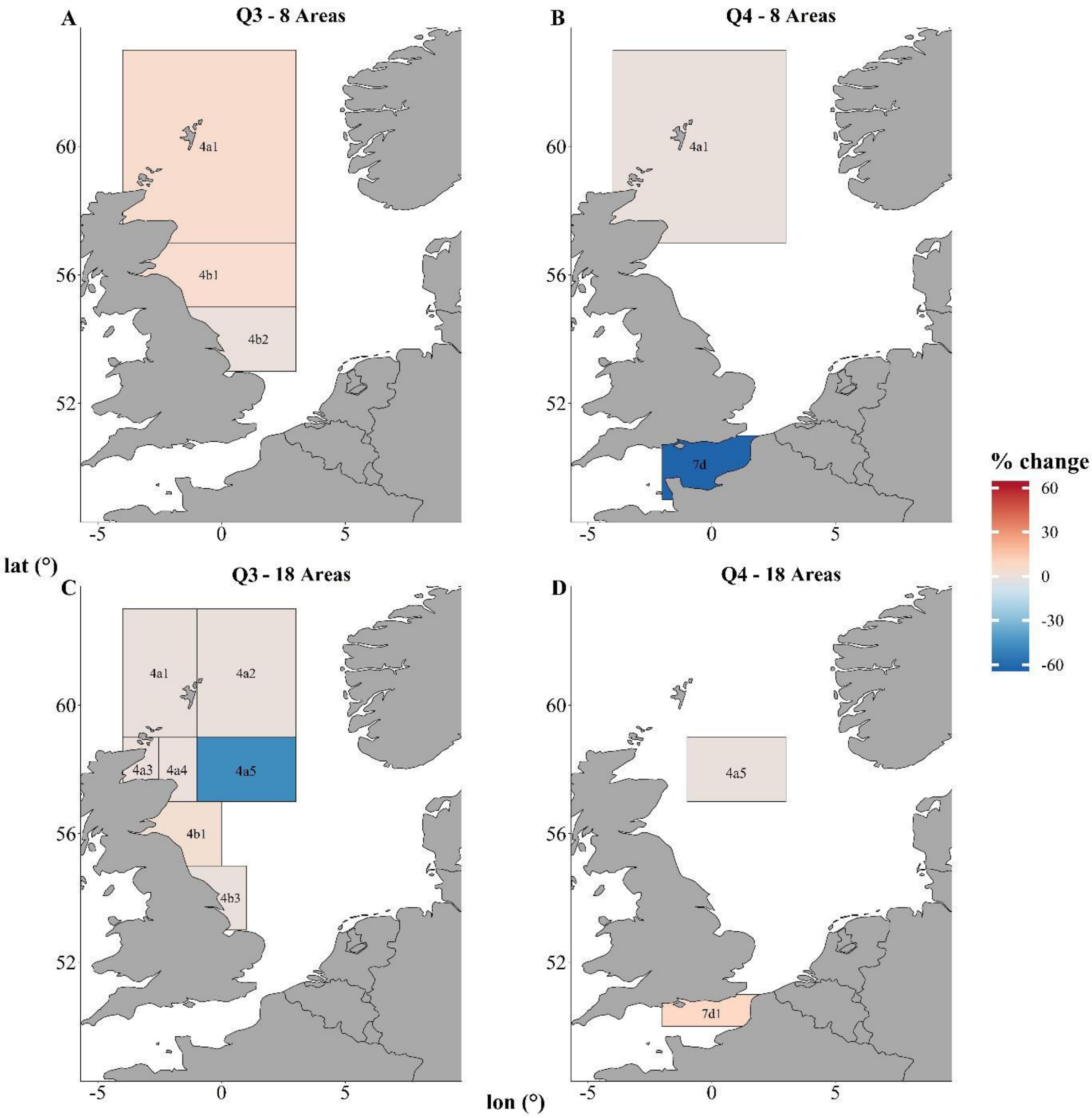


**Figure 8**. Spatial perspective of fishing effort variations (% change in 2030 compared to the initial year 2014) of the German fleet for the 8A (A and B) and 18A (C and D) resolution for season three (left) and four (right). Blue is a negative change compared to 2014, whereas red is a positive change.

In season four, they did not change any effort in area 4a5 (northern North Sea) but increased their fishing effort in 7d1 (eastern Channel), which is also the time of the valuable herring roe fishery in the English Channel (Figure 8 C/D; Herrfurth, 1986; Bledsoe *et al*. 2003). Hence, increasing the number of areas from 8A to 18A provided the possibility to alter and shift the fishing effort in space rather than season.

Another example for the effects of increasing spatial resolution is the fishing effort distribution of the UK fleet in season three (Figure 9). For the 8A resolution, the northern part of the North Sea was not very detailed as the only area, which is available for the fleets, is area 4a1. In this scenario, the UK fleet decreased their effort by approximately 20% in 4a1 (2030 compared to 2014). When increasing the spatial resolution to 18A, on the other hand, the UK fleet was able to increase their effort (and catch) in area 4a4 (+10%) and 5a5 (+ 20%) and only decrease fishing effort in 4a1 but in this case by up to 70% (Figure 9). Again, this illustrates the increase in spatial flexibility of the fleets with a higher spatial resolution.

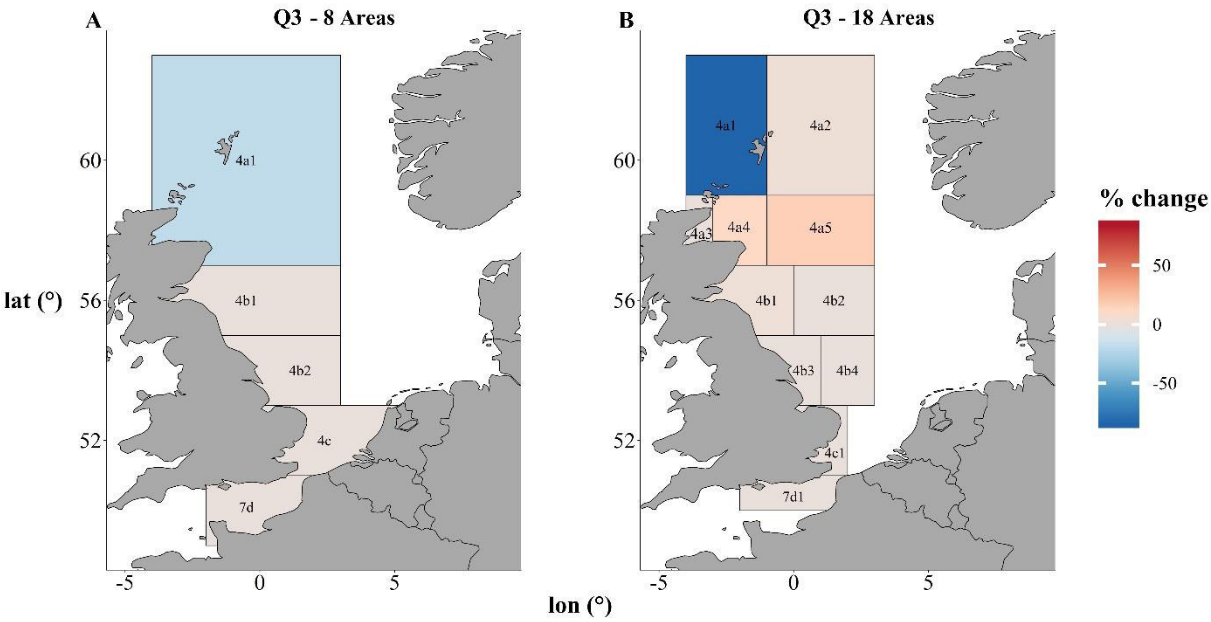


**Figure 9**. Spatial perspective of fishing effort variations (% change in 2030 compared to the initial year 2014) of the UK fleet in the 8A (A) and 18A (B) areas scenario for season three (their main fishing season). Blue is a negative change compared to 2014, whereas red is a positive change.

### 3.2. Scenario 2: Increasing fleets' flexibility

Increasing the access to more fishing grounds did not have the expected effects when it comes to applying the approach on different resolutions. The difference between 8A and 8A_flex was only <0.1%. When comparing 18A to 18A_flex the differences were also very small, except for the German fleet (Figure 10). Under the 18A_flex scenario, profit of the German fleet was 10% higher than under 18A on the long-term (no additional access) (Figure 10). They also reduced their total effort and therefore fuel costs. At the same time, catch slightly increased in area 4a5 (central North Sea) and decreased in 4a2 (norther North Sea) in 2030. Yet, fleets in general stayed in their historical fishing grounds, which are predefined by the underlying data. Therefore, the effects on the stock were also not significant (Figure 11).

### 3.3. Scenario 3: Closing the main spawning grounds

When it comes to implementing area closures, the access to additional areas does make a slightly larger difference on the long-term (Figures 10/11). Yet, there were no effects of the partial closure with an 8A resolution (not shown). Larger impacts could be noticed when implementing the spawning area closure under the 18A resolution scenarios (i.e. 18A_flex _clos). In 2030, the losses of particularly the German fleet were 45% lower in the 18A_flex _clos (Figure 10, light green) than in the 18A_clos (Figure 10, dark green).

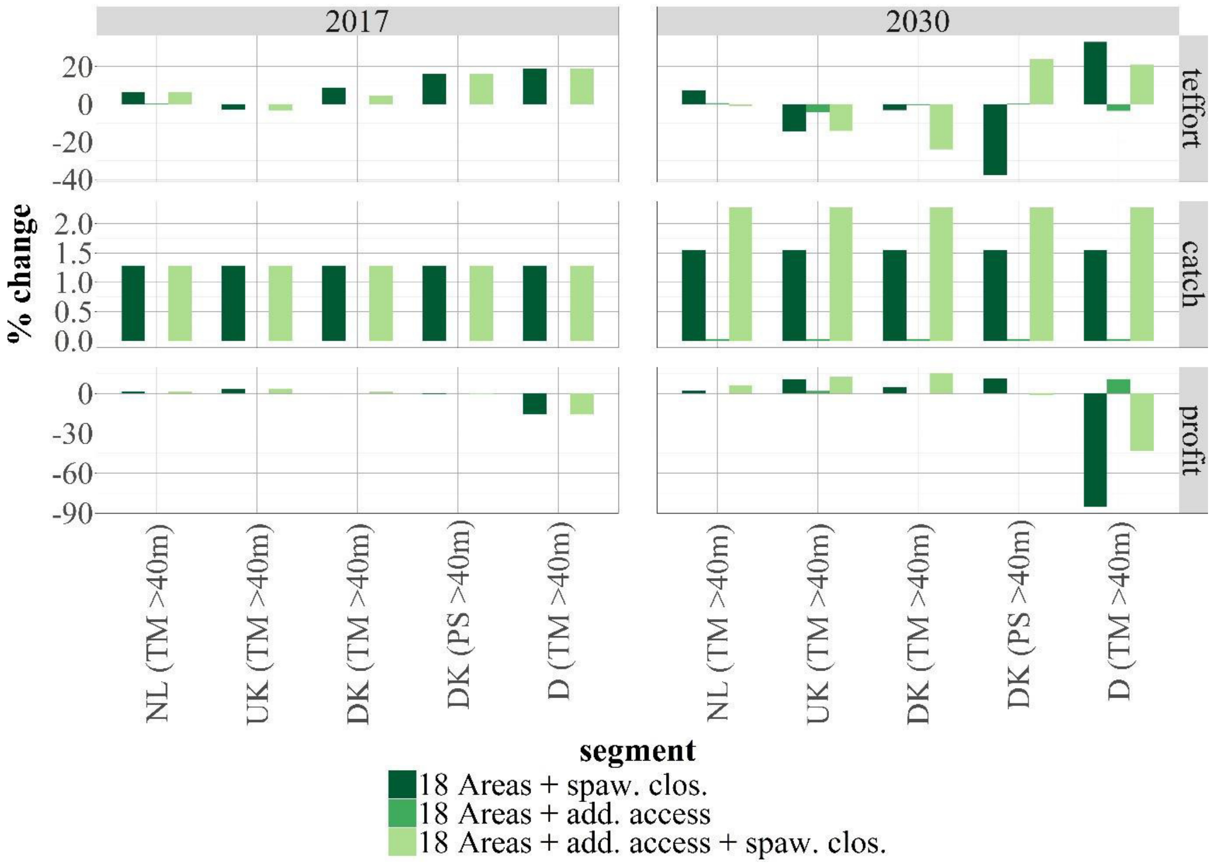


**Figure 10.** Total effort (teffort), catch and profit changes (%) of all five fleets in 2017 and 2030 compared to 18A resolution. Dark green: Eighteen areas resolution with the spawning closure implemented (18A_clos), medium green: the eighteen areas resolution with additional access to areas (18A_flex), the light green: a mixture of both (18A_flex_clos).

In general, results for all fleets using pelagic trawls (TM) were somewhat more positive on the long-term when providing the possibility of more access to areas than without (18A_flex_clos vs. 18A_clos). SSB is also slightly higher (+0.5%) under the 18A_flex _clos scenario compared to 18A_clos, resulting in a 0.75% higher catch rate of all fleets on the long-term (Figure 10/11).

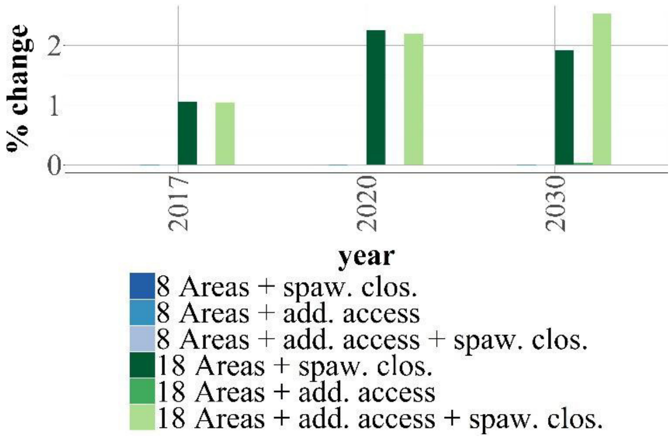


**Figure 11**. SSB change (%) in 2017, 2020 and 2030. Results are shown for the 8A_clos, 8A_flex, 8A_flex_clos compared tp 8A (blue shades) as well as the 18A_clos, 18A_flex, 18A_flex_clos compared to 18A (green shades) scenarios.

As the Dutch and German fleet are very similar in terms of fishing technique (both involve large freezer-trawler vessels), similar outcomes could have been expected. On the long-term, the German fleet increased their effort and catch in 4a2 (northern North Sea) in the third season whereas the Dutch fleet increased their effort and catch in 4a4 (east coast of Scotland; Figure 12).

Both Danish fleet behave very similar when closing the main spawning grounds: On the long-term, they relocate their effort and catch from area 4a2 in season one to 4b2 in the third season, which is closer to their home harbour in Hirtshals (Figure 12). The Danish fleets are the only catching NSAS herring to such an extent in season one. The UK fleet, on the other hand, completely relocate their effort and catch in the third season from areas 4a1 and 4a4 into 4a2 only, where the German also increased catch (Figure 12). The other areas are much further away, which would increase effort and hence fuel cost.

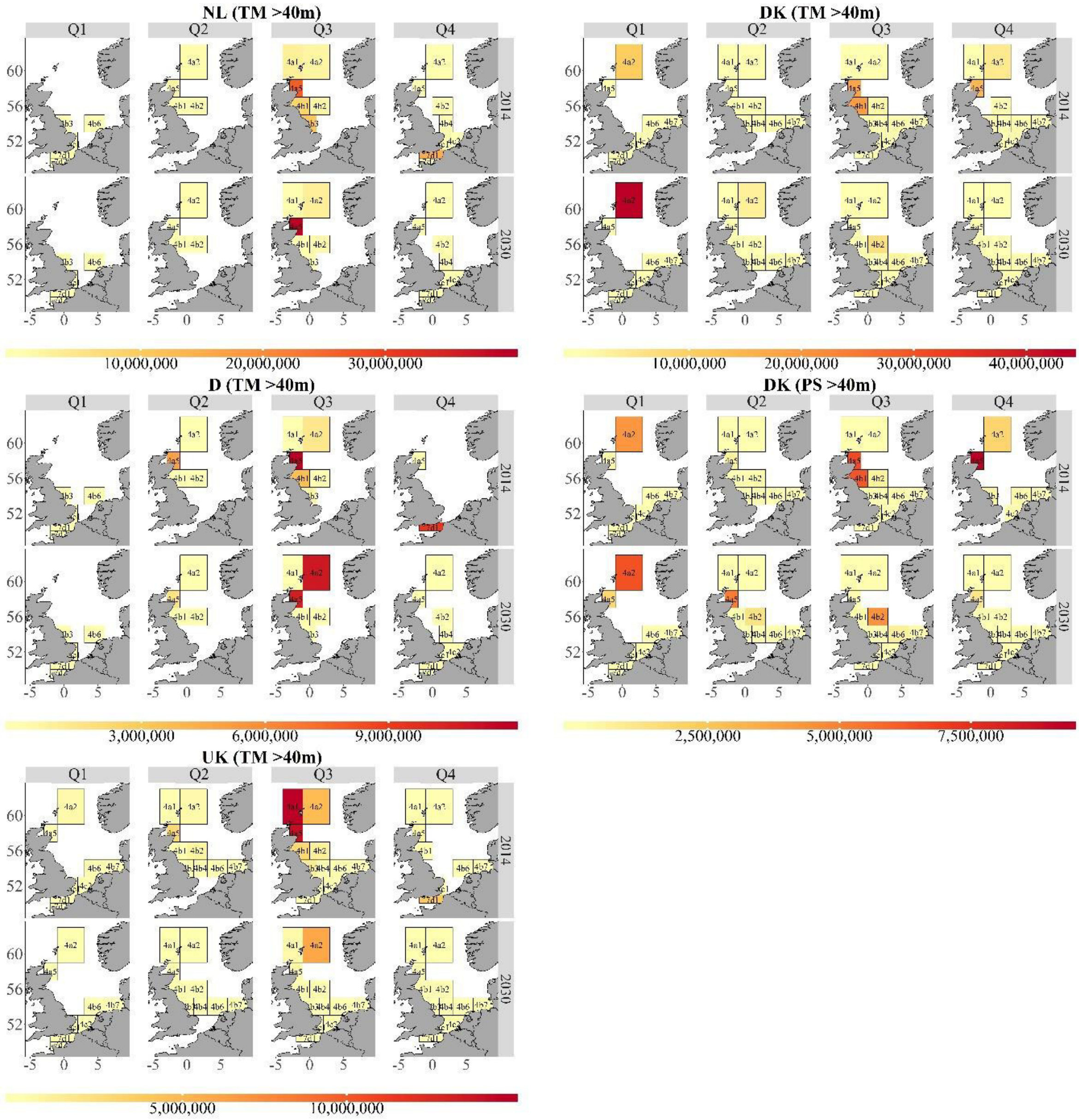


**Figure 12.** Catch distribution (kg) in each season for the start year 2014 as well as on the long-term (2030) under the 18A_flex_clos scenario.

## 4. Discussion

In this study, we adapted the temporal FishRent version of Rybicki *et al.* (2020) for the pelagic NSAS herring fishery, incorporated spatial explicitness with seasonal migration patterns under different spatial resolutions as well as the possibility to close certain areas to different degrees depending on user settings and research question. In this process, our aim was to illustrate the importance of using a tool that is able to deal with multiple fleets at the same time, operating from different harbours with different seasonal preferences when fishing for specific species. Moreover, we discuss major model limitations generated by the underlying data of European pelagic fisheries.

### 4.1. Scenario 1: Increasing spatial resolution

In general, introducing a higher spatial resolution first provided the possibility to integrate seasonal migration patterns of NSAS herring, which can be a very significant feature regarding straddling stocks. When using a resolution of 18A, migrations could be displayed in detail according to Corten (2001, 2013a) and Dickey-Collas *et al.* (2010). Hence, the biomass distribution changed with higher spatial resolution, but the general trend over time was unaffected. Major effects could be seen regarding seasonal variations in catch and effort distribution depending on each fleet and spatial resolution: When using fewer areas, most fleets were not as flexible in space and were therefore forced to vary their effort between seasons to optimise their net profit. This is also due to fishing costs varying between regions when using a higher spatial resolution compared to the 1A scenario, where average costs are used. In this process the division of 4a1 (8A, see Figure 2) into another five areas turned out to be crucial, as this is one of the central fishing areas for all fleets. Annual catch and profit results of all resolution scenarios were very similar to the temporal (1A) model version. Spatially, however, important differences can be seen: Using the highest resolution (18A) allowed fleets to select the attractive fishing grounds with high catch rates and low costs. In contrast, when using lower resolutions (1A, 4A, 8A), fishing hot spots are hidden/spatially averaged in larger areas. This shows that important spatial information gets lost when incorporating a low number of areas and was especially apparent in the northern North Sea, where areas were defined to be rather large, bearing the danger of over- or underestimating effects. An example is the case of the UK fleet, where fishing effort decreased in the whole area of northern Scotland and the Shetland Islands (4a1) with the 18A resolution. With a resolution of 18A, however, 4a1 was further divided into another four areas and fishing effort only decreased in one out of three (around the Orkney and Shetland Islands) instead of the whole area. In the three adjacent areas, fishing effort increased especially in the southern area along the coast of Caithness down to Aberdeenshire (4a3). These results show that questions regarding seasonal and spatial impacts on fleet behaviour patterns can be more realistically captured by using the higher spatial resolution of 18A.

Effects on fleet net profit were rather minor, except for the German fleet, for which the 18A resolution was the least profitable (although the difference between 8A and 18A was still only 8%). By using a smaller number of areas, the sizes of each area are very large and the fleets are always able to reach the biomass within an area. By using a larger number of areas, on the other hand, the distance towards the area with the highest biomass may change and the related fishing costs start to matter. Driven by the underlying data, the German fleet also had the least access to other areas compared to all other fleets, with their main NSAS herring fishing season in the third and fourth quarter of the year. This significantly decreases the flexibility of the model to find an optimal solution, especially when having a very low resolution, and bares the danger of over- or underestimating effects of implemented management measures. This is one reason why we used the approach of increasing the possibility to access other/additional areas that were not present in the underlying data before (see next section).

Due to the similarity between the 1A and 18A resolution in terms of fleet profitability and NSAS herring SSB trend over time, a resolution higher than 18A does not seem to be necessary for the scenarios implemented in this study. Hence in case of pelagic species, which cover a very large area and move over larger distances than demersal species, this study showed that a high degree of resolution is not necessary when being interested in the general development of a population. The general assessment of pelagic species might thus not necessarily need to incorporate the spatial aspect. If the interest is, however, to understand the behaviour of different fleets at the same time, seasonal as well as spatial aspects need to be considered on a higher resolution. In general, there have been only few attempts though to quantify the effects of different resolutions and the role of matching scale of data when applying bio-economic models. The common view seems to be to use the highest possible resolution without testing for the model performance at other scales (Núñez-Riboni *et al.*, in prep.). One study by Hamon *et al.* (2014) investigated the effects of Tasmanian rock lobster (*Jasus edwardsii*) price changes and climate change on the fishery by applying three different spatially explicit models that each increase in complexity (from static over linear to agent based). Their findings, for example, also promoted the usage of the most complex model of all three, implying that the local economic and social impacts can only be realistically captured when including an explicit and detailed representation of economic drivers. Other than this, most studies that engaged in the question of matching scales and different resolutions to the data accessibility and model performance have been conducted in terrestrial habitat modelling exercises. Some claim that the usage of a lower (e.g. Rahbet and Graves, 2001; Louto et al., 2007; Núñez-Riboni *et al.*, 2019) or higher (e.g. Seo *et al.*, 2009; Guisan *et al.,* 2017) resolution produces better results, while others rather highlight the importance of replicating the characteristic scale of the processes of interest when choosing a certain resolution level (Pearson *et al.,* 2004; Bellier *et al.*, 2010; Kärcher *et al.,* 2019). Results of this study also show that this letter point seems to be very important. Simons *et al.* (2015) and Bartelings *et al.* (2015), for example, used a spatial resolution at an ICES rectangle (1°x0.5°) level to model the North Sea demersal fisheries. In this study, we used the common knowledge of migration routes, which is only available on a broader scale (Corten, 2001/2013; Dickey-Collas *et al*., 2010). Without the appropriate data, it is much more difficult to implement migration patterns on a fine scaled resolution as used by Bartelings *et al*. (2015), introducing more uncertainty to the results but not more information. In the end, we argue that the implementation of finer spatial resolution highly depends on data availability and quality as well as the question of interest.

**4.2. Scenario 2: Increasing fleets' flexibility**

Although additional areas were introduced to modelled fleets, they remained in their historically observed fishing areas. This is a reasonable result and represents the reality due to various reasons that will be explained in this paragraph. Throughout the development of the temporal, 1A model version and performance of the scenarios the relatively inflexible and non-dynamic behaviour of the fleets became apparent, i.e. their behaviour is relatively static and they are not able to vary much of their traditional patterns in terms of space and season. FishRent was originally developed for demersal fisheries, with relatively fixed fishing grounds and low seasonal patterns. During the spawning season in autumn, the NSAS herring fishery targets herring with a specific quality for specific products. Therefore, the main fishing grounds and fishing seasons are fixed to the spawning grounds and seasons, making them very static and inflexible. An attempt to increase fleet flexibility, other than introducing spatial stock dynamics, was to increase the amount of areas accessible for the fleets. Yet, instead of providing access to the whole North Sea (i.e. also areas where no fleet has fished in the input data), we limited the access to the areas where at least one of the fleets fished in the initial data. This decision was made due to data accessibility limitations: Theoretically, it is possible to provide fishing access for the whole North Sea if enough data is present. Within the present model version, the fleets would follow the general migration patterns of the NSAS herring stock to the areas where most biomass is available (if this is the most profitable solution also considering expenditures), but where the fleets do not fish in reality due to following reasons: i) fish size and quality, ii) fishing for other species.

First, a large processing industry is concentrated on manufacturing relatively specific products (e.g. different types of marinated herring sold in cans) of herring, i.a. situated in Neu Mukran, Germany. For those fishing companies, it is very hard to find any substitution products since the quality, fish size and fat content of NSAS herring have to meet specific requirements in order to be able to produce products such as matjes (Stroud, 2001; Nielsen and Olesen, 2008). Usually, the decisions on where to fish best are not only made by the amount of stock biomass available and expenditures to catch this fish but largely depend on fish quality. In case of NSAS herring, this changes seasonally (personal communication; Tülsner and Koch, 2010). It is primarily targeted from August to October along the Scottish and northern English east coast, although spawning can already start in July. Directly at the beginning of the spawning season the fat content is yet too high and products would crumble too easily (personal communication; Tülsner and Koch, 2010). During the feeding season in the second season, a large amount of NSAS herring can be found along the northern/north-western North Sea. However, fleets do not fish in this area and during this time of the year because the fat content would not be high enough for manufacturing most products (personal communication; Tülsner and Koch, 2010). In this model version, no fat content or quality information is included. Moreover, the weight at age is treated as constant over time and space. Sufficiently detailed data is hard to find and to include into the model. A possibility to handle this problem could be to incorporate fish prices that vary seasonally as well as in space and can be implemented if data availability allows for this. Therefore, the areas and seasons of which knowledge of less desirable fish quality exists could be distinguished by assigning a lower fish price.

Secondly, the pelagic fleets included in this model target different species (e.g. mackerel, sprat, blue whiting, horse mackerel and pelagic redfish) during different times of the year (ICES, 2019a). Blue whiting (*Micromesistius poutassou*), for example, is widely distributed throughout the Northeast Atlantic but highest concentrations occur along the western British Isles and Faroe Islands at the edge of the shelf, where spawning also takes place between March and April (ICES, 2019a). Most of this stock (88%) is fished by a multinational fleet during spawning season in the first half of the year (mostly by pelagic freezer trawlers; ICES, 2019a). Northeast Atlantic mackerel (*Scomber scombrus*) and horse mackerel (*Trachurus trachurus*) both perform vast migrations, are primarily caught by the same multinational fleets also targeting NSAS herring in the first and fourth season of a year (although separately) and consist of both refrigerated seawater trawler (RSW) and freezer trawlers (ICES, 2019a). Both fisheries take place west of Scotland and northwest of Ireland, to some extent also in Spanish and Norwegian waters. Sprat (*Sprattus sprattus*), on the other hand, is mainly targeted in the North Sea and Kattegat/Skagerrak region (although also to some extent in English Channel; ICES, 2020a/b). The main fishing season is, similar to NSAS herring, in the third and fourth quarter of a year in ICES division 4.b (central North Sea; ICES, 2020a/b). This fishery is dominated by the Danish fleet (80% of total catch) using pelagic midwater trawls and purse seines (ICES, 2019d; MSC, 2020). The five modelled fleets catch NSAS herring to 25% on average, hence approximately 75% other species contribute to their total catch (see also Rybicki *et al.,* 2020). When targeting either species this is considered as a separate fishery. In this model, these “other species” are included as fixed percentage of the revenue. Changes in “other species” biomass, migration patterns, fish prices, etc. are not included as a feedback mechanism in this model version. Therefore, it is not possible for the modelled fleets to switch directly to another species that might be more profitable during the runs themselves and reduces the flexibility of fleet behaviour. Moreover, the pelagic fleets are known to switch relatively spontaneously to another species (e.g. from mackerel to horse mackerel, which may be caught in the same season and a similar area), if catch for one species is unsatisfactory. Including other species that are targeted by the same fleets is possible when data is available, but unfortunately the amount of biological detail is not accessible for all species. Especially biological data for the beaked redfish *Sebastes mentella* is scarce, which is also targeted by the pelagic freezer trawler fleets (stakeholder information; ICES, 2019b).

### 4.2.1. Limitations

When increasing area availability to the fleets, an assumption concerning catchability had to be made in areas where, as in the case of the NSAS herring fishery, there is no catch and effort data available. Catchability is defined as the relationship between resource abundance and the efficiency to capture the resource with a certain fishing gear (Arreguín-Sánchez, 1996). As catchability varies depending on technique and gear type used, we applied the average catchability of the fleets that fished in a certain area within the underlying data and provided this to a fleet that has not. Hereby we differed between trawl type, i.e. freezer or RSW trawler. Freezer trawler might have a higher catchability than RSW trawlers due to using larger vessels and nets. Yet, this approach appeared to be very difficult as the greater the model complexity, the more assumptions have to be made increasing uncertainty and the chances of error. We therefore decided to keep the somewhat simpler version of providing more access to the fleets in regions where there was data available, i.e. where at least one fleet has fished in the input data. The differences between the start access to the areas and the additional access were, however, insignificant no matter the resolution. As before, when increasing spatial resolution, the German fleet was the only changing their behaviour through reducing their total effort and fuel costs by moving slightly closer to their home harbour. Yet, the static behaviour of the fleets when providing additional access to other areas is a validation of the model producing rather realistic results. Discrepancies might occur to some extent as the model does not include all external factors that might affect fleets behaviour, such as weather conditions, but a drastic change of the fleets would be questionable.

Another limitation of this model version, which reduces fleets' flexibility, is the fixed fish price. Fish prices can vary over time especially seasonally, depending on the amount of fish available on the market and costumer demand. Prices for frozen fish may vary less as they can be kept in a storage for a longer time period (EUMOFA, 2019). This is the case for the German and Dutch fleets targeting NSAS herring but using freezer trawler instead of RSW vessels such as used by the Danish and UK fleets. Yet, the quality of herring is also seasonal, hence price seasonality probably remains the same. Within the model, fish prices are not being adapted yet and are set per species by the user. Moreover, currently these prices are assumed to be the same for each season. This input data could be adapted to be seasonal if this information is available. It could even be assigned by area, which would in turn aid in quantifying the attractiveness of certain areas due to external factors such as a higher quality of fish, as described before. Especially when closing areas, such as the spawning grounds which are the major fishing grounds at the same time, results might be worse when assigning different prices to each season and area. Fleets would be forced to relocate to other areas with lower prices due to less product quality, hence not of their preference, which would lower their revenue and net profit. Yet, the prices would still be fixed during the modelling process of this version. The fact that many bio-economic models assume fixed fish prices was also criticized by Elfoutayeni and Khaladi (2012). They used a bio-economic optimisation model and included fish prices depending on the quantity harvested assuming -that the price decreases with increasing harvest, but limiting the minimum price to a fixed positive constant. Again, a trade-off between model complexity and data availability had to be made as their model does include dynamic prices, but is not age-structured or spatially resolved. Yet, the model of Bartelings *et al.* (2015) also incorporated dynamic fish prices by involving price elasticity, which is influenced by the change of volume landed in one year compared to the previous. They state price elasticity to be difficult to estimate and to be only relevant if the fleets land a significant share of the total supply of a species (Bartelings *et al.*, 2015). Fleets in this study catch 61% of the NSAS herring total catch, but other fisheries for herring exist in the Northeast Atlantic (e.g. Atlanto-Scandian). These are primarily targeted by other fleets (e.g. Norwegian), but can in fact be used as substitutional products for NSAS herring. Hence, the share of the total supply of herring might be much smaller than 61% and price elasticity in case of herring might therefore be relatively low but the actual value is difficult to estimate.

### 4.3. Scenario 3: Closing the core spawning grounds

Spatial explicitness also provides the possibility to test for the effectiveness of marine reserves (Pelletier and Mahévas, 2005) as well as their effects on fleet profitability and stock biomass. In our scenarios, closing the main spawning grounds of NSAS herring slightly increased SSB compared to the non-closure scenario, although recruitment continues to vary significantly from 228,000 to 247,000 hundred thousands. This variation is similar to what has been estimated by ICES (2020c) over the last five years and was even larger before. The idea of implementing a marine reserve for the core NSAS herring spawning areas was to reduce the fishing pressure when the stock is most vulnerable and hence aid in its recovery. This scenario, however, shows that additional management measures are needed and that the main focus should indeed be the increase of larvae survival. As several studies suggested, NSAS herring larvae survival, growth and hence recruitment success is thought to be impaired by changes in the physical environment and the planktonic community, negatively affecting food availability, metabolic rates and development times (Gröger *et al.*, 2009; Payne *et al.,* 2009; Nash and Dickey-Collas, 2005; Fässler *et al.*, 2011; Corten, 2013a). The result would be a continued decrease in NSAS herring biomass. Moreover, increasing water temperature is thought to reduce habitat suitability in the whole North Sea area (CERES D2.3 2019). Another possibility might therefore be the introduction of an MPA in the southeastern North Sea, where the nursery area of NSAS herring is situated (Corten, 2013b). Such a management measure would probably have more significant effects on the demersal fleets and would need to be tested with another model version (e.g. Barteling *et al.* 2015; Simons *et al.*, 2015), although one measure already introduced actually affected the pelagic sprat fishery. The so-called sprat box was a closed area for the pelagic sprat fishery in the southern North Sea (division 4.c), close to the Danish coast where a significant amount of herring by-catch occurred (ICES, 2020d). After an evaluation in 2017, however, ICES concluded that other management measures (e.g. max. amount of allowed juvenile herring bycatch) were sufficient to control herring by-catch, which lead to the removal of the sprat box (ICES, 2020d).

Economically, the fleet most affected by the closure scenario was again the German fleet, although a similar behaviour of the Dutch and German fleet might have been expected as they belong to the same company and are both freezer-trawler fleets. The Dutch fleet, for example, continues fishing in 4a4 (western North Sea) whereas the German fleet stays in 4a2 (northern North Sea). Area 4a4 is however closer to the home-harbours of the Dutch fleet (IJmuiden amongst others in the Netherlands) than to the ones of the German fleet (Bremerhaven and

Rostock in Germany), for which area 4a2 is closer. From the beginning, the German fleet also fished slightly more NSAS herring in area 4a2 in the third season than the Dutch fleet. Another reason why the impacts on the German fleet are relatively large compared to the other segments is the small margin between total costs and revenue in the input data. This margin is, for example, twice as high for the Dutch fleet. The reason is thought to be due to costs transfers within pan-European operating companies, which makes it possible to transfer subsidiary profits to the parent company (for further description see Rybicki *et al*., 2020; Gelder and Spaargaren, 2011). Such a profit transition is very hard to capture in this model where fleets but not companies are modelled. Hence, the data available might suggest a large impact on the German fleet whereas in reality this might be an overestimation. In general, closing the English Channel in the fourth season would have a large impact on the NSAS herring roe fishery, which only takes place in the English Channel within the UK EEZ during December and is of high value. Beattie *et al*. (2002) already argued that an implementation of marine reserves or MPA's solely with the goal of species protection usually has a negative affect for the corresponding fisheries operating within the North Sea area. In reality, impacts of the English Channel area closure would be much larger as the prices are thought to be higher than the ones for NSAS herring caught during the third season along the UK east coast. For several years, NSAS herring roe has become increasingly important on the Japanese market (Herrfurth, 1986). Those prices are, however, hard to determine and might be higher than the ones employed in this model, again adding to the problem of data availability and possibly underestimating the effects of such a closure.

Another point to mention is the fact that both Danish fleets fish herring in the northern North Sea during season one, but none of the others do. This already occurs in the underlying data and then becomes intensified on the long-term during the spawning grounds closure scenario, because this area presents a good alternative for the Danish fleets when fishing activities are prohibited in this region in the third season. In the raw data, a gradually increasing amount of herring catch by the two Danish fleets in the northern North Sea between the Shetlands and Norway in season one could already be observed from 2012 to 2016 (raw data from DCF partner; STECF, 2020). It is yet unclear, which factors promoted this trend as neither the sprat fishery, in which herring occurs as by-catch, nor the Norwegian Spring Spawning herring fishery take place in the first season and in ICES subarea 4a (ICES, 2020a/b/e). Similar to the NSAS herring fishery, the sprat fishery takes place during season three and four in the central North Sea (ICES, 2020a/b). Norwegian Spring Spawning herring is usually targeted further north (e.g. ICES subarea 2a) and even the occurrence closer to ICES subarea 4a during feeding times would take place in season two and three, not one (ICES, 2020e). In 2017, however, the largest amount of NSAS herring caught by the Danish fleets primarily appeared again in season three and four instead of one (STECF, 2020). Hence, the trend seen in this scenario, where the Danish fleets significantly increase their catch in season one when the major spawning grounds are closed in season three and four, might not be completely realistic. Depending on the underlying reason, the trend to switch completely to season one could be balanced by incorporating seasonal fish prices, with slightly lower herring prices in season one. This might produce more realistic results, but in the end this example shows how large the influence of underlying data on such simulations can be.

## 5. Conclusion

We adapted the temporal FishRent version of the economically valuable pelagic NSAS herring fishery by Rybicki *et al.* (2020) to be spatially explicit according to Bartelings *et al.* (2015) and included seasonal migration patterns. During this process, we tested the effects of incorporating different spatial resolutions on biomass levels as well as effort and profitability of five European fleets. Further, we closed the main spawning grounds, and discussed model limitations generated by data availability issues and the relatively static behaviour of those fleets.

In general, the difference between using four and eight-areas was very small. Profit also remained nearly unchanged even with higher spatial resolution. Catch changed seasonally when using a smaller number of areas (four or eight), whereas the fleet behaviour was mainly affected spatially with eighteen areas or more. For the evaluation of changes over time only, the eight-area resolution might even suffice, as the differences between resolution scenarios were relatively small. With the higher resolution of eighteen-areas, however, the migration patterns could be implemented in more detail and spatial effects were more visible, which were spatially more averaged with a lower resolution bearing the risk of misinterpreting fleet behaviour changes. A major issue of the NSAS herring fishery is the inflexibility of the fleets, which results from the fishing grounds and times being extremely static due to being a spawning fishery. We provided the fleets with a larger access to fishing grounds than the underlying data of each fleet allowed for, which did not lead to significant impacts but validated the model results, as it would have been highly questionable if the fleets would have drastically changed their patterns due to the additional area access. Yet, providing further access to areas where a fleet has not fished in the underlying data always comes with trade-offs, of which some are assumptions concerning catchability, effort and activities in other fisheries. Other methods for increasing fleets' flexibility might be to add seasonal prices or other species into the model process. In the end, the model complexity needs to fit the purpose of the modelling exercise and the research question. If the purpose is to understand the behaviour of different fleets with various harbours and target areas, a larger resolution should be considered. In case of pelagic species, the highest degree of complexity (18A) also provided better results when implementing management measures such as marine reserves. If the interest is the general development of the population, a high degree of resolution does not seem to be necessary in case of pelagic species.

**Supplementary material**

Supplementary material is available.

**Acknowledgements**

Many thanks are given to the CERES project (Grant agreement No 678193), which partly funded this research, as well as the numerous researchers of the Data Collection Framework (DCF) for providing the economic data and their expert knowledge (in no particular order): MMO, Seafish, DTU Aqua, DST, TI-SF. Also, acknowledgements are given to Norbert Rohlf for plenty of information concerning the biology of herring as well as Marc Taylor and Alexander Kempf for their modelling expertise (all TI-SF, no specific order). Last but not least, many thanks for a lot of feedback and new ideas are given to Miriam Püts and Bernhard Kühn (both TI-SF).

**Funding**

This study has been partially funded by the Thünen Institute of Sea Fisheries and the CERES project (Grant agreement No 678193).

**Author Contributions**

All authors contributed to the conception and design of the study; SR wrote and designed the first draft of the manuscript. All authors also contributed to manuscript revision, read and approved the submitted version.

**Data Availability Statement**

Detailed economic, catch and effort data analyzed in this study was obtained from EU national labs. More data can be accessed from the STECF (open source). Biological data was obtained from ICES assessments and is open access. Requests to access these datasets should be directed to Matt Elliott (MMO, matt.elliott@marinemanagement.org.uk), Arina Motova (Seafish, Arina.Motova@seafish.co.uk), Josefine Egekvist (DTU Aqua, jsv@aqua.dtu.dk), Kim

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**Conflict of Interest**

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Supplementary material

## S.1. Model functions

### S.1.1. Effort calculation

**Eq. S.1a:**

$$TEff_j = \frac{\sum_{k,t}[(Eff_{j,k,t} \times \beta s_{j,k,t}) \times Eff_{j,k,t}]}{1 - DASOTH_j}$$

$TEff_j$ is total effort for $j$th segment, $Eff_{j,k,t}$ is the fishing effort for $j$th segment, $k$th area at time $t$, $\beta s_j$ is a fishing effort multiplier (see equation below) and $DASOTH_j$ is the proportion of total days at sea observed of other species.

$$\beta s_{j,k,t} = \frac{TEff_{j,k,t0} - Eff_{j,k,t0}}{Eff_{j,k,t0}}$$

**Eq. S.1b: Minimum effort**

$$TEff_j > 0.6 \times DASR0_j \times FLE_j$$

$DASR0_j$ is the proportion of total days at sea observed (including NSAS herring and other species) and $FLE_j$ is the number of vessels.

**Eq. S.1c: Maximum effort**

$$TEff_j < MIN(maxeff_j\,,\ maxeffv_j \times FLE_j)$$

$maxeff_j$ is the maximum effort observed based on historic values and $maxeffv_j$ is the maximum observed effort per vessel. The lower of the two is then used as maximum limit.

### S.1.2. Profit calculation

**Eq. S.2: Profit**

Catch determines revenue. Together with a fixed proportion of revenue earned from other species not included in this study and fuel, crew, variable, fixed, and capital costs, profit is defined.

$$PrF_{j,t} = Rev_{j,t} - FuC_{j,t} - CrC_{j,t} - VaC_{j,t} - FxC_{j,t} - \mathrm{CaC}_{j,t}$$

$PrF_{j,t}$ is the profit for $j$th fleet at time $t$, $Rev_{j,t}$ is revenue, $CrC_{j,t}$ are crew costs, $VaC_{j,t}$ are variable costs, $FxC_{j,t}$ are fixed costs and $CaC_{j,t}$ are capital costs.

**Eq. S.3: Revenue**

$$Rev_{j,t} = \frac{Catch_{j,t} \times fish\,price_j}{proportion\ other\ species_j}$$

**Eq. S. 4: Fuel costs**

$$FuC_{j,t} = \frac{fuel\ usage_j * fuel\ price_j\ \times (E_{j,t} + (beta_j * E_{j,t}))}{1 - Dasoth_j}$$

$E_{j,t}$ is fishing effort, $beta_j$ is a fishing effort multiplier, and $dasoth_j$ are the total days at sea observed proportion of other species fished by each fleet.

**Eq. S. 5: Crew costs**

$CrC_{j,t} = Rev_{j,t} \times CrCO_j$ ; $CrC0_j$ (crew costs share)

**Eq. S. 6: Variable costs**

$VaC_{j,t} = Rev_{j,t} \times VaCO_j$ ; $VaCO_j$ (variable costs share)

**Eq. S. 7: Fixed costs**

$FxC_{j,t} = FxCO_j \times FLE_{j,t}$

$FxCO_j$ is the fixed costs share for *j*th fleet and $FLE_{j,t}$ is the number of vessels operating for *j*th fleet at time *t*.

**Eq. S. 8: Capital costs**

$CaC_{j,t} = CaCO_j \times FLE_{j,t}$ ; $CaCO_j$ (capital costs share)

## S.1.3. Cobb-Douglas catch calculation

**Eq. S. 9**: $C_{t,i,j,k} = c_{t,i,j,k} \times E_{t,j,k}{}^{\alpha_{1j}} \times CB_{t,i,k}{}^{\beta_{1j}}$

where $C_{t,i,j,k}$ is the catch at time *t*, for *i*th age class, *j*th fleet and *k*th area; $c_{t,i,j,k}$ is the catchability coefficient; $E_{t,j,k}$ is the fishing effort; $CB_{t,i,k}$,is the stock biomass and $\alpha_{1j}$ and $\beta_{1j}$ determine the degree of non-linearity in the relation of catch and effort for a given stock size.

## S.1.4. Fishing mortality and TAC determination

**Eq. S.10: Age-specific fishing mortality**

$$F_{t,i} = -log\left(\frac{N_{t,i}}{N_{t+1,i+1}}\right) - M_i$$

where $N_{t,i}$ is the abundance at *i*th age class and time *t* and $M_i$ is the natural mortality at *i*th age class.

**Eq. S.11: Target fishing mortality**

$$F_{tar} = F_{MSY_{advice}} \times \frac{\overline{F}}{\overline{F}_{MSY}}$$

The level of the actual fishing mortalities was kept by adding a multiplier (the average $F/F_{msy}$ ratio of the last eight years from 2008 onwards) to the advised $F_{msy}$.

**Eq. S.12: Partial fishing mortality**

$F_{tar}$ is not age-class specific. Thus, in order to account for an age-structured stock, partial fishing mortalities at *i*th age ($Ftac_{t,i}$) are calculated by using the fishing mortality of the average age classes that are considered to be fully exploited in the assessments.

$$F_{tac_{t,i}} = \frac{F_{tar} \times F_{t-1,i}}{\overline{F_{t-1}}}$$

**Eq. S.13: Catch according to target fishing mortality**

Together with the natural mortality ($M_i$) a total mortality rate, called $Ztac_{t,i}$ can be determined. These two parameters combined with the abundance $N_{t,i}$ and weight at *age* $w_{t,i}$ are used in the Baranov Catch equation (Baranov, 1918) in order to calculate a catch according to $F_{tar}$.

$$Catch_{tar_{t,i}} = \sum_i \left[ \left( N_{t,i} \times \frac{F_{tac_{t,i}}}{Z_{tac_{t,i}}} \times (1 - exp^{(-Z_{tac_{t,i}})}) \right) \times w_{t,i} \right]$$

## S.2. Parameter estimation

**Table S.1.** Parameter estimation, definition and data sources North Sea autumn spawning herring (NSAS HER).

| Parameter | Definition | Value | Estimation | Source |
|---|---|---|---|---|
| $\alpha_{2;HER}$ | Fleeted regression parameter for NSAS herring; Time frame: 2002-2016 | 41 | Estimated by using the R Script, EqSim function, and values from the Benchmark Report 2018 | ICES 2018b |
| $\beta_{2;HER}/B_{lim}$ | | 800,000 | | |
| $\alpha_1$ | Cobb-Douglas production function coefficients | 0.8 | Taken from literature | Frost *et al.* 2009 |
| $\beta_1$ | | 0.2 | | |
| $s_{i,j}$ | Catch share of *i*th age and *j*th fleet | See Table S.3 | Average catch share of 2012-2014 | National labs |
| $F_{MSY;\ HER}$ | Fishing mortality at MSY level for NSAS herring | 0.26 | Taken from assessment | ICES 2018a |
| $F_{multiplier;\ HER}$ | | 0.53 | $F/F_{MSY}$ ratio from 2008-2015 | ICES 2018a |

**Table S.3.** Proportion of other species caught by the modelled fleets (P_other), fuel usage per day (Ufuel), and maximum effort that was allowed for fleets to fish (Maxeff). Country abbreviations: Germany (D), Denmark (DK), United Kingdom (UK), Netherlands (NL), Ireland (IR), Iceland (IS). Pelagic trawler are represented by TM and pelagic purse seiner by PS.

| Fleet | P_other (%) | Ufuel ($Lday^{-1}$) | Maxeff (days) |
|---|---|---|---|
| NL (TM > 40m) | 47 | 69 | 943 |
| UK (TM > 40m) | 81 | 72 | 1921 |
| NL & D (TM > 40m) | 57 | 74 | 868 |
| DK (TM & PS > 40m) | 47 | 36.5 | 1477 |

**Table S.4** Overview of the original catch share according to relative stability (RS) (% of the modelled fleets of TAC), the share of total catch, and fish prices (landings value divided by landings weight) for all modelled fleets and species.

| Species | Fleet | Catch share original (%) | Share of total catch (%) | Fish prices (€$kg^{-1}$) |
|---|---|---|---|---|
| Herring | NL (TM > 40m) | 16 | 1.6 | 0.35 |
| | UK (TM > 40m) | 14 | 1.6 | 0.43 |
| | DK (TM > 40m) | 16 | 1.6 | 0.46 |
| | DK (PS > 40m) | 7 | 1.6 | 0.47 |
| | D (TM > 40m) | 7 | 1.6 | 0.46 |

## S.3. Stock-recruitment relationship of NSAS herring

First, the number of individuals $N_{t,i}$ are estimated using Pope's approximation (Pope 1972; Eq. 2).

**Eq. S.14:** $N_{t,i,k} = N_{t-1,i-1,k} exp^{-M_i} - \frac{\sum_j C_{t-1,i-1,j,k}}{w_{t,i} \times \sum_j s_j} exp^{-\frac{M_i}{2}}$

where $w_{t,i}$ is weight at age and $s_j$ is the catch share. Catch share is a multiplier that determines total catch, hence accounting for the remaining fishing mortality by fleets not included in the model. It is the proportion of each fleets catch from the TAC, i.e. representing their quota shares. The instantaneous natural mortality rate is represented by $M_i$. Both catch share and natural mortality are constant over time.

**Eq. S.15a:** $SSB < B_{\lim}$ $\quad$ $R_t = \alpha_2 \times SSB \times exp^{(D \times CV - 0.5 \times CV^2)}$

Else

**Eq. S.15b:** $SSB \geq B_{lim}$ $\quad$ $R_t = \alpha_2 \times B_{\lim} \times exp^{(D \times CV - 0.5 \times CV^2)}$

The parameters $\alpha_2$ and $B_{lim}$ are species specific (Table S.1). $D$ is a standard normal deviate and $CV$ is the coefficient of variation ($CV$ = standard deviation/mean), which was estimated based on historical stock sizes for herring from 2012 to 2016 (ICES, 2018b).

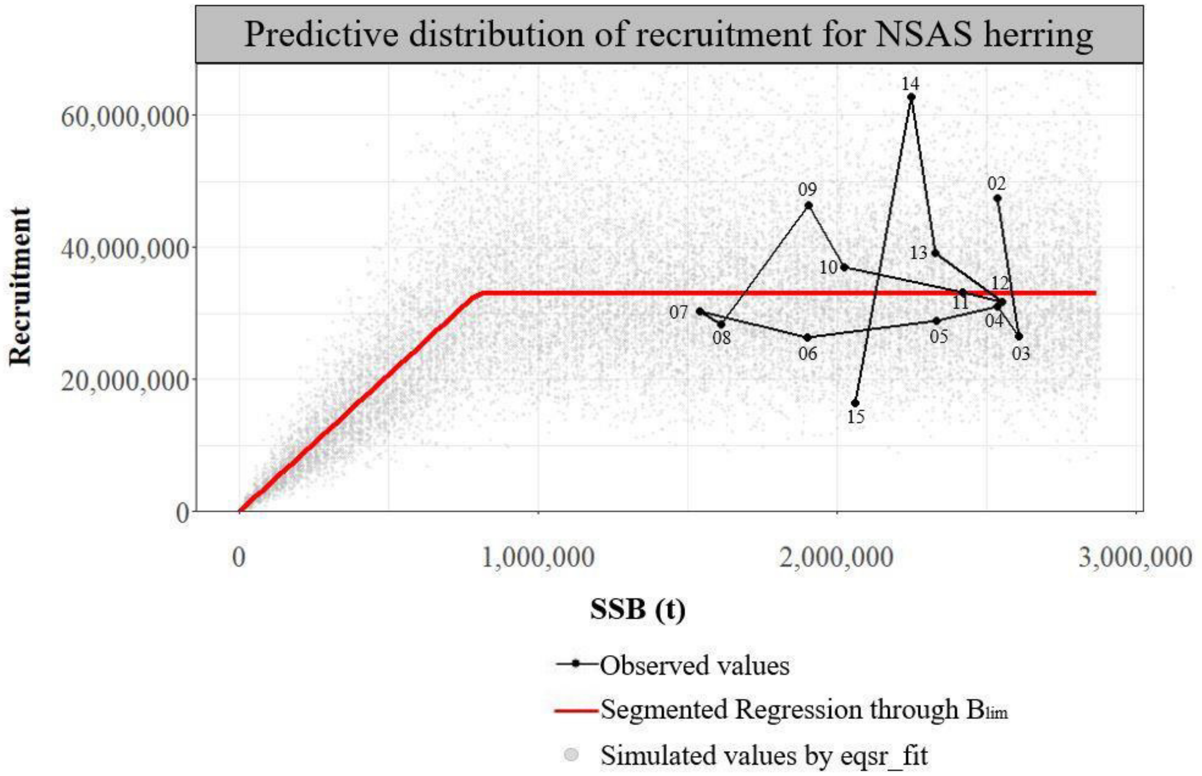


**Figure S.3.** The estimated restricted hockey-stick stock-recruitment relationship of NSAS herring (through $B_{lim}$: 800,000 t). Black points represent observations from the assessment report 2018 (ICES 2018a). The red line represents the corresponding predicted recruitment, which was estimated by using the eqsr_fit function with 1001 simulations in R (Version 3.5.2).

## S.4. Schematics of FishRent

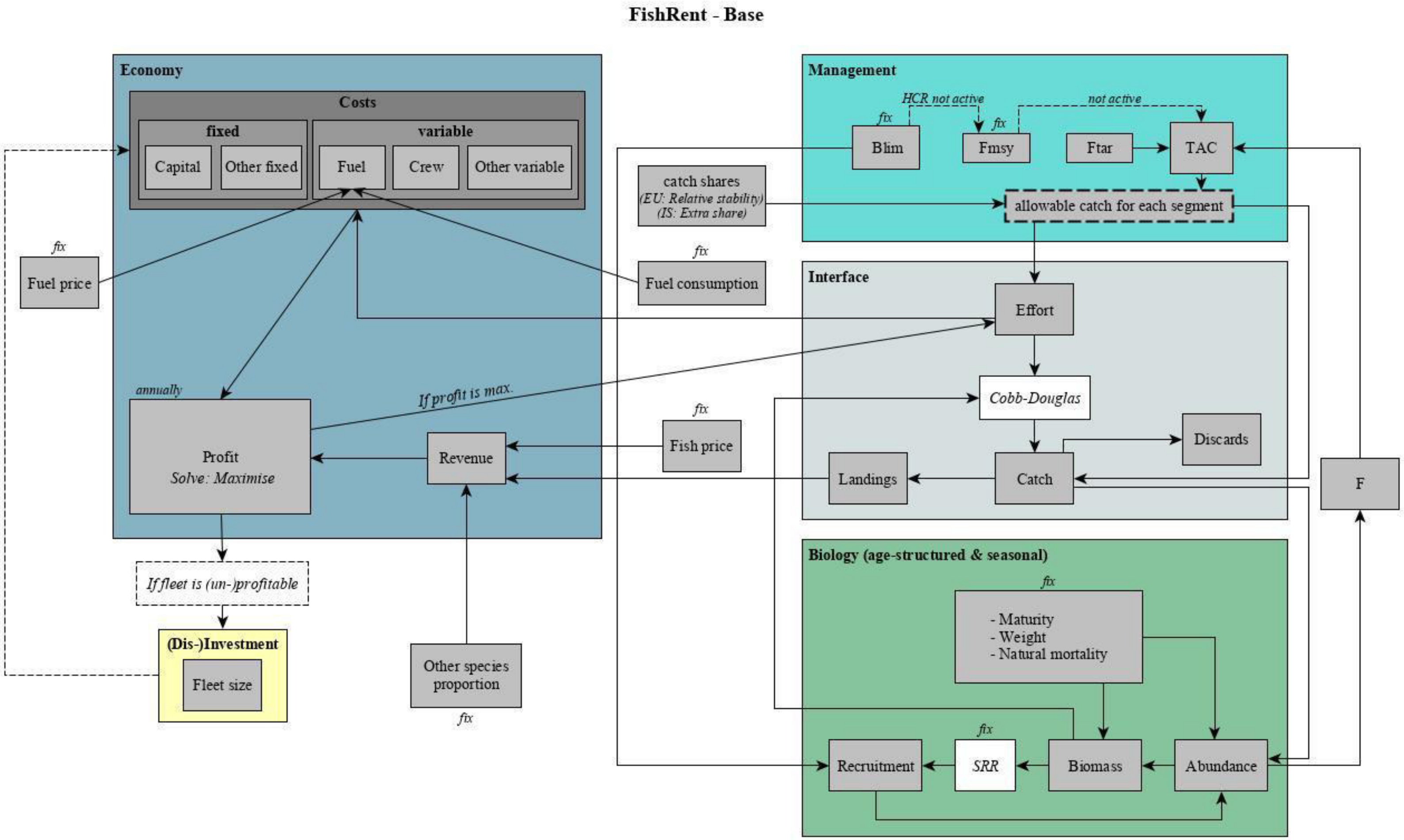


**Figure S.4.1**. Schematic of the model process and the interaction between different sub-modules in FishRent. The effort is calculated until the maximum profit for all modelled fleet segments is estimated. This is used to calculate the catch by using the Cobb-Douglas production function, which has then an impact on the abundance, fishing mortality (*F*), biomass and, by applying and stock-recruitment relationship (SRR) function, recruitment calculation for the next time step (Rybicki *et al.*, 2020).

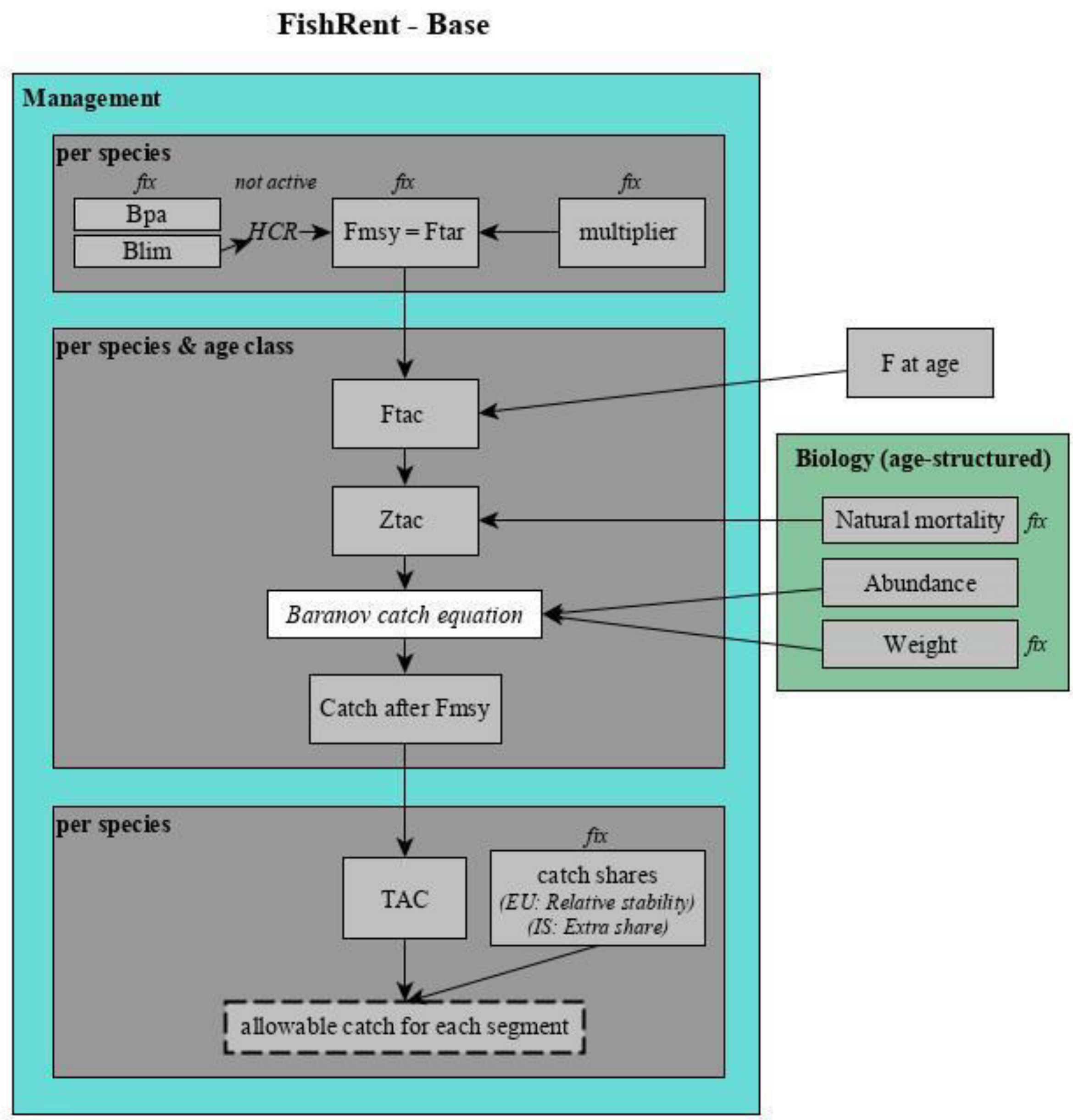


**Figure S.4.2.** Detailed schematic of the management module in FishRent. Note: No harvest control rule (HCR) is currently active for NSAS herring. A multiplier has been used on $F_{msy}$ (here then referred to as target $F$ "$F_{tar}$") in order to keep the level of fishing from the last years (Rybicki *et al.*, 2020).

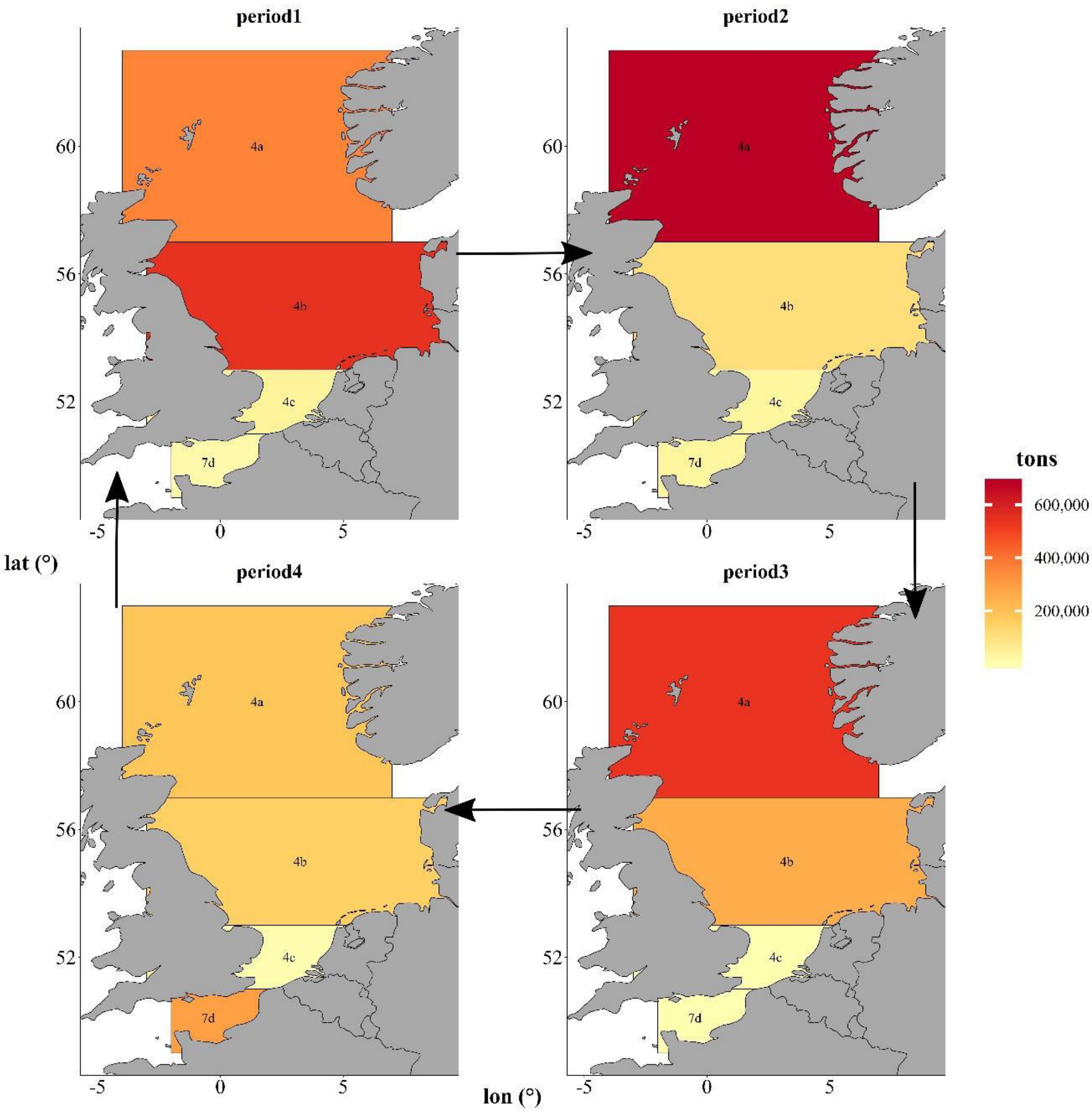


**Figure S.5.** Initial total stock biomass distribution in each season when using four resolutions.

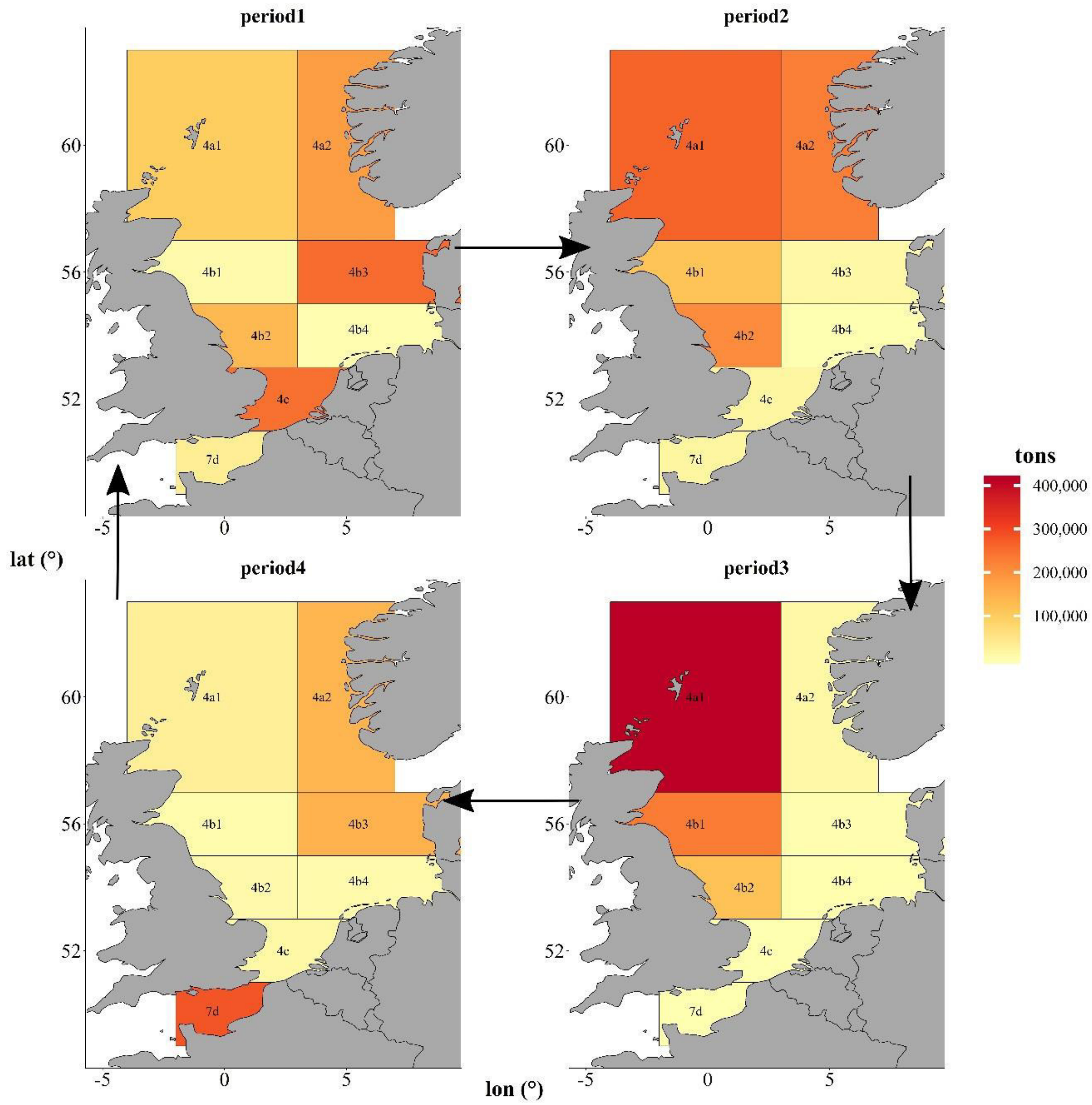


**Figure S.6.** Initial total stock biomass distribution in each season when using eigth resolutions.

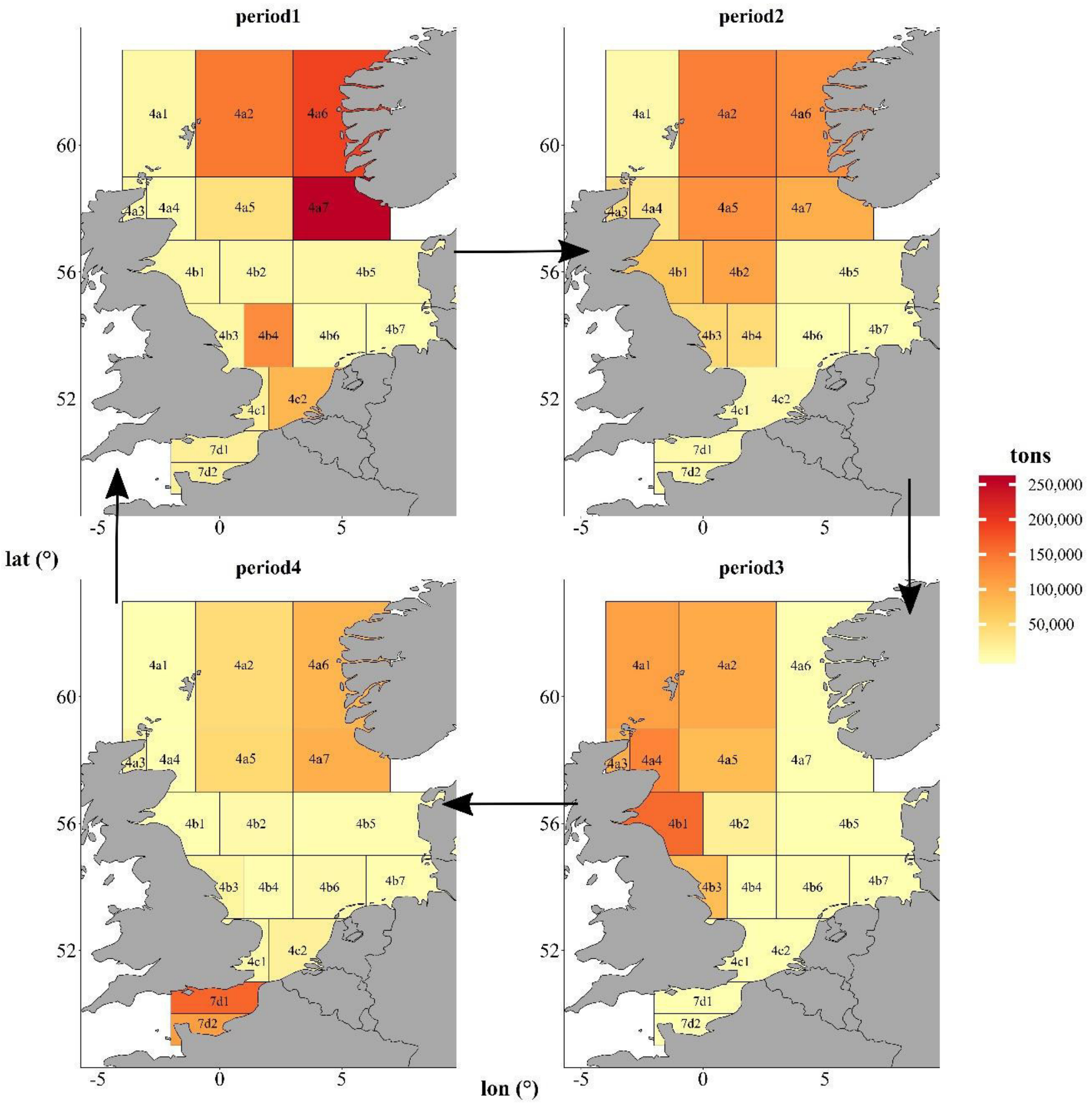


**Figure S.7.** Initial total stock biomass distribution in each season when using eighteen resolutions.

**Area access increase**

**Table S.5.** Overview of each fleets regional access before (# areas input) and after (# areas new) reassigning the areas, where any fleet member fished in, to those fleets that did not fish in this area according to the input data. This is an overview for the eight areas resolution.

| Fleet | period | # areas input | # areas new | % increase | Average % increase |
|---|---|---|---|---|---|
| NL (TM > 40m) | 1 | 4 | 4 | 0 | 0 |
| | 2 | 2 | 2 | 0 | |
| | 3 | 4 | 4 | 0 | |
| | 4 | 5 | 5 | 0 | |
| D (TM > 40m) | 1 | 0 | 4 | 4 | 2.25 |
| | 2 | 1 | 2 | 1 | |
| | 3 | 3 | 4 | 1 | |
| | 4 | 2 | 5 | 3 | |
| DK (TM > 40m) | 1 | 4 | 4 | 0 | 0 |
| | 2 | 5 | 5 | 0 | |
| | 3 | 6 | 7 | 0 | |
| | 4 | 6 | 7 | 0 | |
| DK (PS > 40m) | 1 | 1 | 4 | 3 | 1.75 |
| | 2 | 4 | 5 | 1 | |
| | 3 | 6 | 7 | 1 | |
| | 4 | 5 | 7 | 2 | |
| UK (TM > 40m) | 1 | 3 | 4 | 1 | 1.75 |
| | 2 | 3 | 5 | 2 | |
| | 3 | 5 | 7 | 2 | |
| | 4 | 5 | 7 | 2 | |

**Table S.6.** Overview of each fleets regional access before (# areas input) and after (# areas new) reassigning the areas, where any fleet member fished in, to those fleets that did not fish in this area according to the input data. This is an overview for the eighteen areas resolution.

| Fleet | period | # areas input | # areas new | increase | Average increase |
|---|---|---|---|---|---|
| NL (TM > 40m) | 1 | 5 | 5 | 0 | 0 |
| | 2 | 4 | 4 | 0 | |
| | 3 | 6 | 6 | 0 | |
| | 4 | 9 | 9 | 0 | |
| D (TM > 40m) | 1 | 0 | 5 | 5 | 4 |
| | 2 | 2 | 5 | 3 | |
| | 3 | 7 | 8 | 1 | |
| | 4 | 2 | 9 | 7 | |
| DK (TM > 40m) | 1 | 7 | 9 | 2 | 3 |
| | 2 | 7 | 11 | 4 | |
| | 3 | 11 | 14 | 3 | |
| | 4 | 10 | 13 | 3 | |
| DK (PS > 40m) | 1 | 2 | 9 | 7 | 5.75 |
| | 2 | 5 | 11 | 6 | |
| | 3 | 10 | 14 | 4 | |
| | 4 | 7 | 13 | 6 | |
| UK (TM > 40m) | 1 | 5 | 9 | 4 | 3.5 |
| | 2 | 8 | 11 | 3 | |
| | 3 | 11 | 14 | 3 | |
| | 4 | 9 | 13 | 4 | |

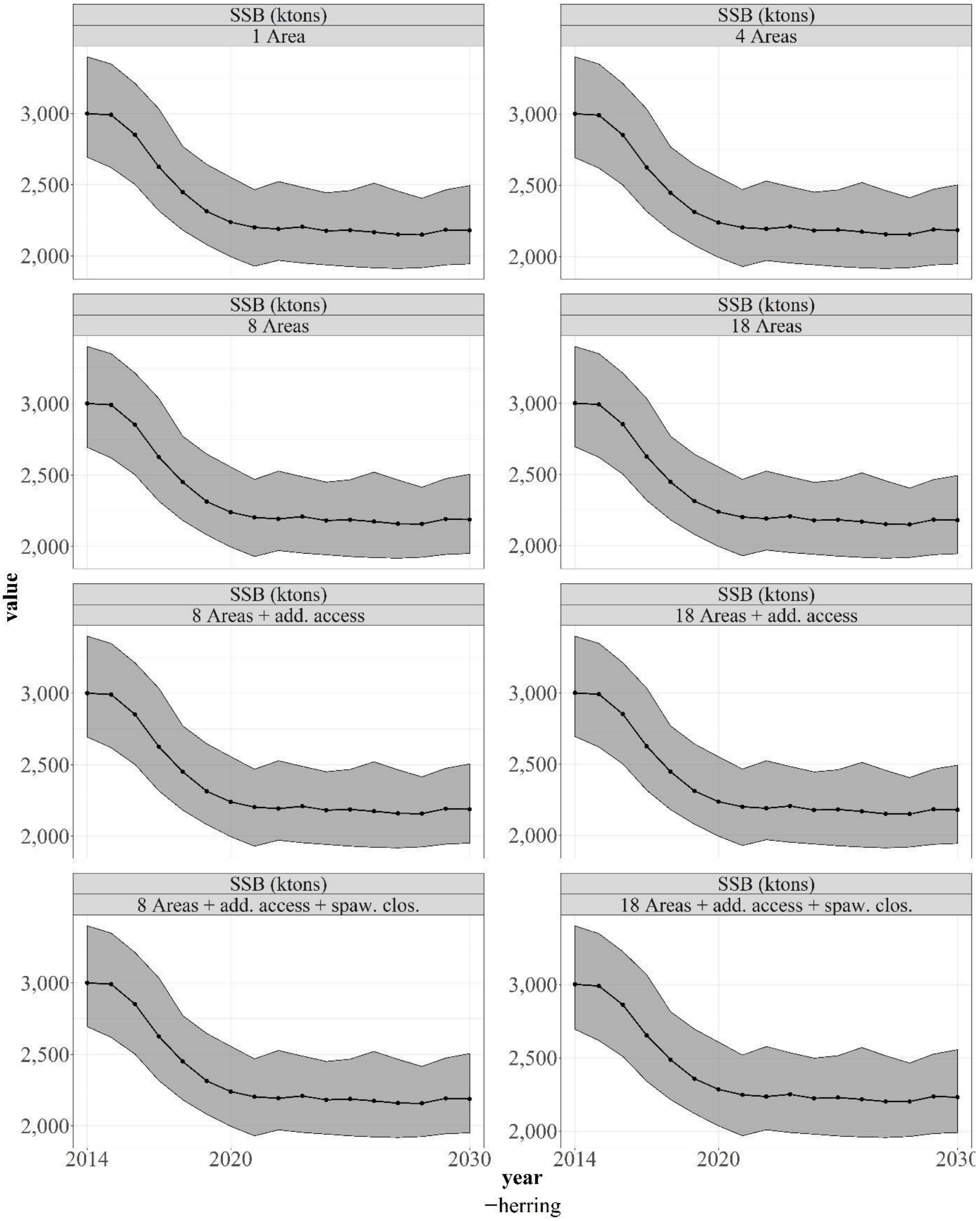


**Figure S.8.** SSB trends (ktons) of NSAS herring from 2014 to 2030 of the four different resolution scenarios (upper four plots) as well as the 8A_flex, 18A_flex, 8A_flex_clos, 18A_flex_clos scenarios. Differences between trends were very small (<0.5%).

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# CHAPTER 3 – Spatio-temporal interactions between Northeast Atlantic mackerel and its fishery - Simulating different futures

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**Submitted to *Marine Policy***

**Abstract**

The mackerel (*Scomber scombrus*) stock is one of the commercially most important pelagic species in the Northeast Atlantic, being targeted by various nations. Due to a change in migration patterns as well as an increase in recruitment a stock expansion appeared after 2007, causing Iceland and Greenland to start a mackerel fishery and the Faroe Islands to increase their catch. This resulted in a yet unresolved conflict, leading to the setting of unilateral quotas and an overfishing of the stock. Here, we analyze the impacts of different TACs on the mackerel stock and possible adaptations in simulated fleet behavior by applying an age-structured bio-economic optimization and simulation model, FishRent. For this, we implement a dynamic seasonal migration module, which alters the spatial extension of mackerel depending on biomass levels. When applying a TAC according to ICES advice, the stock biomass was observed to increase on the long-term. This would primarily benefit the Irish and UK fleets. Effects on the Icelandic fleet were, however, neutral. When applying a TAC under a business as usual scenario or higher, the stock biomass decreased close to $B_{MSY}$ on the long-term. In this case, the Danish fleets would benefit on the long-term, increasing their profit up to 80%. All other fleets, would be negatively affected with a profit decreasing between 50-100% depending on the TAC scenario. During the whole process, we assumed that migration patterns are influenced by density dependent mechanisms.

**Keywords: Atlantic mackerel, management, future, bio-economic model**

## 1. Introduction

The Northeast Atlantic mackerel (NEAM) stock (*Scomber scombrus*) and its fishery have been the cause of many discussions over the last 10 years [e.g. 1-5]. Since 2007, the NEAM stock has been observed to expand towards the northwest into the Icelandic and even Greenland Exclusive Economic Zones (EEZs). This is likely thought to be in response to a larger stock biomass resulting from changed environmental conditions, such as increasing water temperatures and therefore habitat size [e.g. 3,6], although recent stock assessments have varied greatly in their stock size estimation [7-9]. In 2018, the stock was thought to be heavily overexploited and spawning stock biomass (SSB) was estimated to have decreased from nearly 5 million tons in 2011 to 2.5 million tons in 2017 [7]. During an Inter-Benchmark report in early 2019, SSB was estimated to increase from approximately 4 million tons in 2011 to 5 million tons in 2014 and thereafter decrease again to nearly 4 million tons in 2017 [8]. The assessment at the end of 2019, however, does not estimate a continued decreasing trend as the one from the Inter-Benchmark assessment in early 2019, but stays at the same level of approximately 4 million tons until 2020 [9]. Further it estimates a fishing mortality at Fmsy (0.23) by 2020, whereas the 2018 assessment still estimated it to increase up to 0.38 by 2017 [7,9]. Due to this uncertainty, future management strategies should consider both directions, an increase in stock size as well as a decrease, in scenarios to be tested.

The apparent stock expansion after 2007 caused Iceland, Greenland and the Faroe Islands to start fishing NEAM without holding a quota [4]. The situation resulted in a dispute between those three countries and the European Union (EU) and Norway as the fixed quota allocation share only included the two latter players. The definition of those shares called “relative stability” principle was based on catch activities between 1973 and 1978 [10-12]. This system of access rights and quota allocation is relatively fixed. Currently it is beginning to be questioned whether this method is still up-to-date since new conditions of stock distributions, productivity as well as fishing strategies appeared and it remains unclear how those changes can be equitably addressed. In order to determine methods that aid in resolving questions regarding access rights, for example, the changes in biological conditions and the corresponding effects on different fleets need to be estimated first [e.g. 12,13]. Especially changes in species distribution can lead to new management strategies, which can in turn have serious impacts on the stock condition as observed in the case of NEAM. This conflict remains unchanged and only a joint agreement between the EU, Norway and the Faroe Islands could be reached [7]. Iceland and Greenland, however, proceed to set unilateral quotas. Hence, NEAM continues to be overfished by 27% (average 2016-2019) compared to the advised TAC and no harvest control rule is currently active [8,9]. Additionally, as to the United Nations (UN) Convention in 1982, coastal states are not required to reach a dispute settlement if an attempt was made to achieve an agreement [14]. The best possible management according to this convention of the states' share of the stock is then subject to each party. This approach does therefore not suggest a resolution of the conflict in the near future. Moreover, there is no evidence that the EU, Norway and Faroe Islands nor Iceland and Greenland are willing to adjust their quota shares and thus the TAC to a level advised by the International Council for the Exploration of the Seas (ICES). Overfishing the NEAM might consequently continue, which can turn into a serious problem [4].

From 2021 onward, there will even be another player joining the EU, Norway, the Faroe Islands, Iceland and Greenland at the negotiation table, namely the United Kingdom (UK). Many UK fishermen plebiscited the exit from the EU due to being unsatisfied with the Common Fisheries Policy (CFP) [15,16]. In this context, the need for a suitable agreement is further growing in order to keep the stock at a sustainable level. NEAM is defined to be a straddling fish stock since the 1995 UN Fish Stocks Agreement and is managed through the Northeast Atlantic Fisheries Commission (NEAFC). The UK generally played an important role within NEAFC and is therefore thought to enter on its own with the completion of the Brexit [14]. They would then, together with other members of NEAFC, manage shared and straddling stocks in the high seas of the NEA. The management within their own EEZ is, however, of their own business. Depending on the negotiation success with the EU and other third countries, the UK might set their own quota similar to Iceland, Greenland and the Faroe Islands. This could lead to an even more significant overfishing of the stock, seriously jeopardizing it.

A sustainable management of the NEAM stock therefore depends on conflict settlement and willingness to cooperate as well as the position and migration routes of NEAM as a straddling stock. However, Hannesson [1] suggests that there could be a tactical side of leaving the NEAM stock unregulated: The goal of the major players (EU and Norway) could be the prevention of migrations into the minor player's (Iceland) EEZs, therefore excluding them from the fishery. If the observed migration patterns are indeed caused by density mechanisms, i.e. a stock expansion with a higher overall density occurs at high biomass levels and vice versa [18], the major players could achieve this by selecting a high enough fishing pressure through e.g. the setting of a corresponding TAC [1]. For either purpose, tactical or long-term sustainable management decisions, the stock size and the corresponding migration routes are of high importance. Moreover, it is significant to understand the impacts on the stock and how each intention might then influence different player/fleets.

A model that provides the possibility to test for adaptations in management and their effects on the corresponding profitability of different player/fleets and their simulated behavior as well as on feedback mechanisms on the stock biomass, is the bio-economic optimization and simulation model, FishRent [13,20,21]. It is age-structured including spatial and fixed seasonal migration patterns. As the example of NEAM shows, those patterns are, however, not fixed. Therefore an aim of this study is to adapt the spatial FishRent version to the NEAM fishery and include dynamic, density-dependent seasonal migration patterns. Further, we implement different total allowable catches (TAC) in order to simulate two contrasting stock developments assumed to be caused due to different management objectives 1) high TAC scenarios (no agreement between players), accompanied by a biomass dependent retreat of NEAM to its core areas depending on SSB level, and 2) setting a TAC according to ICES advice accompanied by an expansion towards the northwest Atlantic. We will finally highlight corresponding effects on fleet behavior, net profit and total stock biomass.

## 2. Materials and Methods

### 2.1. Model description

FishRent is an optimization and simulation model including the economics of multiple fleets as well as the temporal and spatial interplay between fish stocks and fleets [19-21]. The user interface is the General Algebraic Modeling System (GAMS) and applied is the CONOPT solver (for a detailed description see [22]) to determine the optimal effort allocation. It maximises the total annual net profit of a fishery given the current ecological, regulatory and economic conditions or the ones to be tested. Future simulated effort of individual fleets may vary between a lower and upper limit set at 60% of historically observed total effort and historically observed maximal total effort per vessel (for more detail see Supplementary S.1/2). These limits are used to avoid unrealistic interannual variation of effort as the solver determines the most optimal solution within the given limits. Hence, depending on how the limits are set, a more or less realistic solution might be found. More information about equations, parameter estimation and model overview can be found in Supplementary S.1/2 and Figures S.2/3.

### 2.1.1. Economy

The calculation of net profit includes: 1) revenue of fishing activities, 2) Capital and other fixed costs (e.g. administration, insurance, accountancy, maintenance costs, interest payments, and annual depreciation costs) and 3) operating costs including fuel, crew and other variable costs (e.g. expendables, income tax, landings, and sales costs) [13,19-21]. Fish prices and catch determine effort and revenue. Fish prices were incorporated by fleet and season (quarter), where prices for the main seasons one and four where determined by the landings value/volume ratio. We increased the access to areas for each segment by assigning the average catchability of an area where at least one fleet fished for NEAM to those fleets that did not fish in this area according to underlying data (see also Rybicki et al. (in prep. [39])). This was done depending on fishing technique, since two different techniques are used by the modelled fleets, i.e. freezer trawler (>100m in size; German and Dutch fleet) and refrigerated seawater (RSW) operated vessels (24-80m; Danish, Icelandic, UK, Irish fleets). Usually, the decisions on the best fishing time and place are not only made by the amount of stock biomass available and expenditures to catch this fish but largely depend on seasonal fish quality and corresponding fish price. In case of NEAM, this changes seasonally (lower fat content and quality in the 2$^{nd}$ and 3$^{rd}$ season), hence there is no direct fishery for NEAM for the 2$^{nd}$ and 3$^{rd}$ seasons. Therefore we also included an off-season fish price set to 0.12€$kg^{-1}$ (price for fishmeal and fish oil produced by the leftovers, [23]). For comparison: high-season fish prices in the model differ between fleets and range from 0.76€$kg^{-1}$ to 1.49€$kg^{-1}$, depending on product type (higher prices can be reached for fresh than for frozen fish, see Supplementary material S.2).

Fuel price and revenue influence operating costs, including fuel, crew and other variable costs (see Eq. S.1 to S.7 in Supplementary material), and the fixed costs are proportional to the number of active vessels. Discarding was not considered since reported discards by the NEAM fishery are usually extremely low or not present. More information concerning parameter estimations in general can be found in Supplementary material S.2.

### 2.1.2. (Dis-)investment

After the first modelled year, fleet size can decrease or increase (in terms of vessel numbers), depending on fleet profitability: 1) If fleets are profitable, reach their effort capacity, and are below their maximum investment limit, they are allowed to invest into new vessels by 4% at most. 2) If fleets are unprofitable, they can disinvest by a maximum of 10% per year. Both values were determined by historical observed trends [17].

### 2.1.3. Interface

The Cobb-Douglas catch production function was used, in which non-linear relationships between catch and effort as well as between catch and stock size are assumed ([24], Supplementary material S.1/2). Concerning pelagic species, the application of the Cobb-Douglas function is of particular importance since they usually form large schools. Therefore, a non-linear relationship between effort and amount of catch is common [24,25]. Rybicki et al. [13] already performed a sensitivity analysis concerning the corresponding parameters.

### 2.1.4. Biology

With the calculated catch, the number of individuals $N_{t,i}$ is estimated for each quarter and area using Pope's approximation ([26], Supplementary material S.3). For further detail see [13,20,27]. These are then distributed in each season according to known NEAM migration routes ([2,3,9,28,29,30], Figure 1; Supplementary Figures S.4-7): The NEAM population is divided into three components, i.e. the North Sea, southern and western [2]. The western population is currently defined to be the largest component and their spawning and feeding activities have been well observed over several years [9,28]. NEAM performs seasonal migrations between the spawning and feeding grounds. The western component usually spawns during spring and early summer west of the British Isles and western France. This is the focus of this study as it is currently the major component fished by the modelled fleets. Thereafter, they start migrating north towards the Faroe Islands, Norwegian Sea and to some extent also the North Sea in summer time in order to feed [e.g. 3,8,28]. During winter, they return to their spawning grounds and the process begins anew. The distribution is conducted dynamically via migration matrices (fmcl), depending on SSB level. Hence, we adjusted the matrices accordingly (Eq. 1; Figure 1).

If

$SSB_t >= 2 * B_{MSY}$ $\quad fmc1_{kf,kt,i,t} = sum_{bf=1}[fmc_{kf,kt,i,t,bf}]$ (1a)

Elseif

$SSB_t >= 1.8 * B_{MSY}$ $\quad fmc1_{kf,kt,i,t} = sum_{bf=2}[fmc_{kf,kt,i,t,bf}]$ (1b)

Elseif

$SSB_t >= 1.68 * B_{MSY}$ $\quad fmc1_{kf,kt,i,t} = sum_{bf=3}[fmc_{kf,kt,i,t,bf}]$ (1c)

Elseif

$SSB_t >= 1.4 * B_{MSY}$ $\quad fmc1_{kf,kt,i,t} = sum_{bf=4}[fmc_{kf,kt,i,t,bf}]$ (1d)

Else $\quad fmc1_{kf,kt,i,t} = sum_{bf=5}[fmc_{kf,kt,i,t,bf}]$ (1e)

where *SSB* is the new spawning stock biomass at time *t*, $B_{MSY}$ is the precautionary biomass level, $fmc_{kf,kt,i,t,bf}$ is the migration matrix including all information about the NEAM position and has to be previously defined by the model user and $fmc1_{kf,kt,i,t,bf}$ is the new migration matrix, where *kf* (from) and *kt* (to) define the direction of movement between areas. The proportion of migrating fish is set by the model user and can vary between zero (no presence in a certain area) and one (100% presence). Part 1a of the equation represents an expansion (SSB >5,000 ktons), part 1b the current distribution (SSB 4,500 – 5,000 ktons), parts 1c-e a retreat (<4,500 ktons). Both, the expansion and retreats are based on results from Boyd et al. [5], who used an individual based model to evaluate consequences of ocean warming as well as different fishing pressures on the NEAM stock and its spatial distribution. Finally, the number of individuals are distributed via the corresponding new migration matrix (Eq. 2).

$$Nmig_{t,i,k} = N_{t,i,k} * sum(kt, N_{t,i,k} * fmc1_{t,i,k,kt}) - sum(kf, N_{t,i,kf} * fmc1_{t,i,kf,k}) \quad (2)$$

where $Nmig_{t,i,k}$ is the new number of individuals at time *t*, *i*th age class and *k*th area. This matrix can also include diffusion between areas.

The recruitment is simulated using the Beverton and Holt stock-recruitment function ([8,31], Supplementary Figure S.1 and Eq. S.9), with 1000 random stochastic to include a standard error for recruitment and SSB. Median recruitment and SSB values are then used to calculate survival, fishing mortality and next year's TAC (see management section). At the end of each year, all individuals of one age class are transferred to the next. Those older than the maximum age are accumulated in the last age class (plus group).

### 2.1.5. Management

The NEAM population is currently managed as one and since 2020, the TAC within the EU is theoretically supposed to be set according to the MSY approach. Yet, the fishing mortality was on average (2007-2017) 30% higher than the advised $F_{msy}$ during the Inter-Benchmark assessment at the beginning of 2019 [8] and 22% higher than the assessment report at the end of 2019 [9]. This is because no internationally agreed quotas do yet exist and no harvest control rules are active at the time of this study [9]. Neither the EU nor any other state currently fish according to MSY.

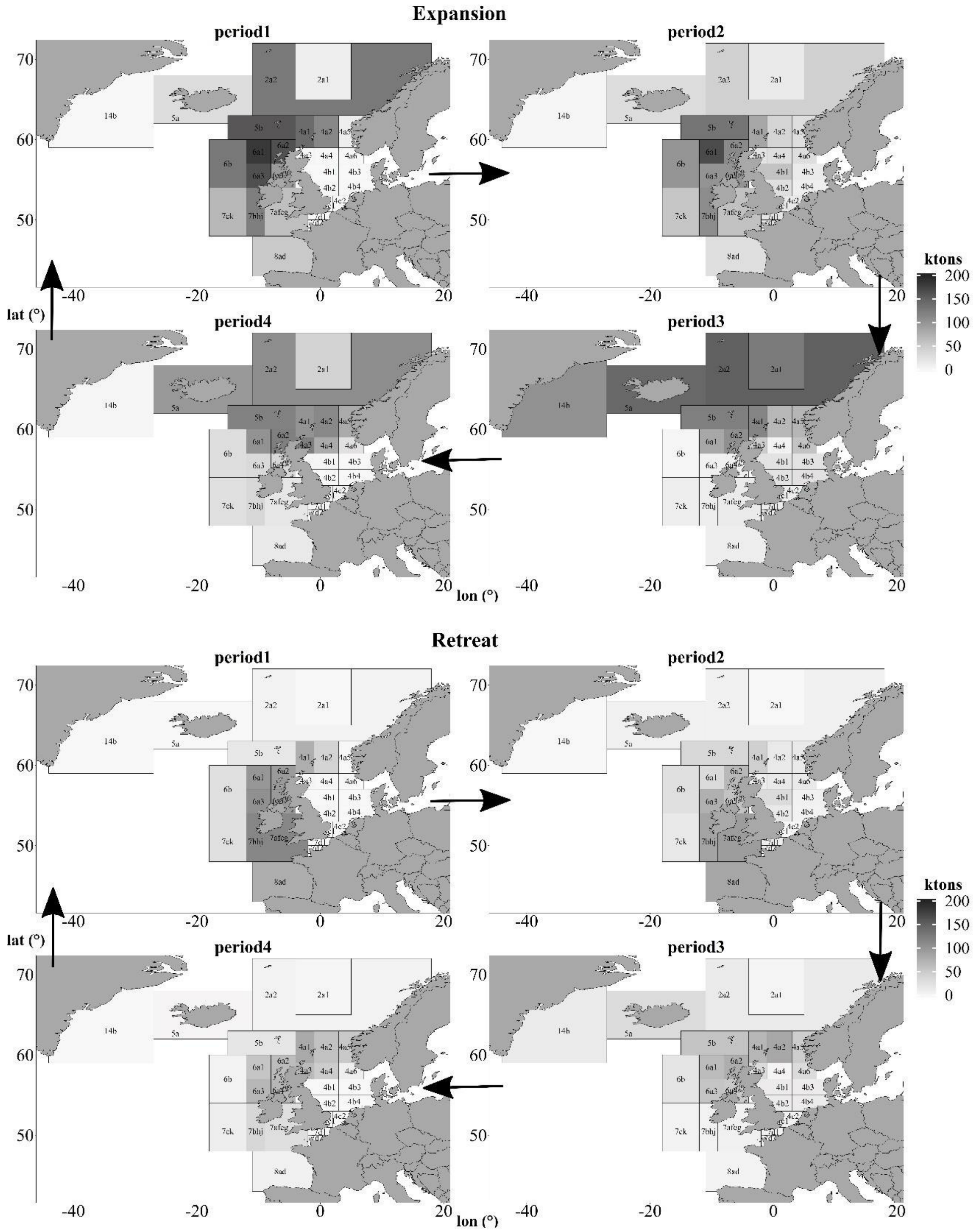


**Figure 1.** NEAM total stock biomass distribution in each season in case of an expansion if eq. 1a is valid (top), as well as in case of the most extreme retreat to their core occurrence areas if eq. 1e is valid (bottom).

Rybicki et al. [13] used a fixed level of the averaged fishing mortality (2007-2017) by adding a multiplier to the advised $F_{msy}$ in order to simulate the continued overfishing that is taking place without any agreement reached. This approach was also applied in this study. In the baseline scenario, the Baranov Catch equation was finally used in order to calculate a catch according to the target fishing mortality (0.29), which is then applied as a dynamic TAC for the following year ([32]; for further detail see [13,20,27]). Fleets, where no data could be received (i.e. Norway, the Faroe Island and Greenland), are included as a fixed proportion into the TAC calculations, remaining the same in all scenarios. Catch of all modelled fleets is limited by their quota, which is also a fixed proportion of the TAC. This proportion remains the same in all scenarios, because under the current political circumstances it is very difficult to make any assumptions about alternative quota shares and would only increase the level of uncertainty. Additionally, catch is limited by the available biomass (i.e. total catch has to be below 95% of the stock biomass in each area). Under current management regulations, area closures are active during the first two seasons in ICES subarea 4a and for the whole year in ICES subareas 4b and 4c in order to protect the North Sea component of the NEAM stock [8]. The closures were implemented in all scenarios according to Bartelings et al. [20] (Eq. 3).

$$95\% * CB_{i,k,t} >= sum_j[C_{j,i,k,t} / (1-clos_{j,k,t})] \quad (3)$$

where CB is the total biomass for *i*th age class, *k*th area at time *t* and *C* is catch for *j*th fleet. The parameter *clos* has to be previously defined by the model user and lies between 0.001 (no closure) and 0.99 (full closure).

### 2.2. Data and Settings

FishRent was run for a period of 16 years (2014-2030) using eight fleets (Table 1) targeting primarily the western component of NEAM and accounting for 44% of the total catch (average of 2012-2014). Only fleets where mackerel constituted more than 25% of the total landings value were considered in the modelling approach. Fleets consist of multiple vessels and were classified by vessel length (vl in meters) using two categories ranging from 24-40m and over 40m as well as two predominant gear types (pelagic trawlers (TM) and purse seiners (PS)). This uses the classification of the European data collection framework as implemented by the Scientific, Technical and Economic Committee for Fisheries [17]. Detailed economic data (e.g. costs, effort, profit etc.) was received directly from national labs, also averaged over the years 2012 to 2014. No detailed catch and effort data from Norway, the Faroe Islands and Greenland could be obtained in this detail as well as no economic data from Iceland. The fleets accounted for approximately 37% (average between 2012-2014) of the total catch [47-49]. Since the large-scale, pelagic Icelandic fleet is similar in structure to the large-scale UK fleet, economic data could be estimated using the UK fleets economic structure.

**Table 1.** Overview of the eight fleets included into the model, their vessel sizes (in metres), primary fishing and cooling technique and the name used within this study. Note: RSW means refrigerated seawater.

| Fleet | Size | Technique | Cooling technique | Name |
|---|---|---|---|---|
| Denmark | >40m | Pelagic Trawler | RSW | DK (TM >40m) |
| Denmark | >40m | Purse Seine | RSW | DK (PS >40m) |
| Netherlands | >40m | Pelagic Freezer Trawler | Freezing | NL (TM >40m) |
| Germany | >40m | Pelagic Freezer Trawler | Freezing | D (TM >40m) |
| United Kingdom | >40m | Pelagic Trawler | RSW | UK (TM >40m) |
| Ireland | >40m | Pelagic Trawler | RSW | IR (TM >40m) |
| Ireland | 24-40m | Pelagic Trawler | RSW | IR (TM 24-40m) |
| Iceland | >40m | Pelagic Trawler | RSW | IS (TM >40m) |

For the calibration process, detailed biological data i.e. abundance, natural mortality, weight, SSB and recruitment) was used from the most recent stock assessment at the beginning of this study [8]. A three year average (2012-2014) was used as biological input for the starting year 2014 [8].

### 2.3. Scenarios

The baseline (or business as usual) scenario includes the management aspects described before and uses a start TAC of 1,075,000t (mean of 2012-2014; Figure 2; Table 2; [8]). The model then dynamically estimates a new TAC for each year. The second scenario is a “fixed business as usual”, in which the TAC stays fixed at 1,075,000t and is not altered dynamically. It is a continued situation of the current, where no agreement between the minor player Iceland and the major players EU, Norway and Faroe Islands exists yet, also continuing overfishing. The third and fourth scenarios are implemented both in two levels. The third scenario uses TAC levels set by ICES for 2019 (770,358t) and 2020 (922,064t) based on a MSY approach, hence assuming an agreement between all parties (Figure 2, [9]). During this scenario, a mackerel expansion is expected due to less fishing pressure and therefore resulting in higher SSB levels. The fourth scenario assumes no agreement between minor and major parties as well as the possibility to prevent Iceland from targeting NEAM by further overfishing the stock. The TAC was therefore set at two levels: 1) The highest level recorded (1,392,000t in 2014, [9]), 2) the level of 1) with an additional 54% (fastest rate of change historically observed, [9]) generating a TAC of 2,143,680t. In this scenario, SSB levels are expected to decrease and the stock therefore to retreat into historic, core occurrence areas.

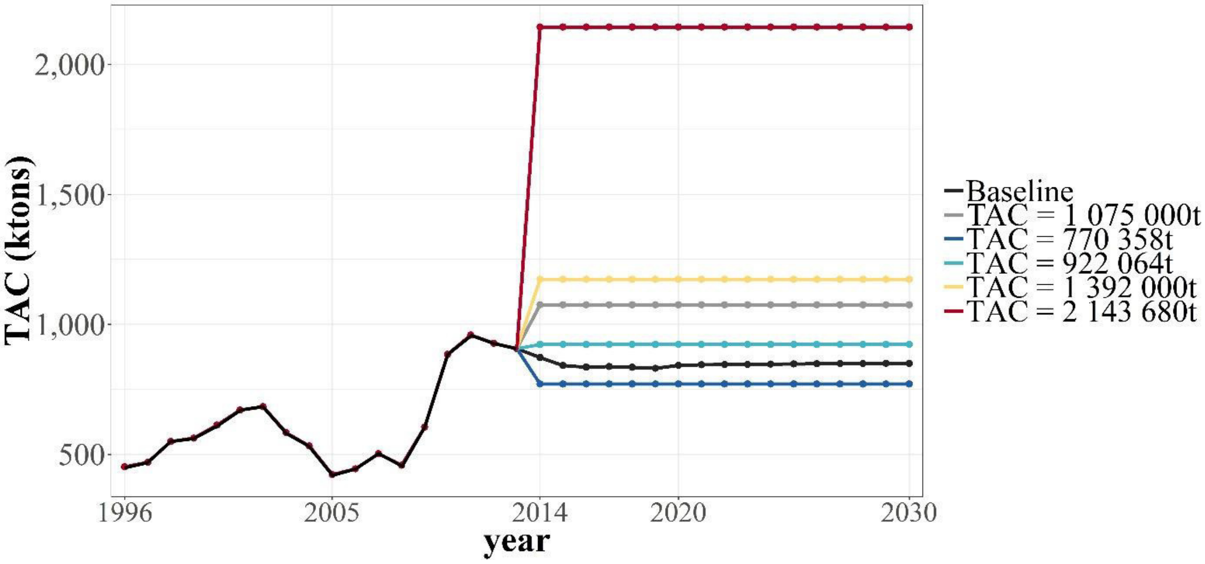


**Figure 2.** Historic TAC (ktons) of NEAM from 1996 until 2013 [8]. Colored lines represent the simulated TAC (ktons) trend for the different scenarios. Note: 2014 is the start year, hence values from 2014 shown in this Figure already represent estimated/set TACs for the following year.

**Table 2.** Scenario overview and implementation description.

| Scenario | Description | Reference |
|---|---|---|
| 1) Baseline (Business as usual) | start TAC = 1,075,000t, dynamic TAC which is adjusted annually | [8] |
| 2) Fixed Baseline | TAC = 1,075,000t, fix | [8] |
| 3) Mackerel expansion | TAC set by ICES advice, fix<br>a) TAC = 770,358t (level of 2019)<br>b) TAC = 922,064t (level of 2020) | [9] |
| 4) Mackerel retreat | Amplifying overfishing, TAC fix<br>a) TAC = 1,392,000t (level of 2014)<br>b) TAC = 2,143,680t (fastest change between years: 2013-2014) | [9] |

## 3. Results

During the baseline scenario, where the TAC was adjusted dynamically at the end of each year, SSB decreased from 4,600ktons to 4,300ktons within four years and stayed on this level on the long-term (Figure 3). This is well above the precautionary limit, which is set at the same level as the biomass at MSY (2,500ktons) according to ICES [9]. As already seen before in Figure 2, the TAC was estimated to continue the decrease that occurred from nearly 1,000ktons in 2011 (observed data) until 800ktons in 2015 (simulated data), after which it stayed relatively constant.

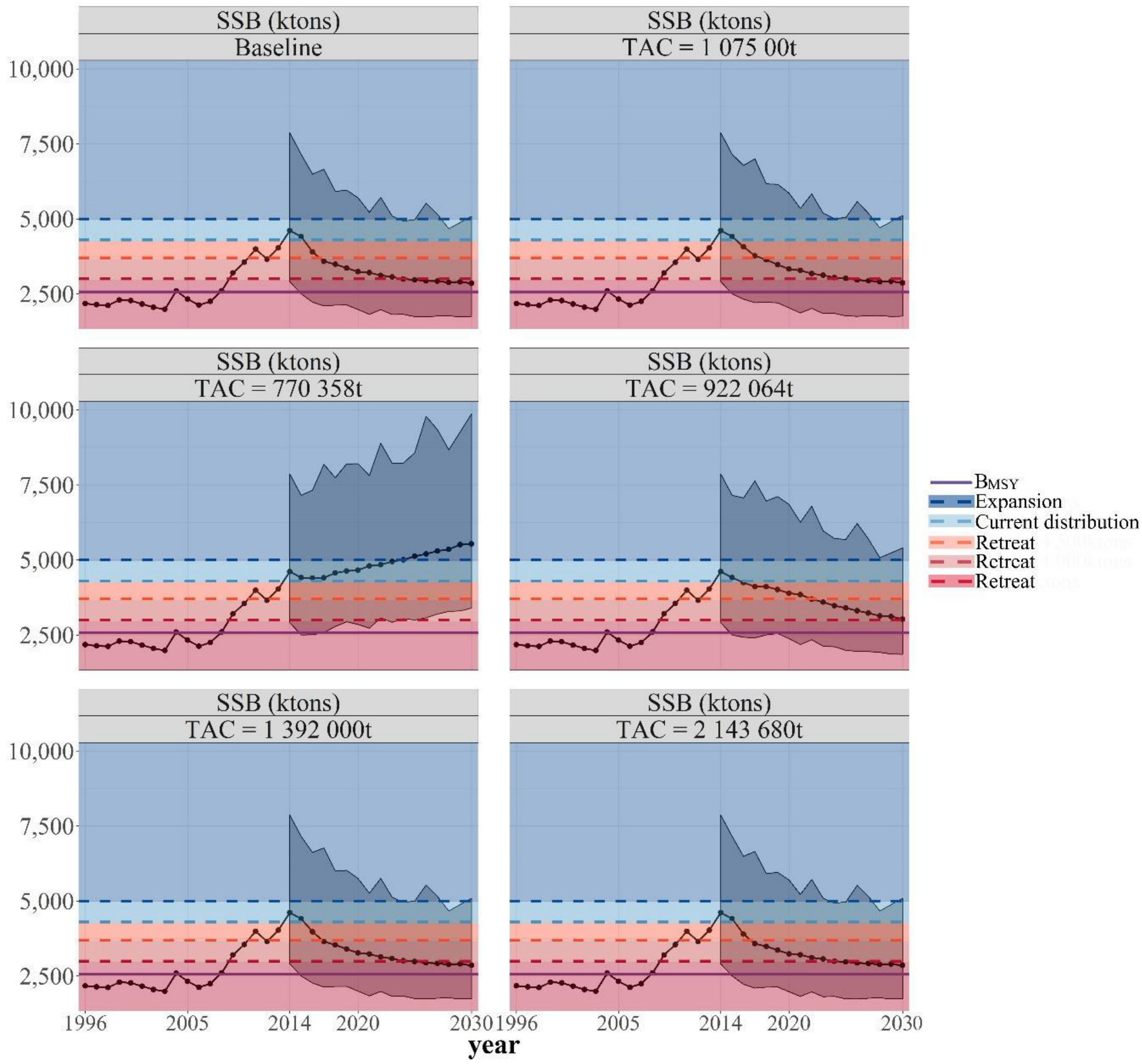


**Figure 3.** Historic SSB trend (ktons) from 1996 to 2013 [8] as well as simulated trends (start year: 2014) for the different scenarios. Straight purple line represents the level of $B_{msy}$ [8] and colored dashed lines as well as shaded areas represent the different SSB levels of the dynamic migration module (>5,000ktons: expansion (dark blue), 5,000 – 4,500ktons: current distribution (light blue), <4,500ktons: retreat (orange to dark red)).

When continuing setting the TAC at 1,075,000t, SSB decreased more rapidly to 3,700ktons during the first four years. Afterwards, the decrease appeared more slowly until reaching 3000ktons in 2030, which is relatively close to $B_{MSY}$ (2500ktons [8]). This is a decrease of 25% compared to the baseline scenario (Figure 4). During this time period the dynamic migration matrix let the stock retreat towards the core occurrence areas (steps are marked with colored dashed lines, Figure 3). Interestingly, the results of the increased TAC levels (1,392,000t and 2,143,680t) are very similar, although the end SSB point is less than 3,000ktons, hence the highest degree of retreat was applied by the model (Figure 3). Using the 2020 TAC level from the MSY approach advised by ICES (922,064t) decreased SSB to 3,000ktons in 2030, which is a decrease of 25% compared to the baseline scenario (Figure 3/4). The decrease is however less intense during the first years, but occurs rather steadily (Figure 3). The only scenario where SSB actually increased to a higher level than 5,000ktons after 2025, hence, expanding the migration patterns towards the north-west, was when using the TAC level advised by ICES for 2019 at 770,358t (Figure 3). SSB increased by 10% until 2020 and by 23% in 2030 compared to the baseline scenario (Figure 4).

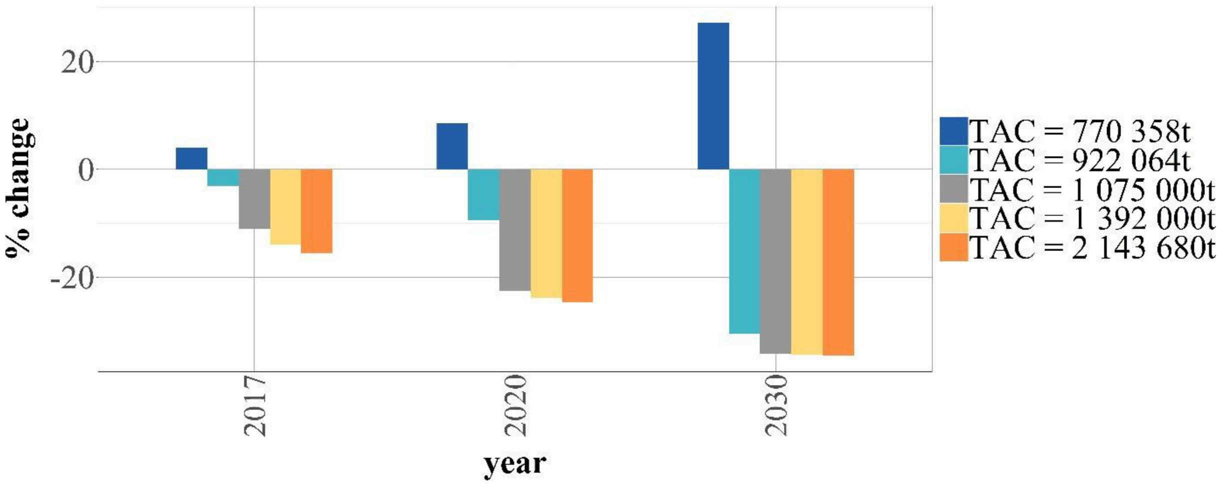


**Figure 4.** Proportional change (%) of SSB from the different scenarios compared to the baseline on the short-term (2017), mid-term (2020) and long-term (2030).

Catch proportion per season varied depending on the TAC level: The most significant variations in seasonal catch proportions over time appeared when setting the TAC to the second lowest level (922,064t; Figure 5): For Iceland, the main catch season at the beginning (2014) is in the third quarter, however, when setting the TAC to 922,064t, catch increased in season two from 2021 until 2025. At the beginning, the other fleets fished the largest proportion of their NEAM quota in the first season and to a smaller proportion also in season four. After 2021, catch in season four first decreased but then in 2022 already started to increase again to a similar level as observed at the beginning (2014). After 2025, catch in both season four as well as season one started to decrease again (Figure 5). After 2015 and 2020/2021, migration patterns were adjusted by the model depending on SSB levels, which lead to a stepwise retreat to NEAM core areas (Figure 5, marked red). In this scenario, a large proportion of NEAM biomass occurs further south along the Irish coast and southwestern England in the first season during the years 2015-2020, instead of around northern Scotland (Supplementary material Figures 4-8). Main fishing grounds therefore shift further away for most fleets during season one whereas they stay rather constant around the Scottish coast, especially the Orkney and Shetland Islands, during season four. Total catch of the Danish fleets stayed on a constant level over time, hence continually using their full quota over time (PS: 13,000t; TM: 18,000t). After 2020, total catch of the Irish, Icelandic and Dutch fleet started to constantly decrease, not using their full quota anymore, and after 2025, the German and UK fleets' catch also decreased (Figure 5). In the scenarios applying the two lowest TAC levels, catch for all fleets except for the Icelandic, increased in the fourth season and decreased in the first, whereas it was the other way around when applying the high TAC levels (Supplementary material Figures 9-14). Generally, it is important to mention that no fleet fished more than 90 days per vessel in a season during any run.

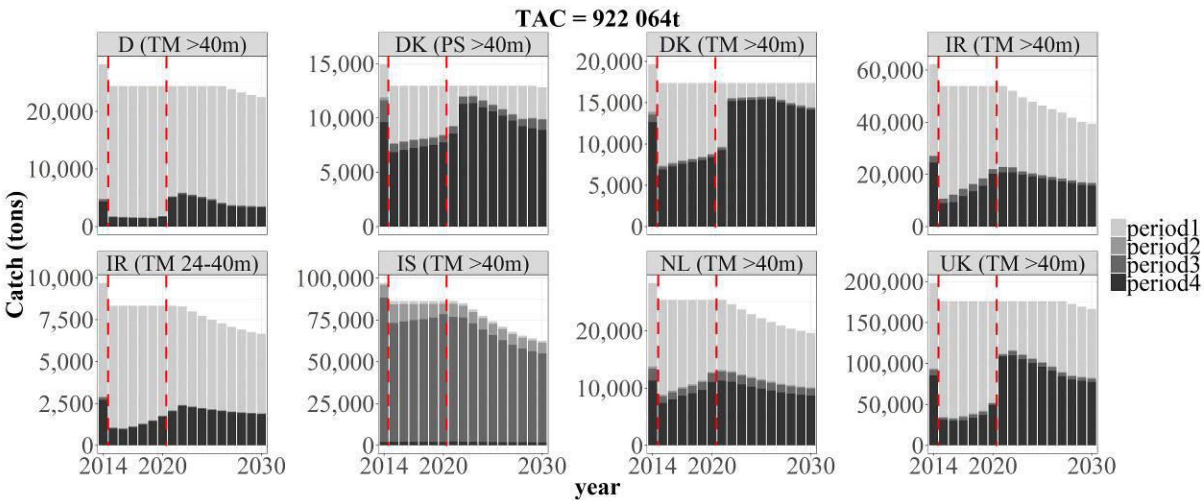


**Figure 5.** Catch (tons) of the eight different fleets in each season (=quarter or period) over time of scenario three with a TAC level of 922,064t. Light grey (top) represents season one, medium grey is for season two, dark grey for season three and black (bottom) for season four. Red vertical lines represent points in time where migration patterns changed according to SSB level.

When it comes to economic changes, we will first describe the outcomes of the Baseline scenario on the mid- and long-term (2020 and 2030) compared to the start year (2014). On the mid-term and long-term, all fleets increased their total effort but differences in the degree of change can be noticed (Figure 6). Primarily the UK fleet increased their effort by 225% in 2020 and by 160% by 2030. The increase of total effort from the other fleets varied between 10% (Dutch fleet) and 60% (Icelandic and small-scale Irish fleets) in 2020 and between nearly no change (German fleet) and again 60% (small-scale Irish fleet) in 2030. The fleets, which decreased in total effort from 2020 to 2030 compared to 2014 also decreased their fleet sizes by up to 40% (large-scale Irish fleet; Figure 6). All fleets, except for the Danish Pelagic Trawler fleet, decreased their catch level between 10% (UK and Danish Purse Seine fleets) and 30% (Icelandic and large-scale Irish fleets) in 2020 compared to the start year (Figure 6).

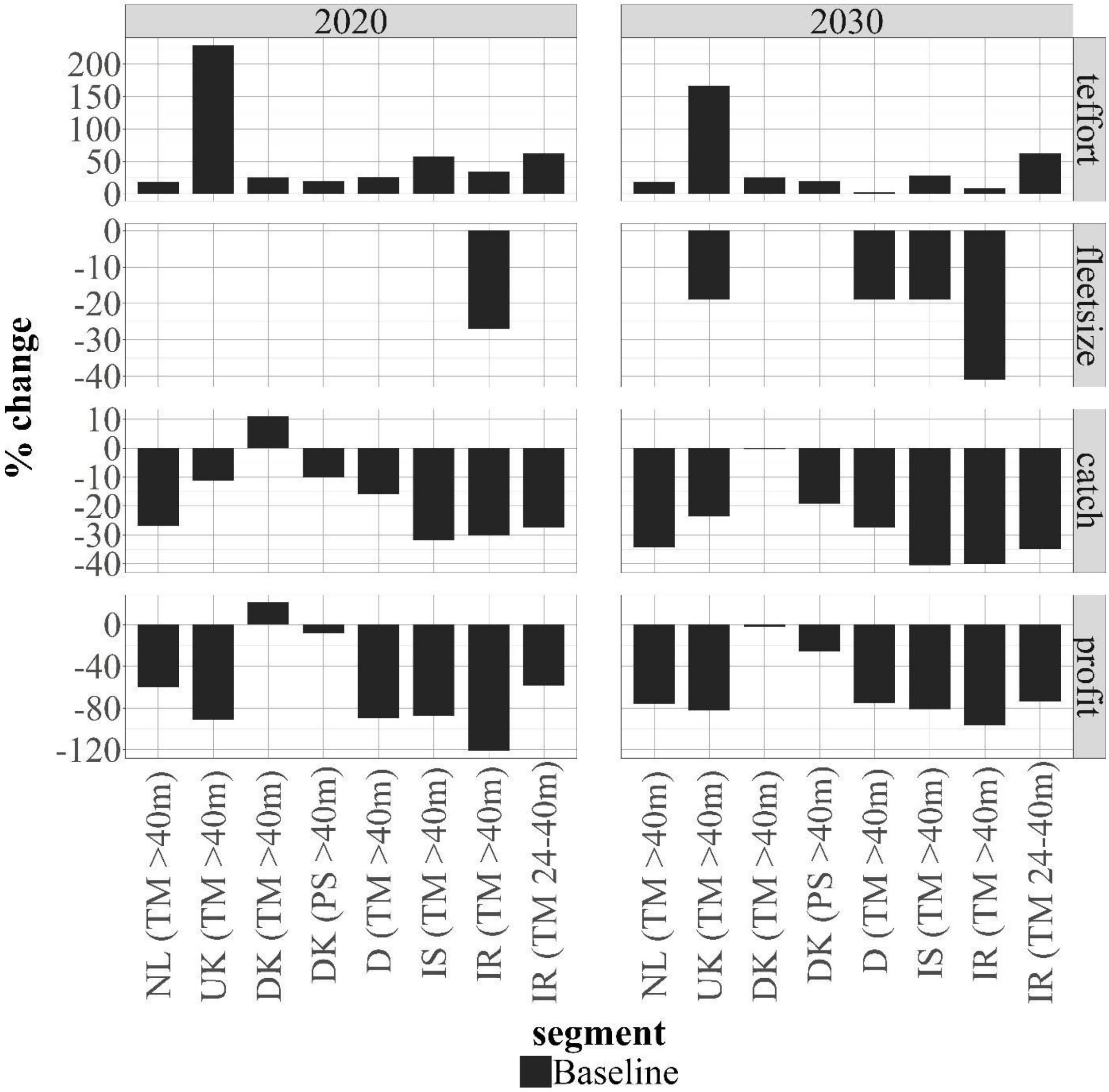


**Figure 6.** Proportional change (%) of total effort (teffort), fleet size, catch and profit of all eight fleets in the Baseline scenario compared to the initial year (2014) on the mid- (2020) and long-term (2030).

The only fleet increasing their catch level by 10% on the mid-term was the Danish Pelagic Trawler fleet. On the long-term, they however returned to their catch level of the beginning in 2014 (Figure 6). The catch level of all other fleets also decreased even further by up to 40% (Icelandic and large-scale Irish fleets) on the long-term compared to the beginning. This affected net profit accordingly: On the mid-term, the large-scale Irish fleet had a loss of 120% compared to the beginning. The Dutch, German, Icelandic and small-scale Irish fleets sustained losses of approximately 70% on average in 2020 compared to 2014, which deteriorated by 80% on average on the long-term (Figure 6). The only two fleets that were least effected were the Danish.

In all tested scenarios, except for the lowest TAC scenario at 770,358t, fleet size of the large-scale Irish fleet is 10% higher in 2030 compared to the baseline scenario (Figure 7). Another point to highlight is that the UK and large-scale Irish fleet size under nearly all TAC levels in 2020 as well as in UK fleet size under the two lowest TAC level settings in 2030 are 20% higher compared to the baseline scenario (Figure 7). The other fleets changed their effort and hence their fuel costs accordingly. All fleets, except for the Icelandic, had a 50% higher total effort in 2020 and 60% higher by 2030 compared to the baseline scenario as well as when applying the lowest TAC level (Figure 7). The Icelandic fleet only decreased their size and total effort with the business as usual and high TAC levels in 2030. In 2020, the German and small-scale Irish fleets had a 60% higher total effort under all TAC levels compared to the baseline, except for the one at 770,358t. In 2030, the German fleet had a 20% larger fleet size than the baseline. As to profit, the only TAC under which especially the UK and large-scale Irish fleet were more profitably than in the baseline scenario was the lowest TAC setting. In fact, the UK and large-scale Irish fleets were the only that increased their profit to 80% more than the baseline until 2030 when applying the lowest TAC level (Figure 7). The only fleet that was more profitable in 2030 (+60%) and had a 20% higher catch than the baseline scenario under all other TAC levels, was the Danish Pelagic Trawler fleet. The segment least affected in terms of net profit on the long-term was the Danish Purse Seine fleet. Both Danish fleets were the only that fished more NEAM in season four than season one at the beginning of all scenarios and although catch of the other fleets also increased in season four, it never reached the level of the Danish fleets (Figure 5).

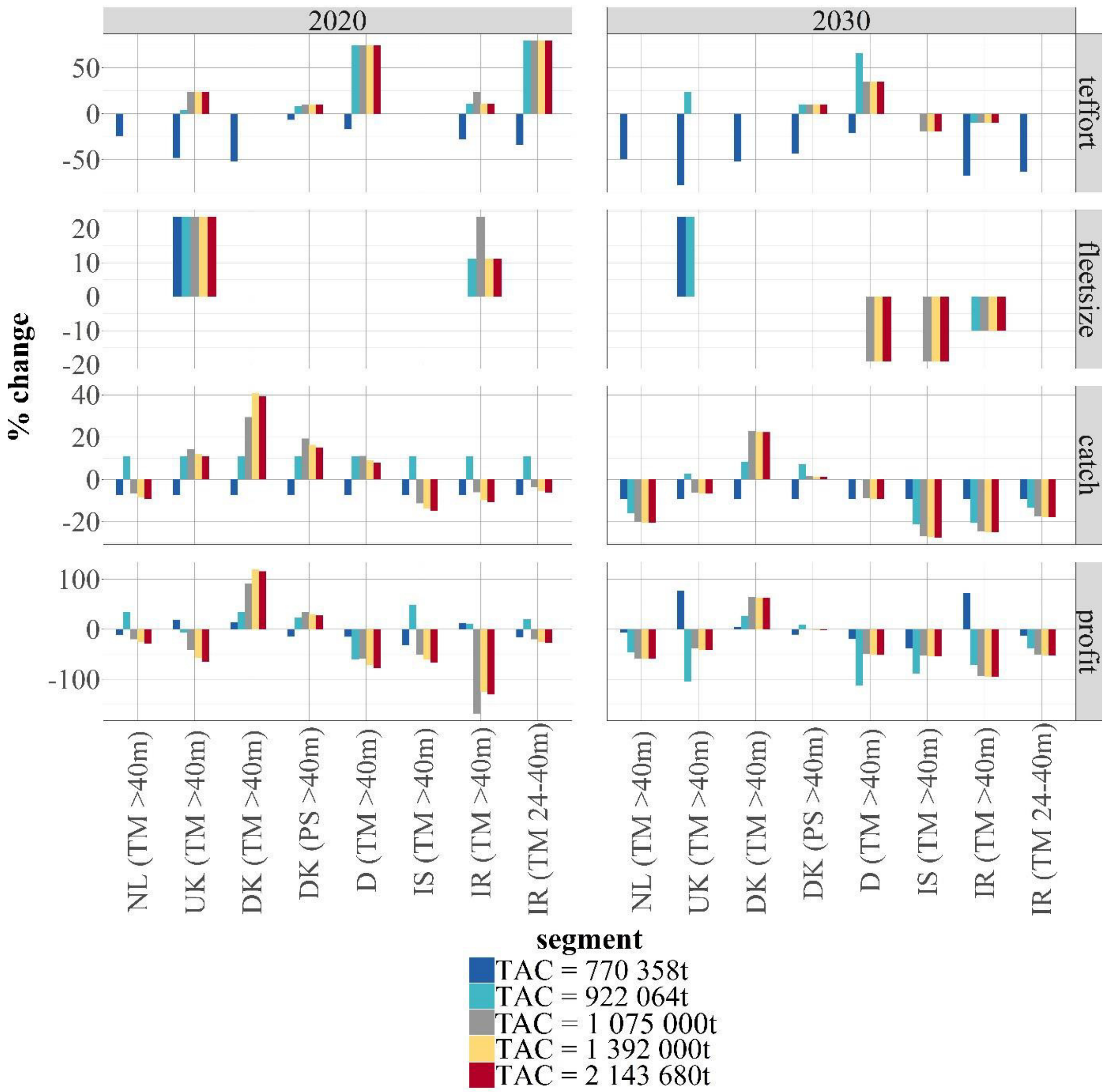


**Figure 7.** Proportional change (%) of total effort (teffort), fleet size, catch and profit of all eight fleets in each scenario compared to the baseline scenario on the mid- (2020) and long-term (2030).

Apparently, the Danish Purse Seine fleet needed to adapt least compared to the other fleets and the baseline. At the beginning, they primarily fished during the fourth season in the northwestern North Sea (4a1-a4) as well a small amount in 2a2 (Figure 8). In season one, the main areas were along the western British coast, especially around Scotland (6a2, Figure 8). This pattern strengthened or stayed similar during the baseline and other TAC level settings in season one. Patterns in season four, however, changed: In the baseline scenario catch shifted from the Scottish east coast (4a3) to the northern North Sea (4a2) in 2030 (Figure 8).

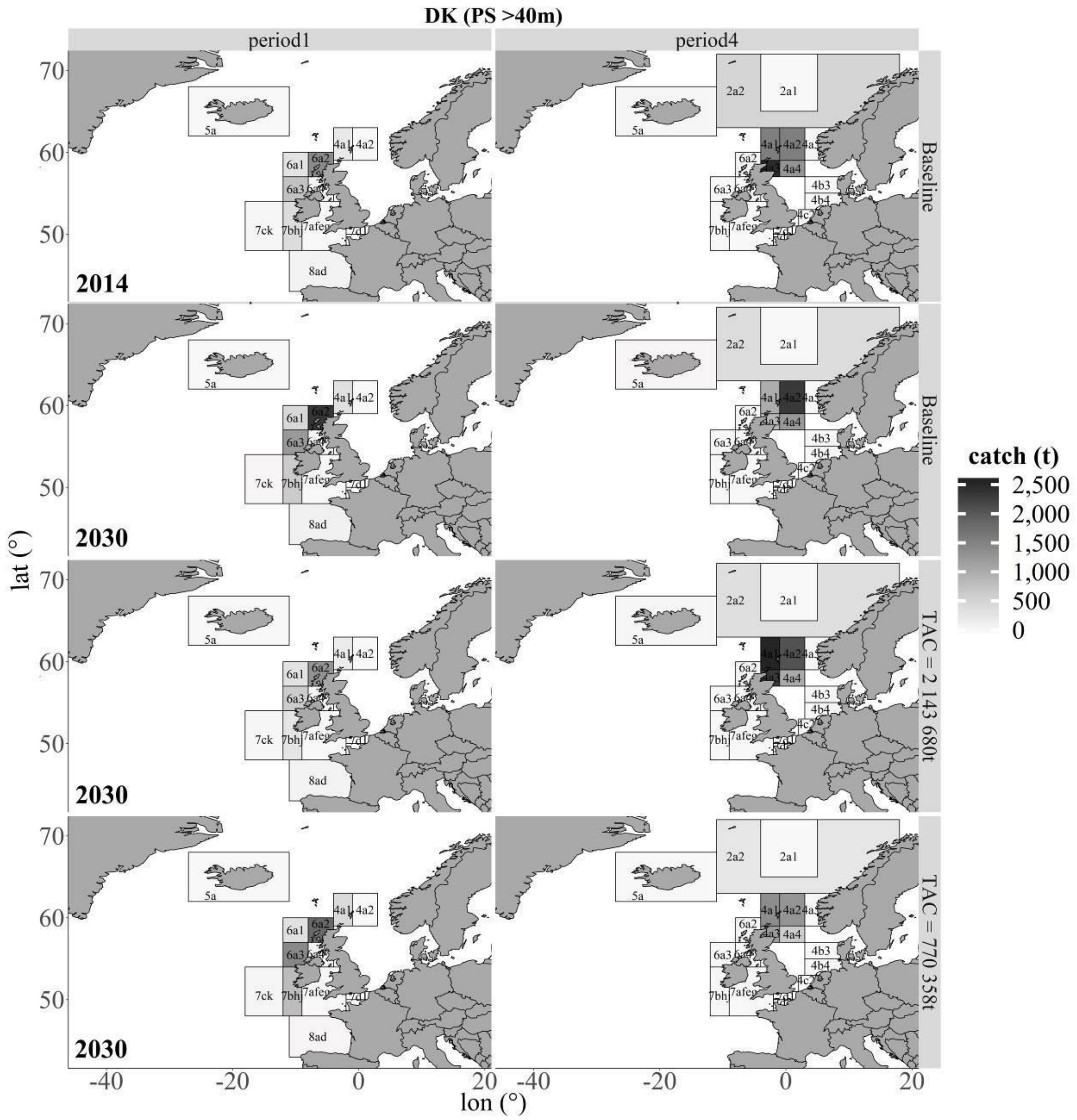


**Figure 8.** Catch (tons) distribution of the Danish Purse Seine segment (DK PS > 40m) in the first and fourth season. Shown are the baseline scenario in 2014 (start year) and 2030 as well as lowest and highest TAC levels in 2030.

It should be mentioned, that most other fleets rather fished along the western UK coast in season one from the beginning instead of the northern Scottish coast as well as the Shetlands in season four as did the Danish. When applying the highest TAC level (2,143,680t), catch of the Danish fleets shifted towards the north and northeastern areas of the Scottish coast and towards the Faroe Islands (4a1, 4a2, 4a3). In this case, a retreat of NEAM biomass due to low SSB levels was assumed and most of the biomass is situated along the western British coast in season one and in the north-western North Sea during season four. During the lowest TAC setting

(770,358t), a similar pattern appeared but was less strong since catch in the first season was higher, especially at the west coast of Scotland and north-west off Ireland (6a2, 6a3, Figure 8). In this scenario, NEAM biomass was less available along the western British coast in season four compared to season one due to an assumed expansion (Figure 1).

To summarize, effects on catch were generally positive under most scenarios on the mid-term, especially for the UK, Danish and German fleets. On the long-term, the effects were the most positive for the Danish Pelagic Trawler and the most negative for the Icelandic, large-scale Irish and Dutch fleets. Profitability wise, most positive effects also materialized for the Danish Pelagic Trawler fleet on the mid-term and least positive effects for the large-scale Irish fleet. On the long-term, net profit of the Danish Purse Seine fleet was affected least, but the most affected was again the large-scale Irish fleet.

## 4. Discussion

In this study, we adapted the spatial FishRent version of Rybicki et al. ([13]; in prep. [39]) to the pelagic NEAM fishery and its regulations as well as incorporated dynamic migration patterns that change spatially depending on SSB. We further applied different TAC scenarios in order to test for impacts on the stock biomass as well as simulated corresponding fleet behaviour changes. Especially in the context of recent changes in stock biomass distribution and related political disturbances this study helps to illustrate possible futures of the NEAM stock and its fishery.

### 4.1. Biomass retreat

If the TAC stays at the same level as at the beginning or would be raised, SSB continues to decrease more or less rapidly but usually ends relatively close to $B_{MSY}$ in 2030. This is because the TAC would not be fished out anymore after four years already due to the low biomass level with a fixed TAC level of 1,075,000t or higher (Supplementary Figure S.15.). Hence, total stock biomass not the stock distribution is the limiting factor in this case, reaching a level at which it is not profitable anymore for the fleets to fish out their whole NEAM quota. This negatively effects most fleets profit correspondingly, except for the Danish, which remain either unaffected (Danish Purse Seine fleet) or even increased their profit (Danish Pelagic Trawler fleet) on the long-term with increased TACs compared to the baseline. Already under the baseline scenario, total effort of the Danish fleets stayed rather constant over time, especially in case of the Danish Purse Seine fleet. The Danish Pelagic Trawler fleet, however, decreased their fleet size by 40% in the baseline scenario as well as all others in order to stay profitable, which most others did not have to do. On the other hand, all other fleet had to massively increase their total effort from 2014 to 2030 under the high TAC scenarios, especially the UK fleet, in order to follow the retreating NEAM biomass towards the southern Irish and southwestern English coast, therefore increasing their fuel costs. This effected the UK fleets significantly, as most home harbours are situated in north-eastern Scotland (Fraserburgh, Peterhead, the Shetlands as well as Orkneys) and a large proportion of NEAM catch was initially taken around the Shetland Islands and Outer Hebrides. The UK fleet therefore had to follow the NEAM biomass in a retreat scenario towards the south, whereas other fleets, such as the German, already fished a large proportion of NEAM south of Ireland and some in west of France from the beginning. In such a biomass retreat scenario, the UK fleet might need to land more catch at the western coast of the UK and let it then be transported to the specific destinations. The German fleet as well as the Icelandic and Irish fleets also had to decrease their fleet size though, which in case of the German fleet leaves two out of four vessels to operate. In fact, the German fleet already sold one of the four vessels targeting NEAM and other pelagics in 2018. Under high TAC levels and the corresponding decrease in SSB, only one vessel of the German fleet would be left to target NEAM. All other vessels might either switch their focus to other species or might be sold to other countries holding enough quota that can be fished with a >80m freezer trawler vessel.

Another possibility to remain profitable is to alter the effort and hence catch pattern, which is what most segments did. When allowing the fleets to catch more NEAM, SSB decreased more rapidly over time compared to the baseline and lower TAC scenarios, leading to quotas not being completely utilized by fleets in the end. A common hypothesis regarding pelagic stock dynamics is the expansion of a population with very high biomass levels. In this case, sub-populations will overlap and mix, increasing overall density, although the density of a sub-population is thought to be rather constant [18]. This system works the other way around: A retreat of a population to its core areas with decreasing stock biomass with lesser density followed by a stock collapse, also called range collapse, can occur due to the impact of negative external factors such as overexploitation [18]. In such a situation, sub-populations, which are considered as a single exploited stock, are thought to mix less, leading to a more dispersed occurrence of schools and in turn bearing the risk of local overfishing [18]. Due to effective, modern eco-sounding techniques catch rates can still be kept rather constant over a long time period, although the stock might already be declining. In this study, the increasing TACs scenarios illustrate such an effect: Fleets used a large amount of effort compared to the baseline scenario on the long-term, therefore increasing their search time although the biomass in this scenario retreats to the core areas, which are closer to many fleets main fishing grounds. Yet, most fleets catch less than the baseline and low TAC scenarios. The Icelandic fleet, on the other hand, would have had to cover a greater distance in order to catch the same amount or more NEAM. Apparently, this was not profitable, which is why they decreased their fleet size instead. Even by doing so, most fleets would be less profitable on the long-term than the baseline scenario due to overfishing the stock.

**4.2. Biomass expansion**

An important result of this study is the increase of NEAM mackerel biomass by 22% on the long-term compared to the baseline scenario when decreasing the TAC to 770,358t. It is the only scenario in which the stock expands further to the north-west after 2025 due to reaching an SSB level of >5,000ktons. With such an expansion and biomass increase, all segments could decrease their total effort in order to catch approximately the same amount of NEAM as in the baseline scenario. This is especially true for the UK and large-scale Irish fleets that would use less effort and profit most as the hot spots in season one, in which both segments catch most, are just in front of their doors.

Interestingly, the Icelandic fleet did not alter their effort or fleet size compared to the baseline scenario, although more SSB appeared in their EEZ when applying the lowest TAC and inducing an expansion of the NEAM stock. This is because the Icelandic fleet increased their catch in the second instead of the third season, resulting from the earlier appearance of NEAM already their EEZ than when applying higher TAC levels (inducing a retreat as already described). The same strategy was used by the Danish trawlers: In the underlying data, the Danish fleets catch most NEAM in season four, whereas the others catch the largest amount in season one (again, except for the Icelandic fleet). During the model runs, the other fleets also increased their catch in season four but not to the extent of the Danish. Hence, targeting NEAM seems to be more profitable in the fourth season on the long-term as the Danish trawlers perform exceptionally well during all runs.

Moreover, the Danish fleets primarily fished in areas along the north-western Scottish coast (4a1-4a4). These areas stay fairly stable no matter if a NEAM retreat or expansion occurs. The fishing grounds off north-western Scotland are also closer to the Danish fleets main port Hirtshals, hence less effort and fuel costs have to be used. The other fleets also increase their catch in those areas in the fourth season but still continue fishing most NEAM along the whole western Irish and British coast during season one. For Irish fleets this is easily explained, as these are the closest areas where most vessels of the two fleets fish for NEAM. In case of the German and Dutch fleets a similar behaviour as the Danish fleets could have been expected in an expansion scenario, as the areas off north-western Scotland are also closer to their main ports than the ones along the western Irish and British coast. However, these fleets consist of freezer-trawlers, which already process their fish on board and therefore do not have to return to the harbour as often as the Danish RSW trawler. In fact, freezer-trawlers usually stay out for several weeks, can cover greater distances and therefore have more access to areas with higher stock densities, which occurred around the western British coast in season one under the lowest TAC scenario (i.e. the areas where the Dutch and German fleets primarily fished). RSW trawlers, on the other hand, have to return to the harbour far more frequently and are thus limited in their operating distance. Moreover, freezer-trawler have larger storage capacities and can therefore catch more NEAM with the same amount of effort compared to RSW trawlers, therefore also being more efficient.

### 4.3. Migration patterns

An important assumption that has to be made by the user before running any scenarios, is the location of the stock in each season. In case of NEAM, this is very well established since a lot of commercial catch data as well as scientific surveys and studies exist [e.g. 2,3,8,9,28,29,30]. When implementing density-dependent migration more assumptions are, however, needed. The larger the stock the farther and wider the migrations in order to search for food [1]. This pattern has been observed for other straddling stocks, i.a. Norwegian Spring Spawning herring [35]. Density-dependent migration is one of the most likely reasons why NEAM could be observed in Icelandic waters after 2007, as after 2004 the stock biomass grew from 2.7 million t to approximately 5 million t in 2015 [8]. Yet, during the late 1970s, the NEAM stock also exceeded 4 million t. An Icelandic fishery targeting NEAM in their own EEZ did not occur though. Hannesson [1] argues that the heavily exploited North Sea component collapsed during this time, whereas now the western component is the primary target. The North Sea component might have been responsible for the high stock biomass during the 1970s and as the migration patterns differ from the western component, the potential to migrate into the Icelandic zone under high biomass occurrences was relatively low [1,36].

Another hypothesis that might explain the current migration patterns is that the migrations are random [1]. Random migrations are unfortunately not possible to implement into FishRent since no environmental variables are included, but might yet change into constant conditions in case of more directed oceanographic changes, such as continued ocean warming [1,6]. In this perspective, individual based models, might be of more use. Boyd et al. [5] currently released a study in which they used a spatially explicit individual based model, where NEAM moves by searching for the most profitable location taking into account the life cycle and the corresponding energy budget NEAM has during different phases. This study was conducted in order to test the impact of different fishing intensities combined with Representative Concentration Pathways (RCP). Those RCPs are used to predict climate forcings (e.g. greenhouse gas emissions) of different possible futures, ranging from low (RCP 2.5) to high (RCP 8.5) forcings [37]. The results from Boyd et al. [5] show that when applying high fishing pressure as well as a high RCP (8.5), NEAM density decreases in the northern areas during the feeding season and migration patterns do not reach the Icelandic EEZ anymore. The opposite occurs with no fishing pressure and the lowest RCP scenario (2.6), although even then the stock would not expand much further than currently observed. These results suggest that our assumptions concerning the position of biomass depending on SSB level were in fact reasonable.

Another point that should be discussed is the fixed quota share in all of the scenarios conducted in this study. We are aware that the current debate about access rights to fishing grounds also includes the question about the legitimacy of the relative stability principle. In future, the current form of a quota reparation key will need to be adapted and the assumed fixed quota share in our scenarios might be unrealistic. Additionally, the TAC would still continue to change dynamically as conducted in the baseline scenario instead of staying constantly fixed. We would like to emphasize though, that it is very difficult to make any assumptions on how a new quota reparation key might be estimated under the current situation [4]. As there is no real trend or solution to these conflicts yet [4], any assumption would have significantly increased the model uncertainty. A possibility might be to apply dynamic shares, depending on the position and size of the stock biomass. For this, an agreement about the initial share distribution would need to be made amongst all parties first. A suggestion made by some studies is to redistribute the quota shares by current biomass distributions [13,45,46]. In fact, Rybicki et al. [13] illustrated the impacts of such a scenario on the NEAM and North Sea autumn spawning herring fishery over a temporal scale. In the end, some major players (Danish, Dutch, German fleets) only received a very small fraction of the NEAM TAC (<0.01%) making this fishery unprofitable immediately. It is therefore highly unlikely that those states would agree to an alternative quota repartition key according to the NEAM biomass distribution.

The modelled fleets do, however, not only target NEAM but also other species (e.g. herring, sprat, blue whiting, horse mackerel and pelagic redfish) during different times of the year [40]. Horse mackerel (*Trachurus trachurus*), for example, also performs vast migrations and is primarily caught by those multinational fleets also targeting blue whiting, NSAS herring and NEAM. Similar to NEAM, blue whiting (*Micromesistius poutassou*) is widely distributed throughout the Northeast Atlantic but highest concentrations occur along the western British Isles and Faroe Islands at the edge of the shelf, where spawning takes place between March and April [40]. During spawning season, most of this stock (88%) is fished in the first half of the year [40]. Other pelagic species, such as Atlantic bluefin tuna (*Thunnus thynnus*), have also been observed to expand their feeding grounds towards northern Atlantic waters, possibly related to rising seawater temperatures [41-43]. The eight modelled fleets catch NEAM to 24% on average, hence approximately 76% other species contribute to their total catch (see also [13]). In this model, these "other species" are included as fixed percentage of the revenue. Changes in "other species" biomass, migration patterns, fish prices, etc. are, however, not considered as a feedback mechanism in this model version. Therefore, it is not possible for the modelled fleets to switch directly to another species that might be more profitable during the runs themselves and outcomes would probably differ with the inclusion of more species. This is possible with the proper availability of data. Unfortunately, the necessary detail of biological data is not accessible for all species, especially the beaked redfish *Sebastes mentella* [44].

## 5. Conclusion

In summary, no matter the cause, NEAM migration patterns have changed and both scenarios of a continued expansion or a retreat into core areas, are possible. When observing the decreasing trend estimated by ICES [8] and our model under current conditions (i.e. our baseline scenario), a retreat might however be more likely. The degree will then depend on the major goal of management and a corresponding agreement between costal states. If it is the protection of the stock on the long-term in order to safeguard NEAM as a resource, results from the baseline scenario suggest that a TAC in between 770,358t and 800,000t is advisable. Over the last six years, ICES recommended TACs between 550,948t (2018) and 922,064t (2020) with an average TAC of 787,780t [38], which supports the outcomes of this study. Actually, the TAC (sum of unilateral quotas) could also be observed to decrease from 1,173,000t in 2017 to 864,000t in 2019 [7,9]. Unfortunately, the TAC (sum of unilateral quotas) was estimated to increase again to 1,090,879t in 2020 [38]. This is a similar level as our scenario using a TAC of 1,075,000t. In this case, all fleets would be less profitable on the long-term than they currently are. This would primarily affect the modelled UK and Icelandic fleets because they hold the highest quota proportion (19% and 9% respectively), hence the NEAM fishery accounts for a large proportion of catch and the dependence of the fisheries sector is very large.

In Iceland, for example, fisheries generate a revenue of approximately 22% of total exports, with 7% of the whole Icelandic population being employed in the fisheries sector [33,34]. After 2016, NEAM suddenly accounted for a total catch volume of 8%, being increasingly important for the economic sector in Iceland [4].

Another objective might be the prevention of migrations into minor player's (i.e. Iceland) EEZs by major players (i.e. the EU and Norway), therefore excluding them from the fishery [1]. If the observed migration patterns are indeed caused by density mechanisms, the major players could achieve this by selecting a high enough fishing pressure [1]. This is also what could be observed in this study when applying high TACs (>1,075,000t), although the TAC would need to be chosen more carefully by the governments because the results shown in this study do represent trends, not the actual future. By simulating migration patterns depending on stock size as well as applying different TACs, we hope to have given some indication of possible impacts on fleets behaviour and net profit, identifying where risks of future management decisions may be and which fleets would be affected most. Going forward it would be useful to couple or apply the knowledge of the individual based model by Boyd et al. [5]. Currently, it is still focussed on the summer feeding period but with an addition to the spawning season in spring, it could provide more detailed information for the biological module in FishRent. This would increase the accuracy of the initial stock distribution, which in turn is crucial for effort decisions made by the simulated fleets and impacts profitability accordingly.

**Supplementary material**

Supplementary material is available.

**Acknowledgements**

Many thanks are given to the CERES project (Grant agreement No 678193), which partly funded this research, as well as the numerous researchers of the Data Collection Framework (DCF) for providing the economic data and their expert knowledge (in no particular order): MMO, MRI, Seafish, DTU Aqua, DST, TI-SF, Marine Institute IR and BIM. Acknowledgements are also given to Anna Ólafsdóttir (MRI) and Jens Ulleweit for plenty of information concerning the biology of NEAM. Last but not least, many thanks for a lot of feedback and new ideas are given to Martin Pastoors (PFA) and Miriam Püts (TI-SF).

**Funding**

This study has been partially funded by the Thünen Institute of Sea Fisheries and the CERES project (Grant agreement No 678193).

**Author Contributions**

All authors contributed to the conception and design of the study; SR wrote and designed the first draft of the manuscript. All authors also contributed to manuscript revision, read and approved the submitted version.

**Conflict of Interest**

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

**Data Availability Statements**

Detailed economic, catch and effort data analyzed in this study was obtained from EU national labs as well as the Marine and Freshwater Institute in Reykjavík (Iceland). More data can be accessed from the STECF (open source). Biological data was obtained from ICES assessments and is open access. Requests to access these datasets should be directed to Anna Ólafsdóttir (MRI, anna.olafsdottir@hafogvatn.is), Matt Elliott (MMO, matt.elliott@marinemanagement.org.uk), Arina Motova (Seafish, Arina.Motova@seafish.co.uk), Josefine Egekvist (DTU Aqua, jsv@aqua.dtu.dk), Kim Normark Andersen (DST, KNO@dst.dk), Emmet Jackson (BIM, Emmet.Jackson@bim.ie), Hans Gerritsen (Marine Institute IR, hans.Gerritsen@Marine.ie), Katell Hamon (WUR, katell.hamon@wur.nl), Jörg Berkenhagen (TI-SF, joerg.berkenhagen@thuenen.de), and Torsten Schulze (TI-SF, torsten.schulze@thuenen.de).

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# Supplementary material

### S.1. Profit calculation

### Eq. S.1: Profit

Catch determines revenue. Together with a fixed proportion of revenue earned from other species not included in this study and fuel, crew, variable, fixed, and capital costs, profit is defined.

$$PrF_{j,t} = Rev_{j,t} - FuC_{j,t} - CrC_{j,t} - VaC_{j,t} - FxC_{j,t} - \mathrm{CaC}_{j,t}$$

$PrF_{j,t}$ is the profit for *j*th fleet at time $t$, $Rev_{j,t}$ is revenue, $CrC_{j,t}$ are crew costs, $VaC_{j,t}$ are variable costs, $FxC_{j,t}$ are fixed costs and $CaC_{j,t}$ are capital costs.

### Eq. S.2: Revenue

$$Rev_{j,t} = \frac{Catch_{j,t} \times fish\ price_j}{proportion\ other\ species_j}$$

### Eq. S. 3: Fuel costs

$$FuC_{j,t} = \frac{fuel\ usage_j * fuel\ price_j \ \times (E_{j,t} + \left(beta_j * E_{j,t}\right))}{1 - Dasoth_j}$$

$E_{j,t}$ is fishing effort, $beta_j$ is a fishing effort multiplier, and $dasoth_j$ are the total days at sea observed proportion of other species fished by each fleet.

### Eq. S. 4: Crew costs

$CrC_{j,t} = Rev_{j,t} \times CrCO_j$ ; $CrC0_j$ (crew costs share)

### Eq. S. 5: Variable costs

$VaC_{j,t} = Rev_{j,t} \times VaCO_j$ ; $VaCO_j$ (variable costs share)

### Eq. S. 6: Fixed costs

$$FxC_{j,t} = FxCO_j \times FLE_{j,t}$$

$FxCO_j$ is the fixed costs share for *j*th fleet and $FLE_{j,t}$ is the number of vessels operating for *j*th fleet at time $t$.

### Eq. S. 7: Capital costs

$CaC_{j,t} = CaCO_j \times FLE_{j,t}$ ; $CaCO_j$ (capital costs share)

## S.2. Parameter estimation

**Table S.1.** Parameter estimation, definition and data sources for Northeast Atlantic mackerel (NEAM).

| Parameter | Definition | Value | Estimation | Source |
|---|---|---|---|---|
| $\alpha_{2;MAC}$ | Species-specific Beverton and Holt for NEAM in 2019; Time frame: 1990-2016 | 10,245,580 | Values self-estimated by using the Solver function in Excel and values from the assessment | Excel (2016); ICES, 2019 |
| $\beta_{2;MAC}$ | | 2,668,788 | | |
| $\alpha_1$ | Cobb-Douglas production function coefficients | 0.8 | Taken from literature | Frost et al., 2009 |
| $\beta_1$ | | 0.2 | | |
| $s_{i,j}$ | Catch share of *i*th age and *j*th segment | See Table S.3 | Average catch share of 2012-2014 | DCF partners |
| $F_{MSY;\,MAC}$ | Fishing mortality at MSY level for NEAM in 2019 | 0.23 | Taken from Inter-Benchmark Report | ICES, 2019 |
| $F_{multiplier;\,MAC}$ | | 1.26 | $F/F_{MSY}$ ratio from 2012-2014 | ICES, 2019 |

**Table S.2.** Proportion of other species caught by the modelled segments (P_other), fuel usage per day (Ufuel), proportional crew (Crew_sh), variable cost (Var_sh), fixed (Fix_sh) and capital cost (Cap_sh) share as well as maximum effort that was allowed for segments to fish (Maxeff).

| Segment | P_other (%) | Ufuel (L/day) | Maxeff (days) |
|---|---|---|---|
| TM VL40XX NL | 47 | 69 | 943 |
| TM VL40XX UK | 81 | 72 | 1921 |
| TM VL40XX NL & D | 57 | 74 | 868 |
| TM VL40XX DK | 47 | 36.5 | 1477 |
| TM VL40XX IS | 45 | 197 | 1004 |
| TM VL40XX IR | 45 | 248 | 500 |
| TM VL2440 IR | 34 | 21 | 177 |

**Table S.3.** Overview of the original catch share according to relative stability (RS) (% of the modelled fleet segments of TAC), the reallocated catch share (proportion of NEAM in each fleet segments EEZ), the share of total catch and fish prices (landings value divided by landings weight) for all modelled segments and species. Note: After 2010, TAC values represent the sum of unilateral quotas, as no international agreed quotas exist.

| Species | Segment | Catch share original (%) | Share of total catch (%) | Fish prices (€/kg) |
|---|---|---|---|---|
| Mackerel | TM VL40XX NL | 3 | 2.3 | 1.18 |
| | TM VL40XX UK | 19 | 2.3 | 1.05 |
| | TM VL40XX DK | 2 | 2.3 | 1.04 |
| | PS VL40XX DK | 1 | 2.3 | 1.02 |
| | TM VL40XX D | 3 | 2.3 | 0.90 |
| | TM VL40XX IS | 9 | 2.3 | 1.49 |
| | TM VL40XX IR | 6 | 2.3 | 0.76 |
| | TM VL2440 IR | 1 | 2.3 | 0.79 |

## S.3. Stock-recruitment relationships of NEAM

### Eq. S.8: Number of individuals $N_{t,i,k}$ using Pope's approximation (Pope 1972)

$$N_{t,i,k} = N_{t-1,i-1,k}e^{-M_i} - \sum_j \left(\frac{C_{t-1,i-1,j,k} \times s_j}{w_i}\right) e^{-\frac{M_i}{2}}$$

where $w_i$ is the weight at *i*th age, $M_i$ is the natural mortality, $C_{t,i,j}$ is catch for time *t*, *i*th age, *j*th segment and *k*th area and $s_j$ is the catch share of each segment *j*.

### Eq. S.9: Stock-recruitment relationships

$$R_t = \frac{\alpha_2 \times SSB_t}{\beta_2 + SSB_t} \times e^{(D \times CV - 0.5 \times CV^2)}$$

The parameters $\alpha_2$ and $\beta_2$ are species specific (Table S.1). D is a standard normal deviate and CV is the coefficient of variation (CV = standard deviation/mean), which was estimated based on historical stock sizes from 2012-2014 (ICES, 2018/2019a)

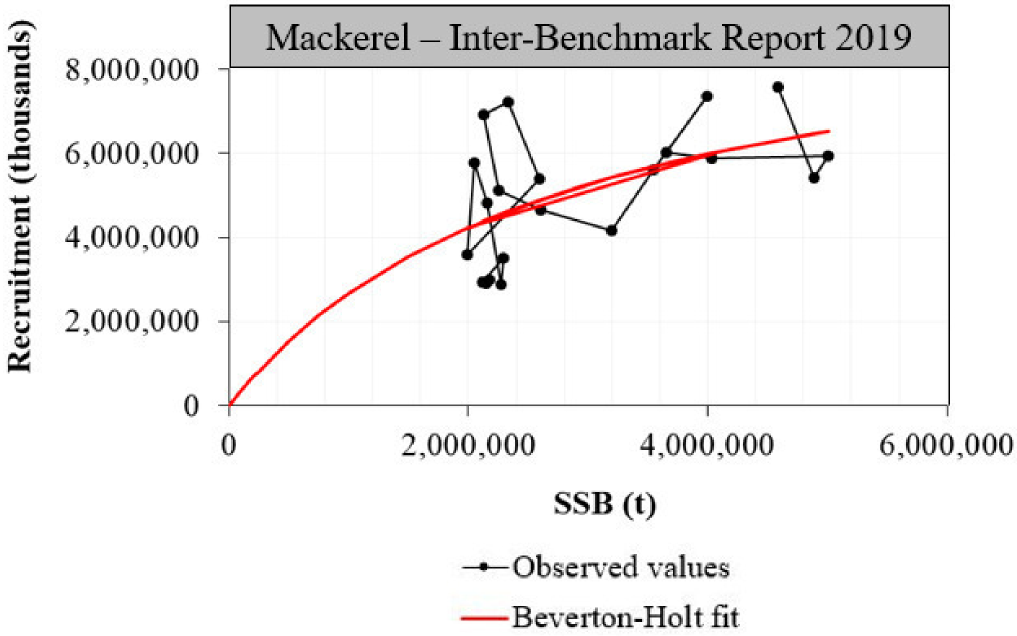


**Figure S.4**. The self-estimated Beverton-Holt stock-recruitment relationship of NEAM. Black points represent observations from the Inter-Benchmark report 2019 (ICES, 2019). The red line represents the corresponding predicted recruitment, which was estimated by using the solver function in Excel.

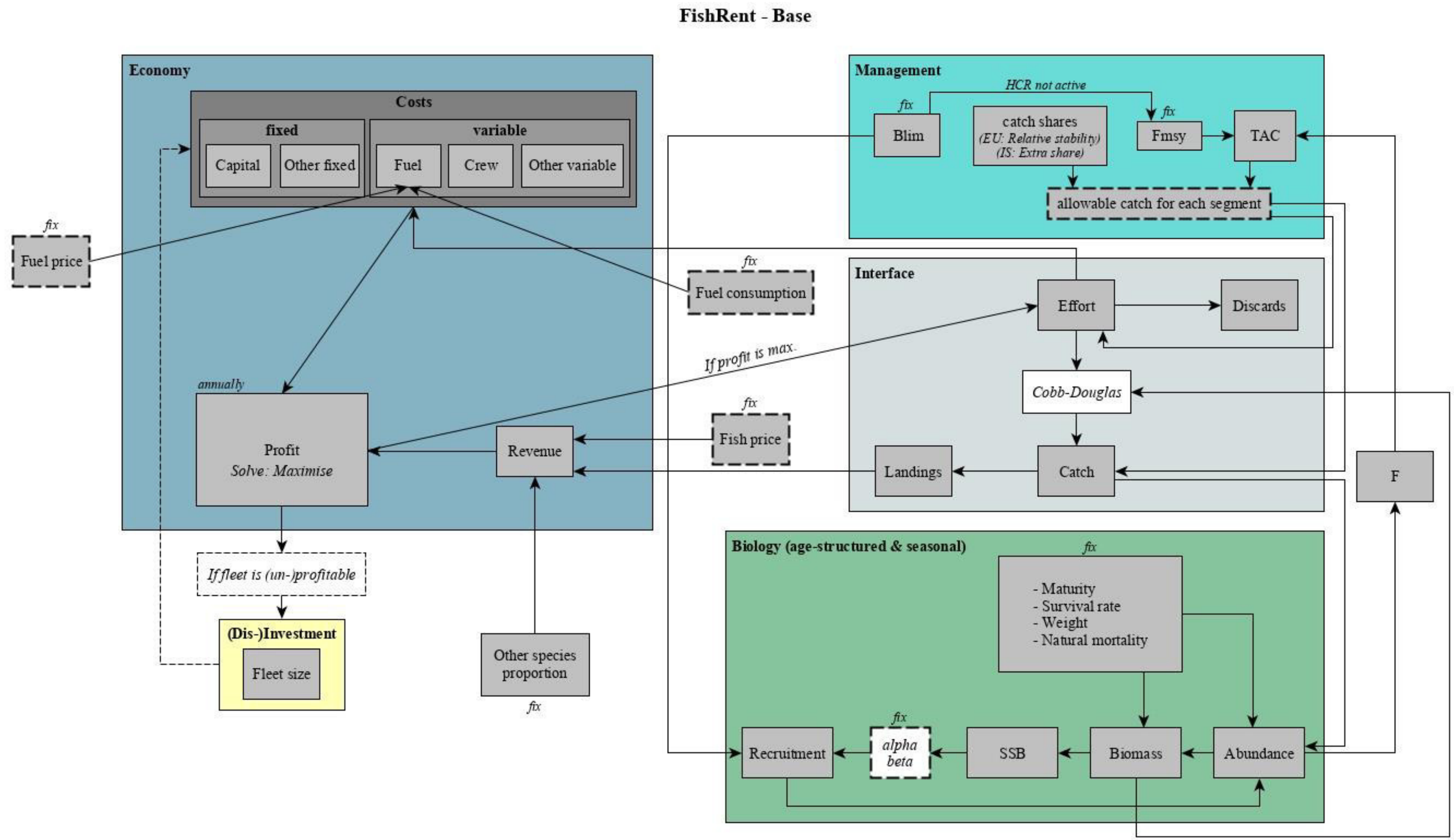


**Figure S.2.** Schematic of the model process and the interaction between different sub-modules in FishRent. The effort is calculated until the maximum profit for all modelled fleet segments is estimated. This, in turn, is used to calculate the catch by using the Cobb-Douglas production function, which has then an impact on the abundance, fishing mortality (F), SSB and recruitment calculation for the next time step.

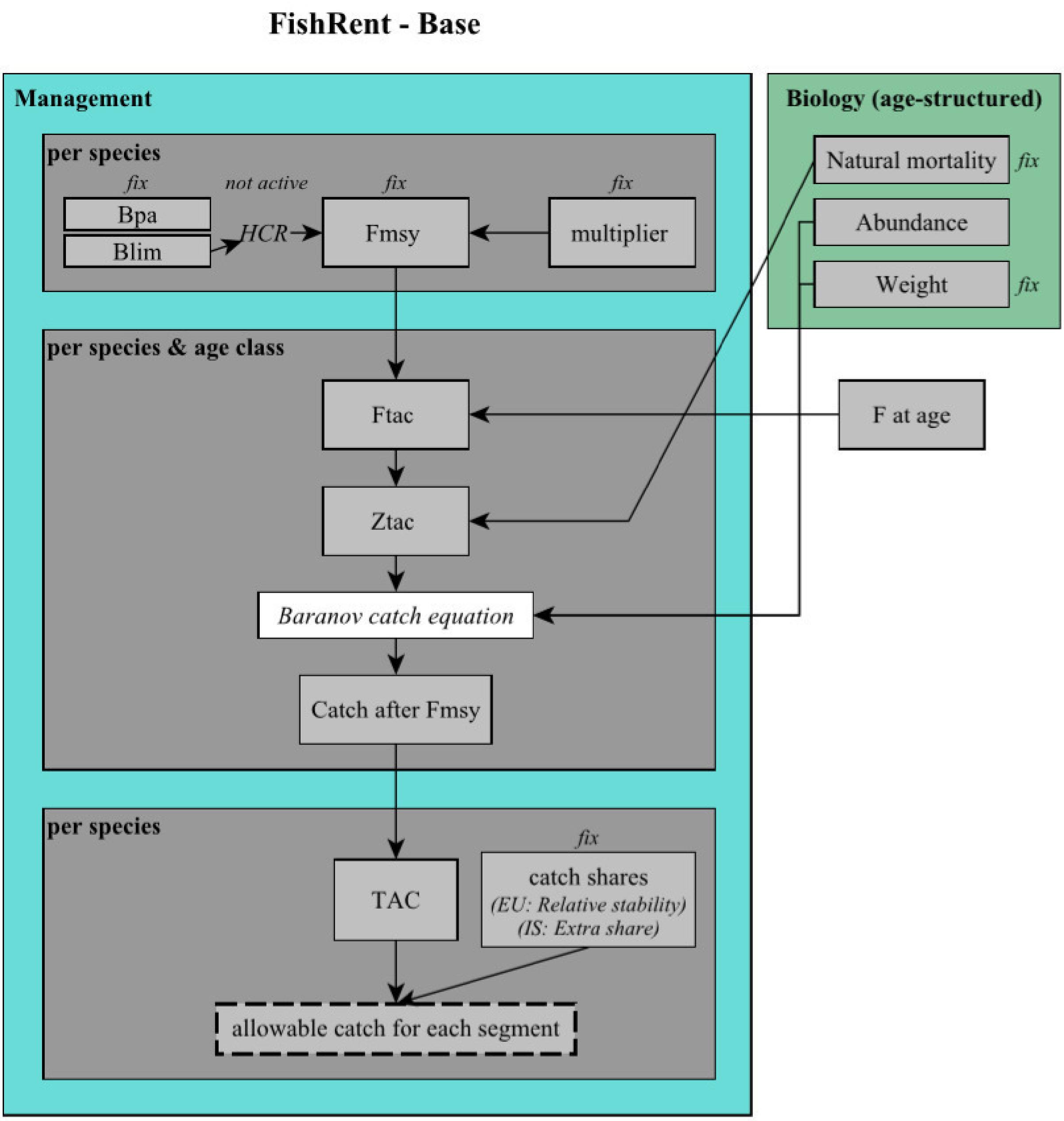


**Figure S.3.** Detailed schematic of the management module in FishRent. Note: No harvest control rule (HCR) is currently active for NEAM. A multiplier has been used on $F_{msy}$ in order to keep the level of fishing from the last years as, for example, in the case of mackerel no unilaterally agreed TAC exists and F has been and still is much higher than $F_{MSY}$ for at least the last 10 years.

## S.4. Additional results (more details)

### S.4.1. Dynamic migration

If

$SSB_t >= 2 * B_{MSY}$ $\quad fmc1_{kf,kt,i,t} = sum_{bf=1}[fmc_{kf,kt,i,t,bf}]$ (9a)

Elseif

$SSB_t >= 1.8 * B_{MSY}$ $\quad fmc1_{kf,kt,i,t} = sum_{bf=2}[fmc_{kf,kt,i,t,bf}]$ (9b)

Elseif

$SSB_t >= 1.68 * B_{MSY}$ $\quad fmc1_{kf,kt,i,t} = sum_{bf=3}[fmc_{kf,kt,i,t,bf}]$ (9c)

Elseif

$SSB_t >= 1.4 * B_{MSY}$ $\quad fmc1_{kf,kt,i,t} = sum_{bf=4}[fmc_{kf,kt,i,t,bf}]$ (9d)

Else $\quad fmc1_{kf,kt,i,t} = sum_{bf=5}[fmc_{kf,kt,i,t,bf}]$ (9e)

where *SSB* is the new spawning stock biomass at time *t*, $B_{MSY}$ is the precautionary biomass level, $fmc_{kf,kt,i,t,bf}$ is the migration matrix including all information about the NEAM position and has to be previously defined by the model user and $fmc1_{kf,kt,i,t,bf}$ is the new migration matrix, where *kf* (from) and *kt* (to) define the direction of movement between areas. The proportion of migrating fish has to be previously set by the model user and can vary between zero (no presence in a certain area) and one (100% presence). Part 9a of the equation represents an expansion (SSB >5,000 ktons), part 9b the current distribution (SSB 4,500 – 5,000 ktons), parts 9c-e a retreat (<4,500 ktons). Finally, the number of individuals are distributed via the corresponding new migration matrix.

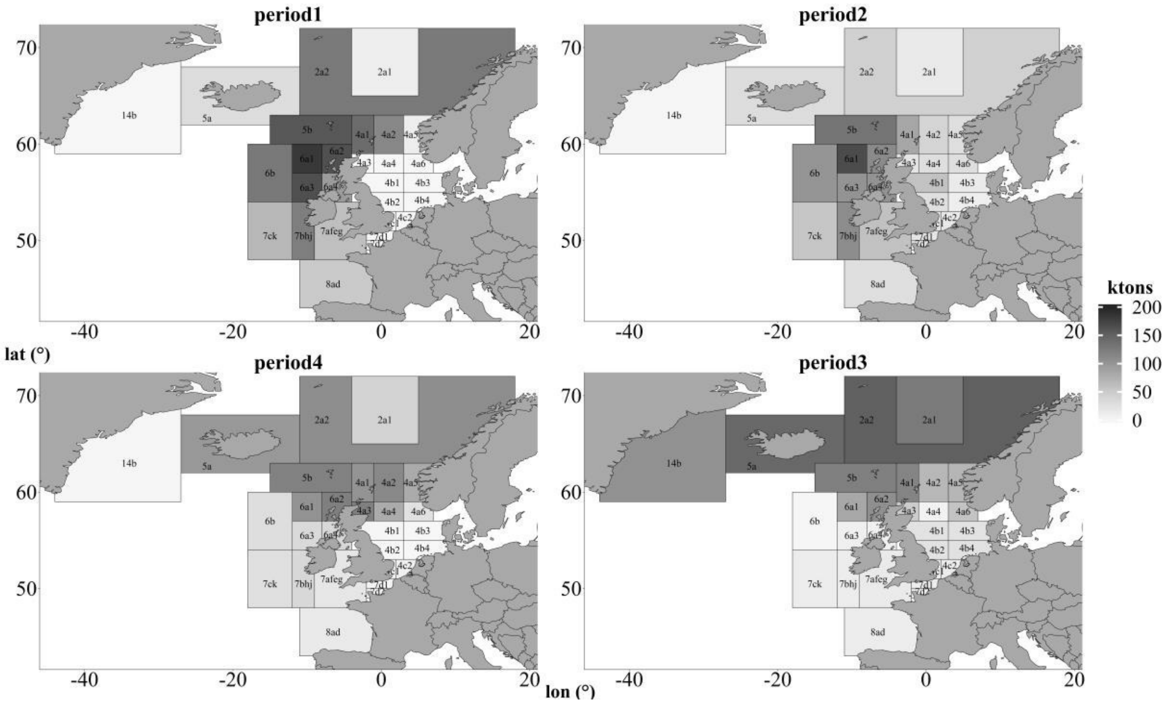


**Figure S.4.** NEAM total stock biomass distribution in each season in case of an expansion if equation 9a is valid.

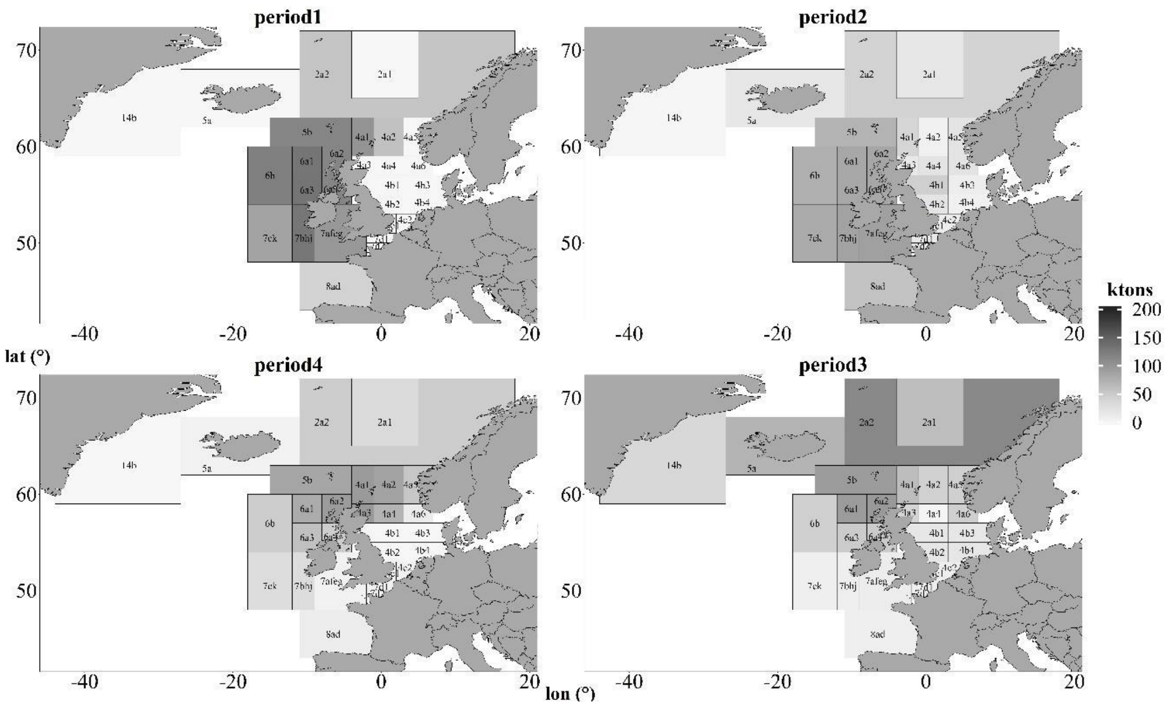


**Figure S.5.** Current NEAM total stock biomass distribution in each season (Eq. S.9b).

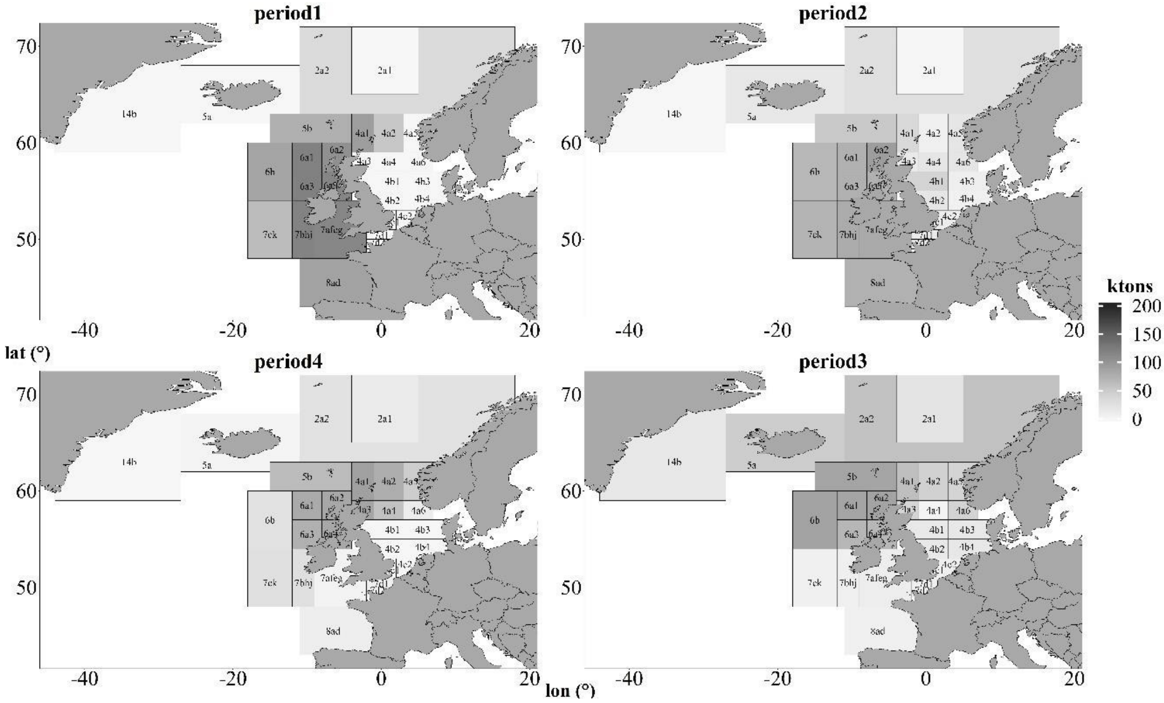


**Figure S.6.** NEAM total stock biomass distribution in each season with a retreat towards historic core areas (Eq. S.9c).

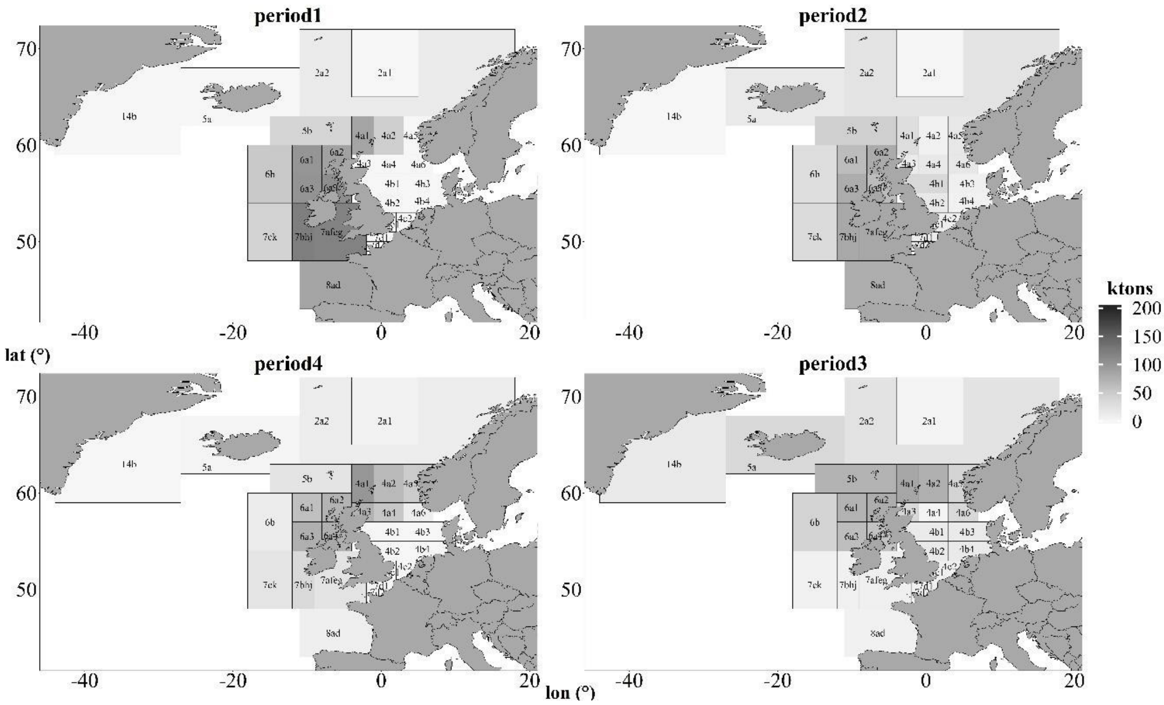


**Figure S.7.** NEAM total stock biomass distribution in each season with a further retreat towards historic core areas (Eq. S.9d).

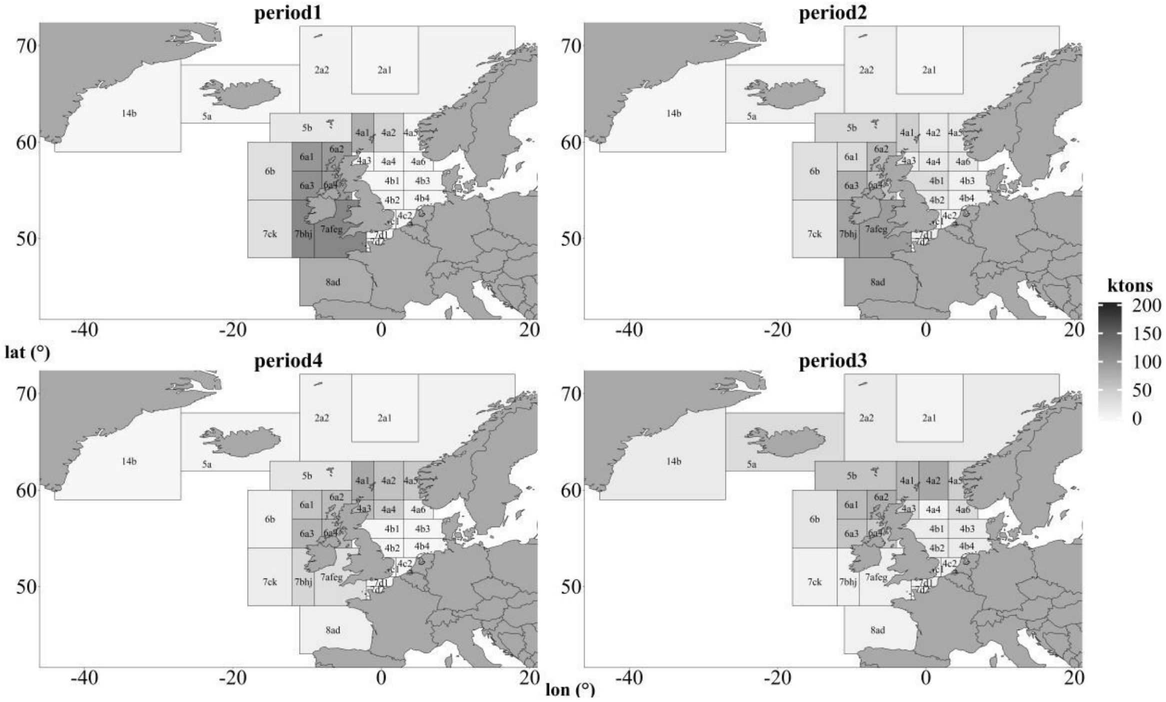


**Figure S.8.** NEAM total stock biomass distribution in each season with the most extreme retreat towards historic core areas (Eq. S.9e).

## S.4.2. Catch per season and segment for each TAC level

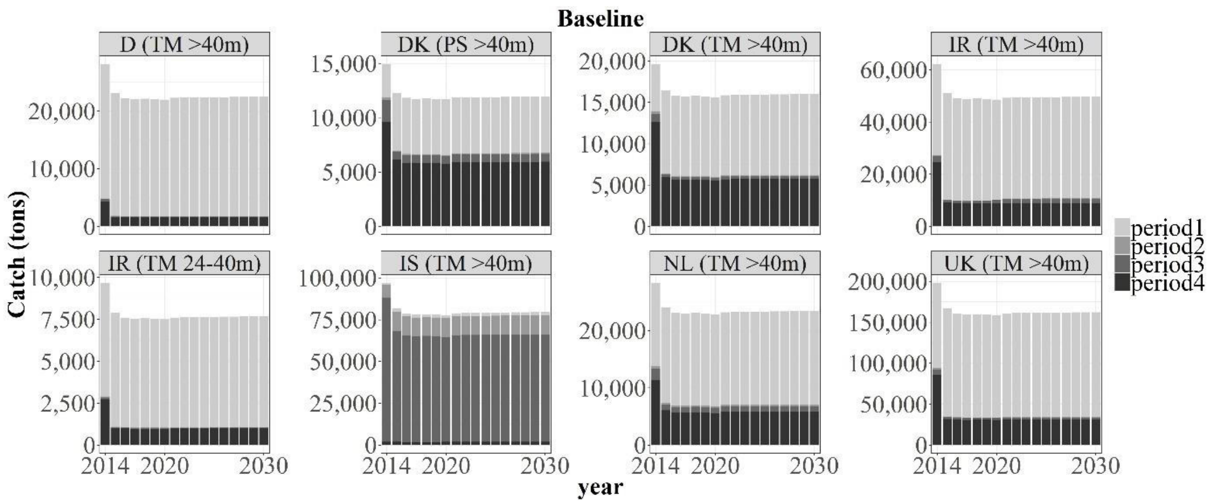


**Figure S.9.** Catch (tons) of the eight different fleets in each season (period) over time of scenario three with a dynamic TAC. Light grey (top) represents season one, medium grey is for season two, dark grey for season three and black (bottom) for season four.

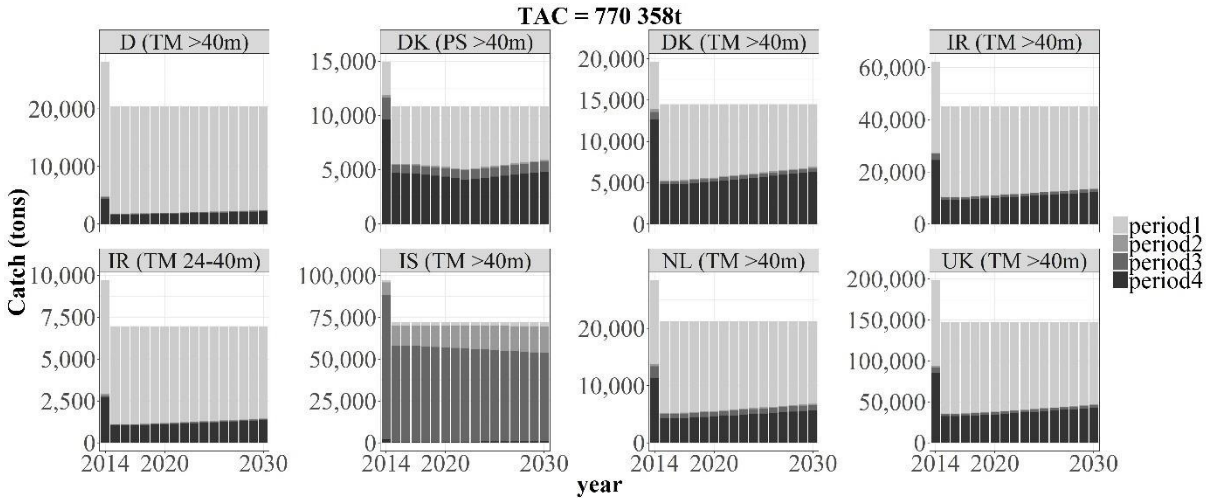


**Figure S.10.** Catch (tons) of the eight different fleets in each season (period) over time of scenario three with a TAC level of 770,358t. Light grey (top) represents season one, medium grey is for season two, dark grey for season three and black (bottom) for season four.

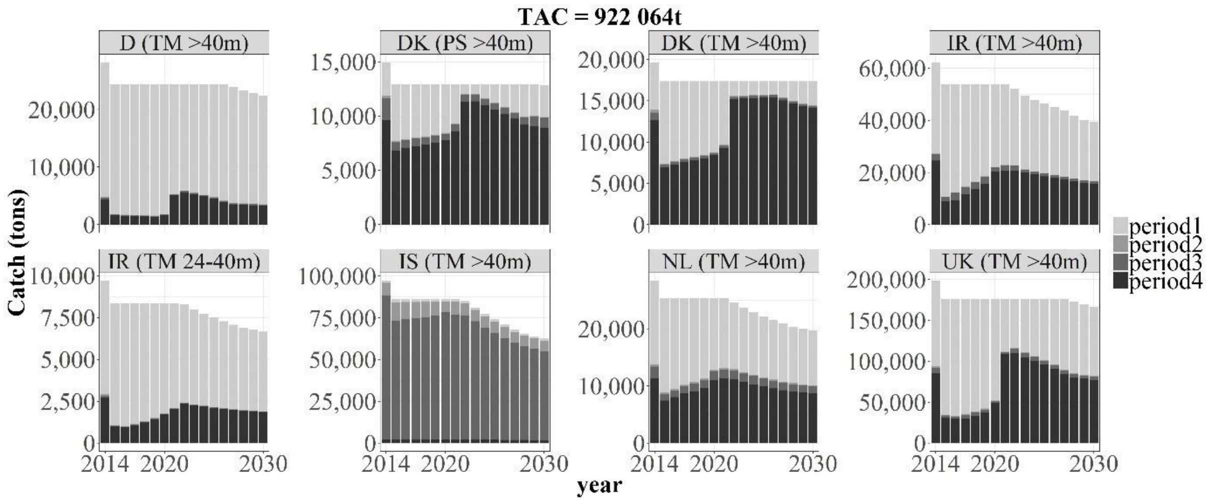


**Figure S.11.** Catch (tons) of the eight different fleets in each season (period) over time of scenario three with a TAC level of 922,064t. Light grey (top) represents season one, medium grey is for season two, dark grey for season three and black (bottom) for season four.

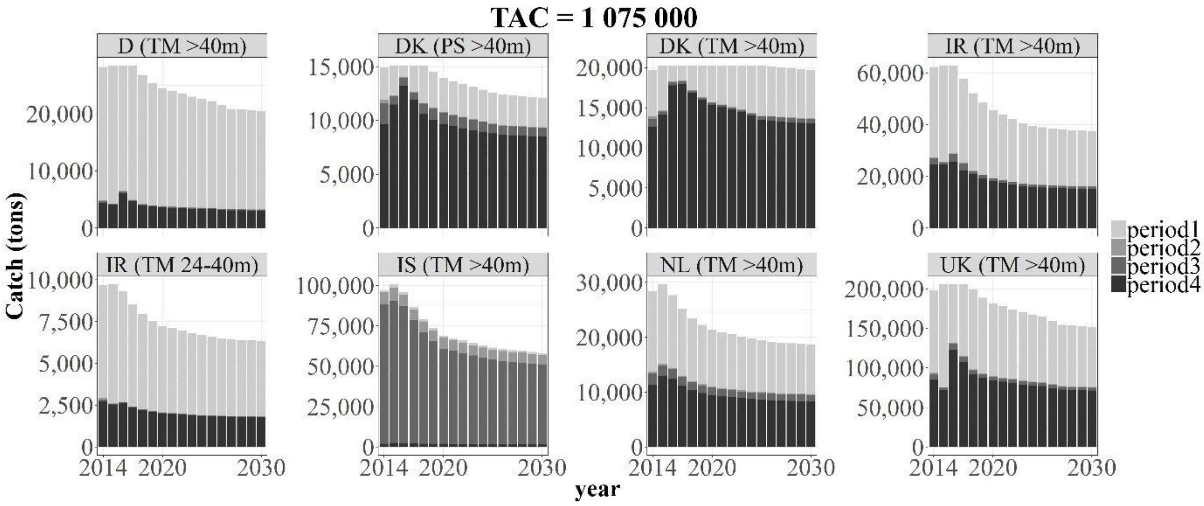


**Figure S.12.** Catch (tons) of the eight different fleets in each season (period) over time of scenario three with a TAC level of 1,075,000t. Light grey (top) represents season one, medium grey is for season two, dark grey for season three and black (bottom) for season four.

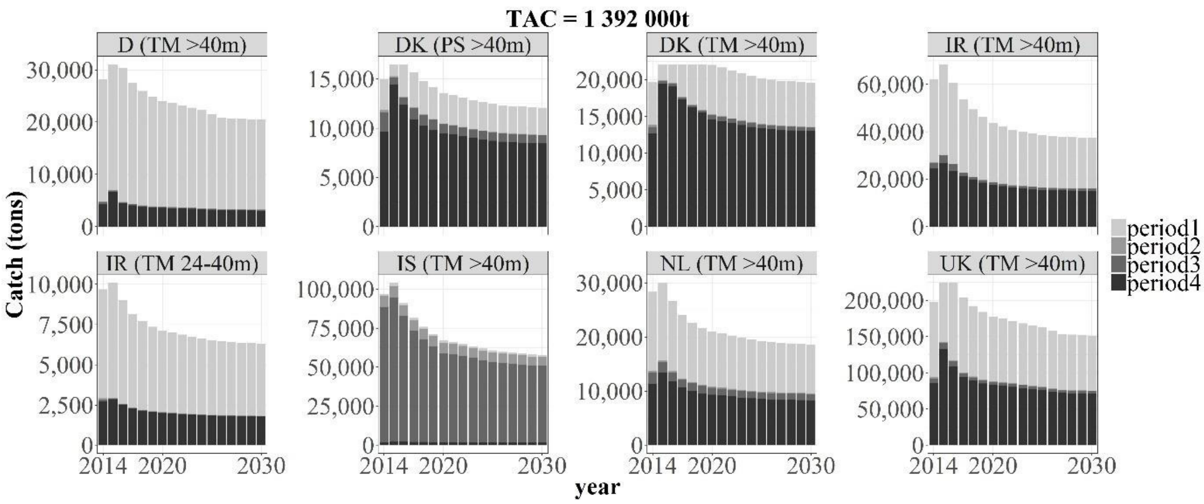


**Figure S.13.** Catch (tons) of the eight different fleets in each season (period) over time of scenario three with a TAC level of 1,392,000t. Light grey (top) represents season one, medium grey is for season two, dark grey for season three and black (bottom) for season four.

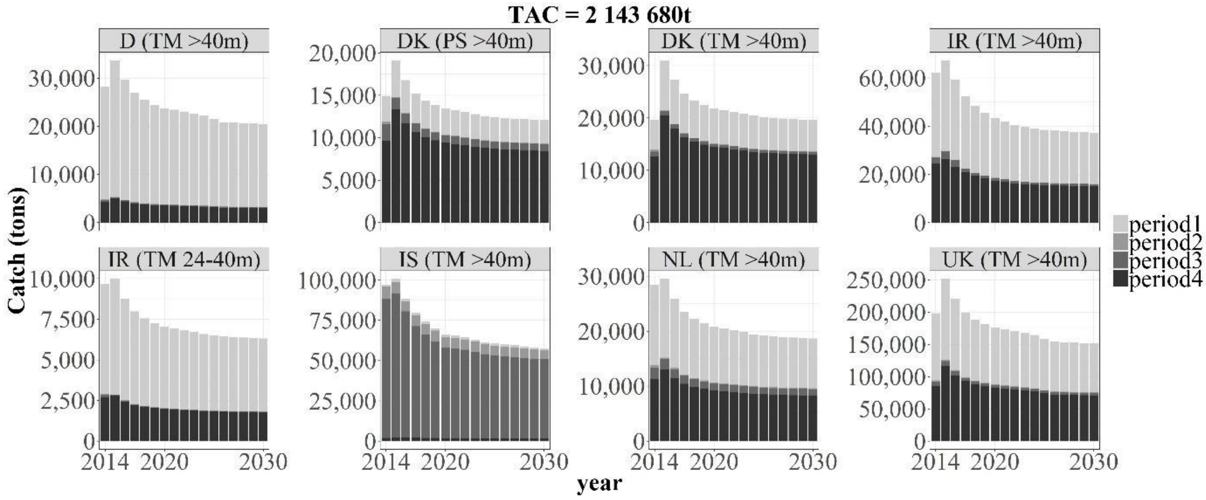


**Figure S.14.** Catch (tons) of the eight different fleets in each season (period) over time of scenario three with a TAC level of 2,143,680t. Light grey (top) represents season one, medium grey is for season two, dark grey for season three and black (bottom) for season four.

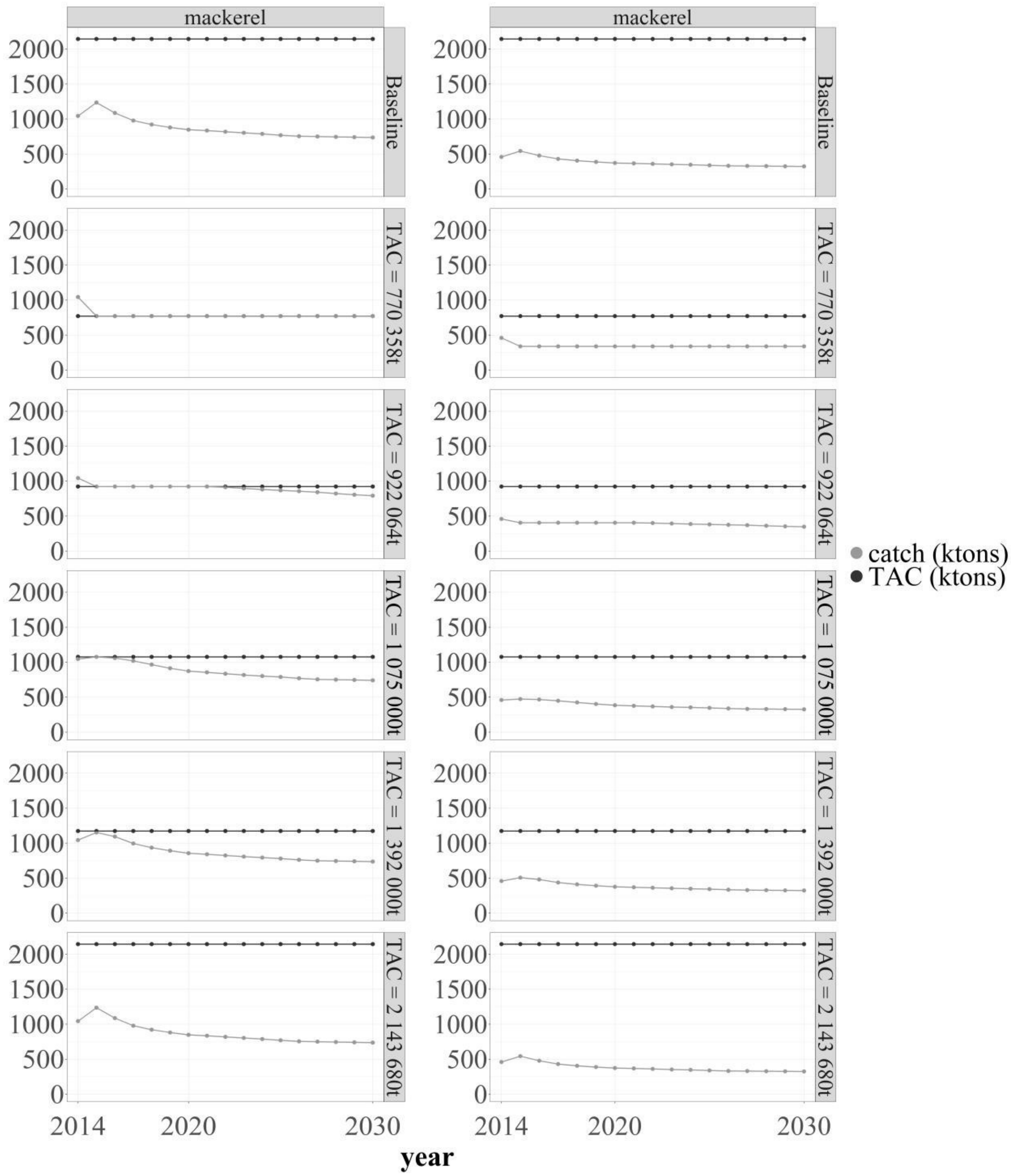


**Figure S.15.** Total catch (ktons, left) and catch of modelled segments (ktons, right) targeting NEAM versus TAC of each scenario from 2014 to 2030.

**References**

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ICES (2019). Norway special request for revised 2019 advice on mackerel (*Scomber scombrus*) in subareas 1-8 and 14, and in Division 9.1 (the Northeast Atlantic and adjacent waters). *In* Report of the ICES Advisory Committee, 2019. ICES Advice 2019, sr.2019.09.

## GENERAL DISCUSSION

This thesis illustrates the economic structure of eight fleets targeting NEA mackerel and NSAS herring. Further, the influences of changing environmental, economic and political situations on the highly valuable NEA mackerel and NSAS herring stocks as well as the corresponding fishery are demonstrated. For this purpose, the bio-economic simulation and optimization model FishRent was adapted from a demersal fishery to a pelagic fishery, in the first instance on a temporal scale. It was important to engage with the corresponding fishery and adapt the model accordingly, as mixed, demersal fisheries function differently from pelagic fisheries in terms of effort and catchability. Demersal fisheries use different gear types, which are often in contact with the ocean floor, therefore increasing effort and fuel costs with higher friction (Parker and Tyedmers, 2015). Compared to other fishing techniques, pelagic trawlers and, especially, purse seiners are thought to be most efficient, using the least effort for a very large amount of catch (Parker and Tyedmers, 2015). Moreover, there is a difference in the discarding of unwanted fish. The discard-ban plays an important role for the mixed, demersal fisheries, since many demersal species share the same habitat and the gears are not able to catch completely selectively (Simons et al., 2014). Under the discard-ban, species with low-quotas can become so-called choke-species, limiting the vessels to continue fishing for other species with a higher quota (Simons et al., 2014). In the pelagic fisheries, this is not of major concern as they target large schools of fish, which rarely mix with others, and are operated as a single fishery separated by seasons and major fishing grounds.

By using the temporal model version, effects of changes in recruitment, the quota repartition key as well as fish and fuel prices were tested. The temporal version was then further developed, adding a spatial component. The necessary degree of spatial complexity in order to incorporate seasonal migration patterns and area closures was then determined. Finally, dynamic seasonal migration patterns, that alter the spatial distribution of biomass depending on total biomass level, were introduced and different TACs were employed to evaluate the effects on the stock biomass and simulated fleet behaviour.

### Economic implications for the fleets

*Price alterations* – Two current situations illustrate the urgency to determine the resilience and sensibility of fleets regarding price shocks, which was tested in Chapter 1. The first situation is the case of the Atlanto Scandian herring stock: Due to the currently overfished stock, the corresponding fishery will probably soon lose its MSC certification. Similar to what occurred in case of NEA mackerel, major fishing nations (Norway, Iceland, EU, UK, Greenland and Russia) could not reach a TAC agreement yet and continue to unilaterally set their quotas (Evans, 2020). On the German market, the request for MSC certified products by retailers is increasing. The NSAS herring stock is currently still certified by MSC (2020), although this might also change according to results from Chapter 1 and 2, in which stock biomass was simulated to continually decrease from 3,000ktons to 2,500ktons over a time frame of 16 years. With the Atlanto Scandian herring fishery losing its certification, the demand for still certified NSAS herring products will therefore increase massively, also raising the fish price. At the same time, the quota for western Baltic Sea herring was decreased by 50% for 2021 (ICES, 2020a). This significantly reduces the available fishing opportunities on herring further, especially for the German fleet, presumably also increasing the pressure on the NSAS herring population.

The second current situation is the Covid-19 outbreak at the beginning of 2020: Due to the closure of restaurants and bars, price shocks (significantly lower prices) and sales issues could be observed on the fresh fish market worldwide (unpublished results from the Thünen-Institute of Sea Fisheries). This will have mainly affected the UK, Danish, Icelandic and Irish fleets as those are the ones selling fresh herring, mackerel and other pelagic species for first sale. The Dutch and German fleets freeze directly on board, but due to a temporary ban on imports due to the Covid-19 pandemic the largescale fishery could not export their products to Asia and Africa anymore, which represent the most important markets. This pushed the price down and until now, the level before the pandemic could not be reached again (unpublished results from the Thünen-Institute of Sea Fisheries). Besides, the processing industries increased technical automatism (hand processing with machine processing) in order to reduce human interactions, hence decreasing the risk of disease transmission. Another effect of the Covid-19 outbreak is an increased demand in canned and other preserved fish products (unpublished results from the Thünen-Institute of Sea Fisheries), which might turn out to be particularly beneficial for the Dutch and German freezer-trawler fleets. Moreover, these two fleets mostly continued to operate throughout the pandemic closure (stakeholder information). As shown in Chapter 1, all fleets selling fresh fish on first sale were also the ones most affected when experiencing a fish price shock. Especially the large-scale Irish fleet was significantly impaired, whereas the freezer-trawler fleets (Dutch and German) were least affected.

Similarly, Saudi Arabia flooded the market with oil in March 2020, after the World Health Organization (WHO) reported the first cases of Covid-19 and due to a significant decrease in the global oil demand (Albulescu, 2020). This lead to an oil price drop of more than 20% from one day to another and lies within the same range applied in Chapter 1, which also illustrated the effects of sudden oil price shocks on fleet profitability. These results show that the German and again large-scale Irish fleets would be most significantly affected. Fuel costs have a major effect on the fleet behaviour and effort decisions by the fleets as also shown by Simons et al. (2014). Therefore, results of this thesis indicate that the consequences of the pandemic on the oil price combined with a crude oil ban, which is expected to raise fuel costs by up to 30% (stakeholder information), might cause severe problems for the fleets.

**Implications for management**

*Relative Stability* – Many changes, such as in stock productivity, new fishing strategies, changes in demand and the evolution of fleets, have occurred before causing troubles and dissatisfaction amongst the states targeting shared, straddling stocks in the NEA (Bjørndal and Munro, 2020). This dissatisfaction already developed with the introduction of the Common Fisheries Policy (CFP), which is one of the reasons why the UK fishing industry highly supported an exit from the EU. From their perspective, the share they received when introducing the relative stability principle was too small (Cardwell, 2014). Other major points for criticism of the CFP are the fostering of a static, inflexible and conservative management approach of yet highly diverse and dynamic resources (Phillipson and Symes, 2018). Coping with changes became difficult and made the fishing industry less resilient to those changes (Phillipson and Symes, 2018). Additionally, the increased usage of quota swaps as well as the NEA mackerel dispute are yet other examples of economic interests not being entirely met by the current management approaches (Hoefnagel et al., 2015; Penas Lado, 2016; Sobrino and Sobrido, 2017). The importance of reconsidering the quota repartition key applied in the EU is also the most important lesson learned from Chapter 1. One scenario was to redistribute NEA mackerel and NSAS herring quotas according to current biomass proportion in each modelled fleets EEZ, which left the Dutch, German and Danish fleets without any quota really. In case of NEA mackerel and NSAS herring, this also illustrates the dependence on access to primarily the UKs and Irish EEZs as most of the biomass is situated in these EEZs. Hence, depending on how negotiations between the UK and the EU turn out in the Brexit debate and depending on the method used to adapt the quota repartition key, the pelagic German, Dutch and Danish fleets might have to switch to other fisheries. In preparations to Brexit, the German and Dutch fleets actually do already seek alternatives by expanding their fisheries in the Pacific as well as in western African waters, where they just renewed in an agreement with the Kingdom of Morocco to proceed fishing (stakeholder information).

*Distribution changes* - Political disputes concerning access to fishing grounds will probably increase in future, as other species might enter these fishing grounds after changing their range of distribution. One known example of a demersal species, known to have changed in distribution since 1997, is European hake (*Merluccius merluccius*; Staby et al., 2018). It covers most of the Northeastern Atlantic and is targeted by many European coastal states, becoming more and more frequent in the North Sea and western Scottish waters (ICES, 2016; Staby et al., 2018). As in the case of NEA mackerel, this expansion is thought to be density-dependent, i.e. a result of an increase in stock size with high recruitment over several years and low juvenile fish mortality (Staby et al., 2018), as well as related to warming sea temperatures (Baudron and Fernandes, 2015). Similar to other species, the stock was overexploited during the 1990s, reaching the historic low point in 1998 (ICES, 2012). In 2001, a recovery plan was introduced and since 2004, the hake SSB has increased (ICES, 2012). A problem occurring with such a high hake SSB is the so-called “choke species” concept, i.e. a low quota species that limits the catch of other high quota species in a mixed fishery due to the implementation of the discard ban (Baudron and Fernandes, 2015). As pelagic species are often caught in single fisheries that are relatively clean, this is not so much of an issue in the case of the NSAS herring and NEA mackerel fishery.

Another example of a pelagic species is the one of Atlantic bluefin tuna (*Thunnus thynnus*), which occurs both to the western and eastern Atlantic Ocean and is known for its vast migrations between the northern Sahara, the Mediterranean and up to the Celtic Sea. After 1963, however, the northern European tuna fishery collapsed and since then the abundance in these waters is very low (Bennema, 2018). Recently, an expansion of their feeding grounds towards northern Atlantic waters (up to east Greenland) could be noticed. Similar to the expansion of NEA mackerel, the bluefin tuna expansion is attributed to rising seawater temperatures possibly related to the North Atlantic Oscillation (Fromentin et al., 2014; MacKenzie et al., 2014; Faillettaz et al., 2020). Historic data suggests a previous occurrence of Atlantic bluefin tuna in the North Sea and that a fishery already took place before ICES records in 1927 (Enghoff et al., 2007; Bennema, 2018). Until now, the European quota for bluefin tuna is mainly divided between France, Spain, Greece, Portugal, Croatia, Italy, Malta and Cyprus (EC, 2018), but northern countries may start to reclaim their fishing rights in future, similar to the NEA mackerel conflict. However, the currently observed changes in species distributions acted somehow as the straw that broke the camel's back, causing increased discussions regarding access rights in the NEA.

This was also dealt with in Chapter 3, in which migration dynamics dependent on SSB levels have been coupled with variations in TACs. The results illustrates the impacts of different management possibilities on NEA mackerel biomass level, with a) no reached agreement (i.e. very high levels of TAC through setting unilateral quotas), b) continue with business as usual, or c) an agreement where the MSY approach is followed as advised by ICES. This, in turn, defines the spread of the biomass (expansion or retreat). Under the current circumstances, Chapter 3 shows that a continued biomass decrease combined with a retreat to its core areas is most likely to occur if the TAC is not decreased considerably. On the long-term, with a TAC of 1,075,000t or more this means that the biomass is at a level at which it is not profitable anymore for any fleet to fish out the whole quota. If the stock dynamics are indeed caused by density mechanisms, as assumed in Chapter 3, Hannesson (2013) suggests that the major fishing nations (EU/Norway) might be able to prevent migrations into minor player's EEZs by carefully selecting a high enough fishing pressure and therefore exclude them from the fishery. This would likely cause an escalation of the conflict, as the NEA mackerel fishery has now become a very important part of the Icelandic fishing industry (see also General Introduction). As described and illustrated through a game-theoretic approach by Hannesson (2013) and Bjørndal and Munro (2020), the EU and Norway oppose the unilateral mackerel quota setting by Iceland and the Faroe Islands and might even try to strategically prevent NEA mackerel migrations from accessing the Icelandic EEZ through directed overfishing of the stock. This would only work if the stock expansion is indeed caused by density dependent mechanisms, which is not completely known but it is what could be observed by many studies (e.g. Astthorsson et al., 2012; Berge et al., 2014). As Norway is another important player, it would have been interesting to include the Norwegian fleet particularly when considering Chapter 3, but this was unfortunately not possible (to be further discussed later).

Another management objective could be to reach an agreement and start following the ICES advice in order to keep the resource at a higher biomass level. The study conducted in Chapter 3 showed, that this would be possible with a TAC reduction to at least 800,000ktons, which was also recommended by the latest ICES Advice (ICES, 2020b). In this study, a slightly lower TAC (770,358ktons) would even cause an increase of biomass as well as an expansion to the north-western Atlantic and would primarily benefit the UK and Irish fleets as Chapter 3 illustrated. However, all fleets would stay profitable in general.

*Recruitment and spawning ground closure* – Another major problem that was considered in Chapter 1 was the ongoing low NSAS herring recruitment, despite high biomass levels. In general, the study illustrates that the NSAS herring biomass is going to decrease further. On the long-term, this is going to be problematic for the fleets owning a large NSAS herring quota (i.e. the Netherlands, Denmark and Germany), as they all became up to 40% less profitable than they currently are. If a further reduction in recruitment was assumed those fleets would be even less profitable in future. Such a scenario is actually not far-fetched as current studies of the European Horizon 2020 project CERES show: On the long-term, the habitat suitability for NSAS herring will be reduced in the whole North Sea area with a possible increase in water temperature. This also increases larvae mortality (Fässler et al., 2011; CERES D2.3, 2019). Therefore, one management measure that was tested in Chapter 2, was to decrease the pressure on the NSAS herring stock, by closing the core spawning areas along the east coast of the UK. Unfortunately, this did not generate the desired results and the effect on NSAS herring recruitment and biomass was relatively small. On the long-term, most fleets slightly increased their profits though, except for the Germany fleet. As already determined in Chapter 1, the reason is thought to lie in the small margin between total costs and revenue, which makes them very susceptible to any changes. The cause behind this is likely to be explained by costs/profit transfers within pan-European operating countries. The margin of the Dutch parent company, for example, is double as high as for the German subsidiary. Such transfers are unfortunately very hard to capture in a model and the simulated behaviour of the German fleet might therefore be on overestimation. In summary, findings of Chapter 2 suggest that implementing a NSAS herring spawning ground closure over a time-frame of 16 years might not be enough in order to sustain the current biomass level and protect the stock. Another possibility might therefore be the introduction of an MPA in the southeastern North Sea, where the nursery area of NSAS herring is situated (Corten, 2013b). Such a management measure would probably have more significant effects on the demersal fleets and would need to be tested with another model version (e.g. Barteling *et al.* 2015; Simons *et al.*, 2015), although one measure already introduced actually affected the pelagic sprat fishery. The so-called sprat box was a closed area for the pelagic sprat fishery in the southern North Sea (division 4.c), close to the Danish coast where a significant amount of herring by-catch occurred (ICES, 2020d). After an evaluation in 2017, however, ICES concluded that other management measures (e.g. max. amount of allowed juvenile herring bycatch) were sufficient to control herring by-catch, which lead to the removal of the sprat box (ICES, 2020d).

**Lessons learned: Limitations by underlying data**

*The input* - In this thesis, eight fleets from six different countries were included, not all belonging to the European Union. Gathering this data in the necessary detail was challenging, as no official database existed where data exchange between research institutions could be facilitated (Figure 1). It was possible to access spatial catch and effort data via the STECF website in 2017/2018, but the segmentation of the fleets was poor and corresponding economic data was only partly available. Since then, the STECF considerably improved the available data, but for this thesis each DCF partner had to be contacted separately. Moreover, accessible economic data provided by the STECF has to be clustered when a fleet consists of less than ten vessels, which is however mostly the case when working with large trawlers.

Data concerning the pelagic German fleet, which only consisted of four vessels between 2012 and 2014 and now further reduced its size to three, is not officially available. Hence, no absolute values could be shown and led to the results being only officially available as relative values (proportional change) or by clustering data with the Dutch fleet (vessels belong to the same company). Additionally, it is not possible to receive any logbook data directly due to data confidential issues, making the clarification of the data structure needed more complicated for both the data processor and user. Processing time was also an issue when trying to receive any data from the Faroe Islands, Greenland and Norway, which are important fishing nations especially when it comes to targeting NEA mackerel (Figure 1). Therefore, it was unfortunately not possible to include any of the named countries, although other fleets targeting NEA mackerel and NSAS herring are indirectly included as a fixed proportion in the modelled TAC calculations.

As to the Icelandic fleet, it was possible to receive detailed catch and effort data but not the necessary economic data. In order to be able to include the Icelandic fleet, we had to make a trade-off assuming a similar cost structure of the UK (>40m) and Icelandic fleet (Figure 1). Actually, investigations during Chapter 1 indicated a certain similarity as both fleets do mainly consist of RSW trawlers and fish under similar environmental conditions. Moreover, amongst NSAS herring and NEA mackerel, the UK fleet targets a higher quantity of the latter. It would be very interesting to receive the economic data of the Icelandic fleet under a future cooperation and compare scenario outcomes. This would provide further insights in how underlying data influence and increase/decrease uncertainty of model results.

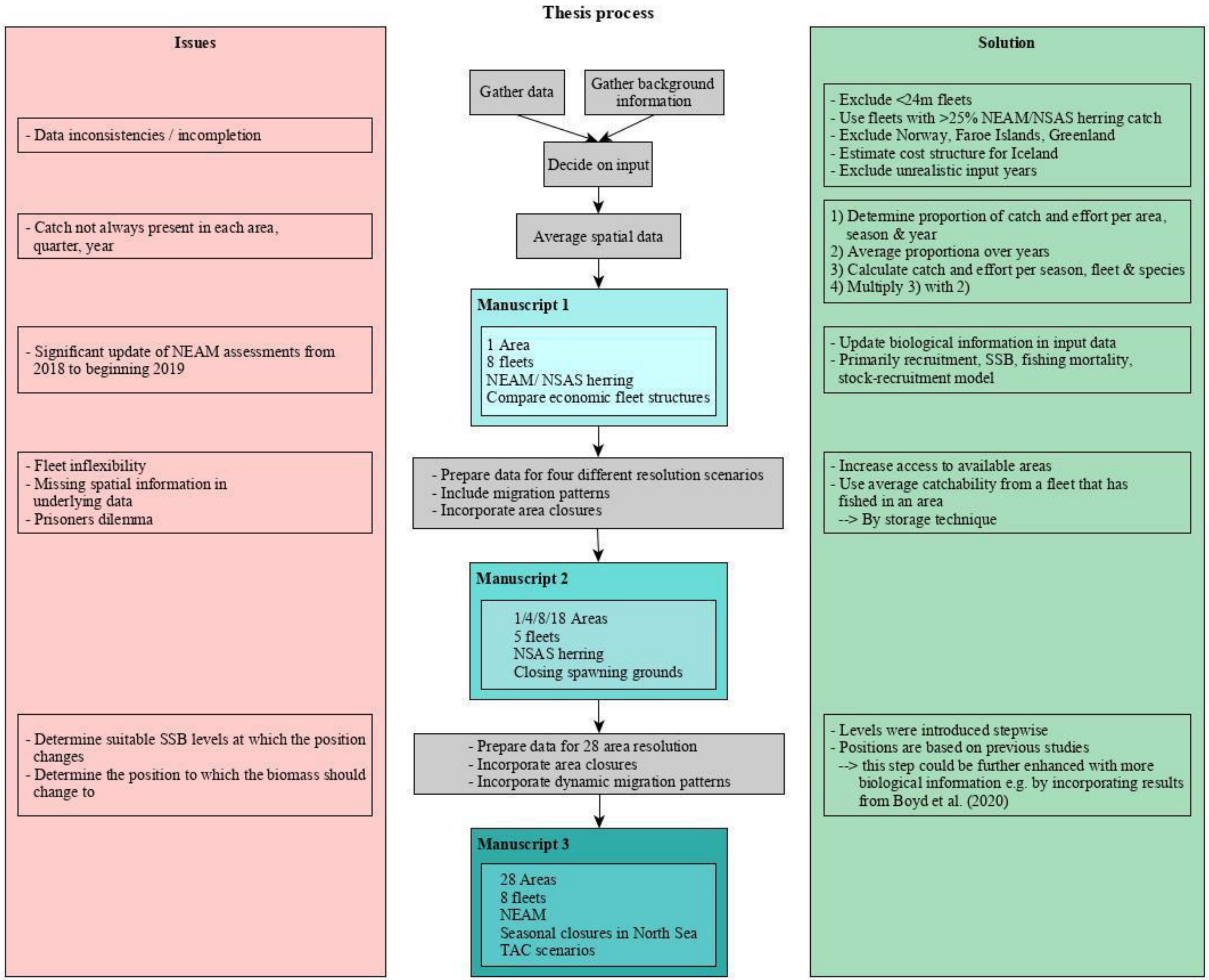


**Figure 1.** Schematic of the thesis process with the main problems and corresponding solutions that appeared throughout the studies.

Another point that should be mentioned is the fragmented data availability of <24m vessels. The initial thought of this thesis was to compare small-scale and large-scale fleets as well as their impacts on the NEA mackerel and/or NSAS herring stock. A common perspective is that the large-scale fleets have a stronger influence on the stocks than the smaller-scaled fleets, as they are thought to catch a much larger quantity. There are, however, cases where this assumption does not hold. In the Baltic Sea, for example, the recreational fishery caught almost the same amount of cod (*Gadus morhua*, 2,962t) as the commercial fishery (4,250t) in 2010 due to only being regulated by a minimum landing size (Strehlow et al., 2012). Consequently, a bag limit of five cod per day and two per day during spawning season was introduced in 2020 (EAA, 2019). The same could be observed in the eastern Australian region regarding pelagic species, e.g. spotted mackerel, suggesting that recreational fisheries significantly contribute to fishing mortality (Zischke et al., 2012). In the case of targeting NSAS herring and NEA mackerel, especially the UK and Irish fleets do consist of a high number of smaller scaled vessels mainly using other gear types in addition to pelagic trawls or purse seines, such as handlines (STECF, 2018/2019). The way they operate does significantly differ from large-scale vessels >24m in size and so does the cost structure, even resulting in much higher first sales prices linked to freshness and size grading (STECF, 2019). Moreover, small-scale fleets often do not have the same flexibility to adapt to changes as large-scale fleets, which are able to transfer costs as well as profits between subsidiaries as already mentioned therefore lowering taxes. After the economic crises for example, the small-scale fleet recovered on a much slower rate than the large-scale fleet (STECF, 2019). When it comes to area closures or large changes in migration patterns, small-scale fleets are also less capable to adjust and are hence more susceptible to such impacts, although an increase in vessel sizes and investments in new technologies could be observed (STECF, 2019). It would have been important to determine how these fleets would have to alter their behaviour under given scenarios. Due to many inconsistencies and incompletion of the underlying data, which could also not be cleared in aid of corresponding DCF partners the small-scaled fleets were, however, not included in the analysis (Figure 1). Even regarding the large-scale fleets trade-offs had to be made, i.a. the explained estimation for the Icelandic cost data, and not all three years (2012-2014) could be incorporated for each of the eight fleets. In case of the German fleet, for instance, years 2012 and 2013 were unprofitable, although this is highly unlikely as the subsidiaries belong to a large, pan-European operating company. The inclusion of these two years as a start value for the model would have led to an unrealistically bad performance of the German fleet during model runs. A reason for this seemingly bad fleet performance in 2012 and 2013 could not be determined when consolidating with the people in charge, which is why the year 2014 was finally used for a start value only. As discussed in Chapter 1, the pan-European company structure enables to a high degree of self-financing and cost as well as subsidiary profits to the parent company (Gelder and Spaargaren, 2011). This could be a reason for the observed bad fleet performance in 2012/2013 and was also thought to be a major reason for the relatively low margin between total costs and revenue compared to other fleets.

For the underlying biology input, data from the ICES (2018/2019) assessments were used in all three Chapters, although for Chapter 1 it was not spatially resolved. During Chapter 1, another Inter-Benchmark assessment for NEA mackerel was performed upon a request of Norway, as already explained in the Introduction. This was of major concern as the results were significantly different and influenced the simulated NEA mackerel stock biomass accordingly (Figure 1/2). SSB, for example, decreased from 4,200ktons in 2014 (the start year), to nearly 3,000ktons when using input data from the 2018 assessment whereas it only decreased until 4,000ktons under the Inter-Benchmark 2019 assessment (Figure 2; ICES, 2019a). The biological data for the model, primarily recruitment, SSB and fishing mortality, were therefore updated as well as the underlying stock-recruitment relationship and finally used in Chapter 1 and 3. The assessment that was published at the end of 2019, however, illustrated major differences again, being even more positive than at the beginning of 2019 and possibly significantly affecting the results from model runs. Unfortunately, the effects of this change could not be included into this study anymore. Yet, during the process of the 2020 assessment, another update was made, suggesting more negative outcomes than from the late 2019 assessment (ICES, 2020b). The usage of the Inter-Benchmark assessment results from early 2019 therefore seem to be appropriate under the current circumstances, but this illustrates how alterations of the underlying data can significantly influence the results and projections of different scenarios to be tested. In this perspective, it is important to note that any scenarios and results of this study represent general trends and not absolute futures.

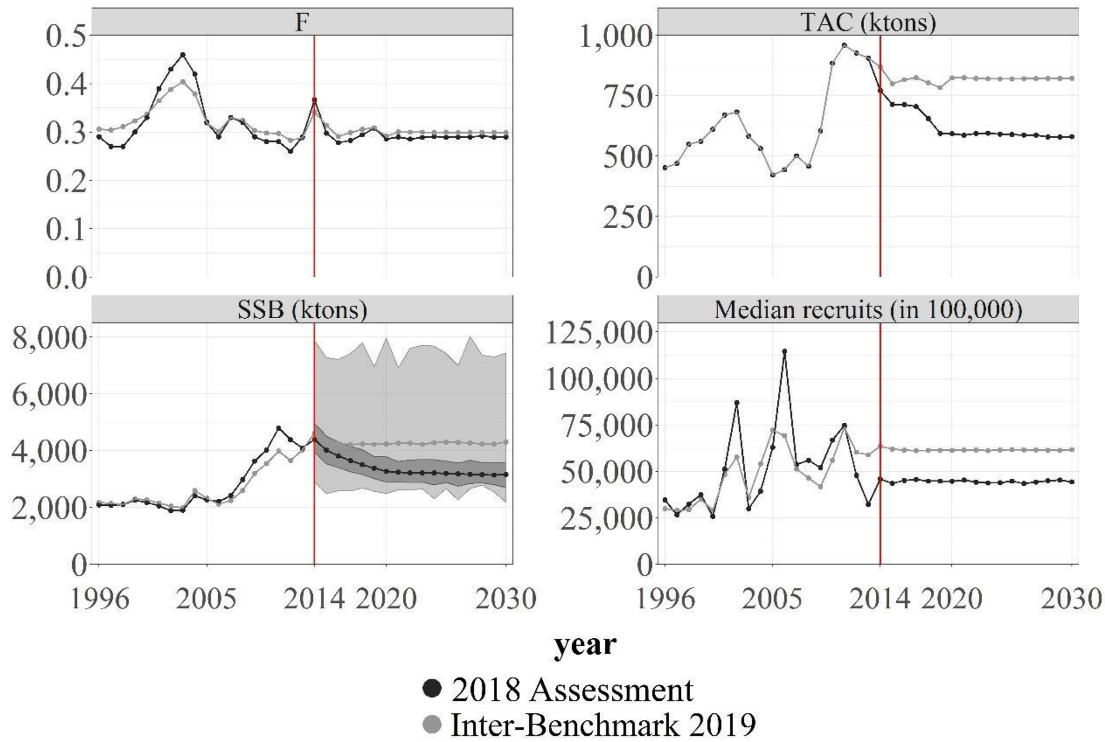


**Figure 2.** SSB (ktons), median recruits as well as TAC and fishing mortality (F) from the 2018 (black) and early 2019 (gray) assessment simulations for NEA mackerel. The Beverton-Holt SR relationship was used in both cases but with different parameters (2018: $\alpha_2$ = 35,272,845, $\beta_2$ = 193,772; early 2019: $\alpha_2$ = 10,269,723, $\beta_2$ = 2,854,680). SSB is shown with the 95% CI calculated from 1000 iterations; median recruitment is however shown without the corresponding CI. From 1996 to 2013, historic TAC, recruitment and F values were incorporated from the 2018 and the early 2019 assessment (ICES, 2018; ICES 2019a). Note: After 2010, TAC values for mackerel represent the sum of unilateral quotas as no international agreed quotas exist.

*Adding spatial explicitness* - In general, the data required for a temporal and spatio-temporal model differs greatly. With increasing spatial resolution, the data need raises substantially as does the uncertainty, which is one of the reasons why spatially and seasonally explicit models are often not used for assessment models yet (ICES, 2020c). For Chapter 1, yearly input data sufficed and might have reduced the effort for the DCF partners to extract it. With regard to the spatial adaptation of the temporal model in Chapter 2, a relatively high spatial resolution of the underlying catch/effort data was, however, necessary and was therefore obtained per ICES rectangle (90x90nm each). This is a typical resolution used, for instance, in surveys in the North Sea area (e.g. ICES, 2010). Consequently, the spatial data had to be aggregated and averaged for Chapter 1, considering that fleets do not fish in the same rectangles each year and season (Figure 1).

*Fleet inflexibility* - During the work for Chapter 2, another major observation was the inflexible behaviour of the fleets, i.e. the fleet behaviour was rather static staying relatively fixed in their traditional fishing grounds (Figure 1). This is due to being a pure spawning fishery with relatively static fishing grounds and times, onto which product quality is also highly dependent. The approach, that was used in Chapter 2 and 3, was therefore to increase the access to areas in which at least one fleet has fished in the underlying data. As only three years of input data were used, it is possible that area availability in the underlying data will be slightly larger when also considering other years. In this perspective, it would be interesting to update the underlying data with the latest data available and compare the effects of additional data points on area availability as well as fleet performance.

**Pelagic FishRent in comparison to other models**

*Spatial resolutions of FishRent* - In case of the NSAS herring stock and its fishery, findings from Chapter 2 suggest that the highest resolution available is not always of need but when considering seasonal effects in space, information are lost or averaged out when using a very low resolution. In this perspective, it is important to note that FishRent optimises in each area, hence computing space and time increases considerably with higher resolution also making it more difficult for the model to find an optimal solution. This would have been especially difficult for the analysis of Chapter 3, in which a large part of the NEA had to be included instead of the North Sea only. In another version of FishRent a maximum number of 152 ICES rectangles was used (Bartelings et al., 2015), whereas in Chapter 3 a resolution of 430 ICES rectangles would have been necessary (with a larger number of fleets and species this could be even more). Again, as the results of Chapter 2 showed, eighteen areas were sufficient to capture the major migration patterns of NSAS herring as well as seasonal effects in space. However, the NEA is four to five times larger than the Greater North Sea region and therefore Chapter 3 used 28 areas instead of 18. The amount of areas outside the North Sea region was primarily linked to the usage of ICES subareas, which was previously discussed with and favoured by stakeholders. This study shows that models do not always have to be very highly resolved. In the end, it depends on the question to be answered and the case study. Pelagic species cover a very large area, migrating large distances. Moreover, not many management measures, such as MPAs, exist regarding pelagic species and due to the low impact of the gears applied, the fishery is relatively “clean”. Pelagic fish live in schools throughout the water column and especially straddling stocks do not interfere much with spatial planning measures such as submarine cables, windmill parks or aquaculture sites (both relatively close to shore). In future, a problematic interaction regarding the NSAS herring fishery could emerge from an increasing amount of oil platforms along the Scottish east coast (Figure 3, top right with yellow dots), but until now no significant interactions have been reported (Marine Scotland, 2015).

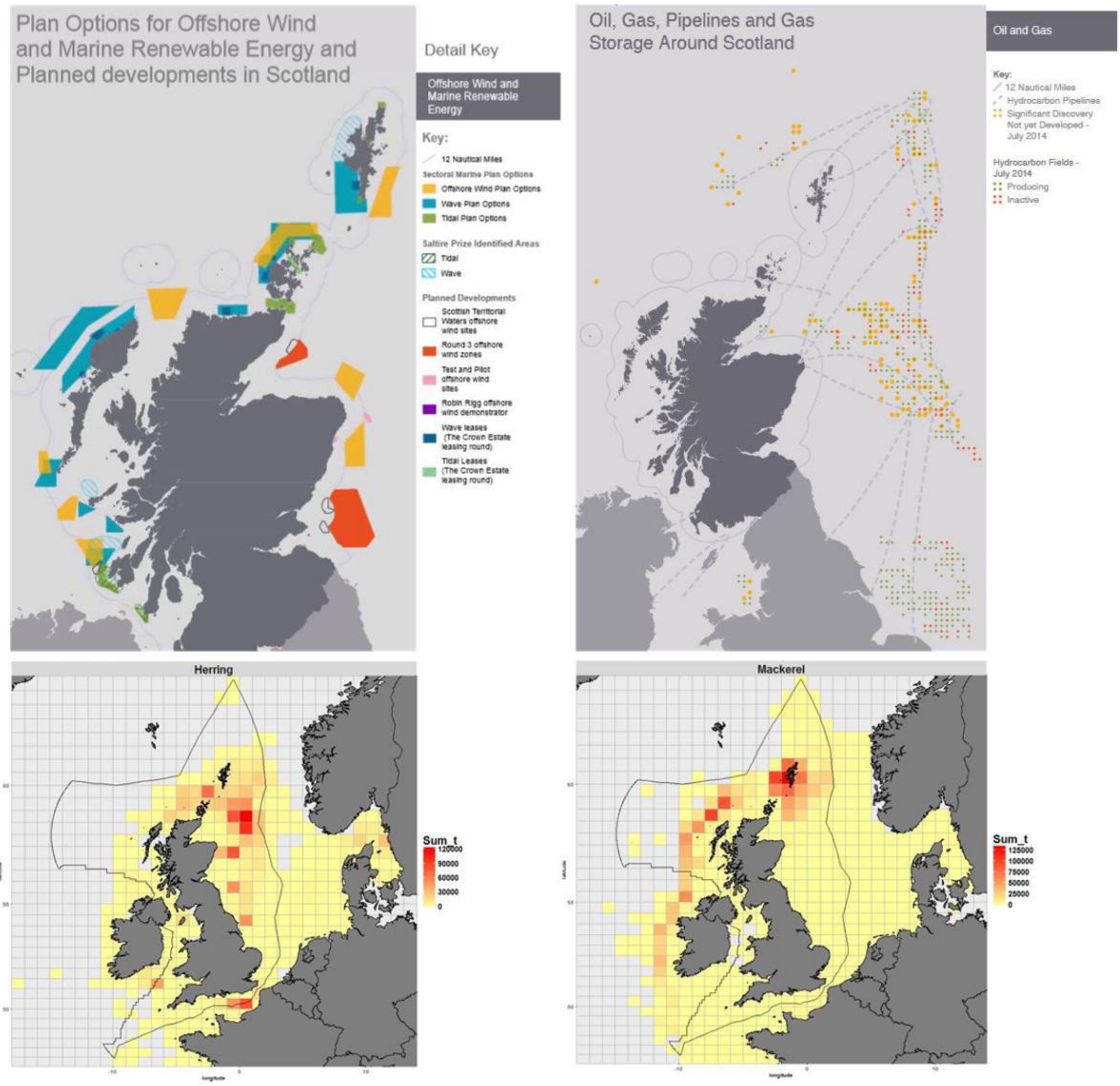


**Figure 3.** Scottish marine spatial plans for active (yellow) and planned (orange) offshore wind sites and other marine renewable energies (top left). Moreover, active (green) and planned (yellow) oil, gas, pipelines as well as gas storage sites (top right; Marine Scotland, 2015). In contrast to this are summed of EU fleet catch (tons) maps for herring (bottom left) and mackerel (bottom right) from 2011-2015 (Doering et al., 2017).

In general, most marine spatial management plans for which a relatively high-resolution mapping is usually needed, are relatively close to shore and occur to a large extend in the southern North Sea where the NEA mackerel and NSAS herring fisheries are not very active (EC, 2020). Other fisheries, for example targeting flatfish or demersal species, are much more impacted as the study from Bartelings et al. (2015) shows. They used a high-resolution version (ICES rectangles) of FishRent and applied area closure scenarios of windmill parks and nature conservation areas (Natura 2000) to the flatfish fishery targeting sole, plaice and shrimp in the southern North Sea. Profit generally decreased over time with those closures active although the impact was larger for flatfish than for shrimp (Bartelings et al., 2015). Similar to results from Chapter 2, biomass of flatfish was not projected to be significantly impacted over time. In their study, the resolution had to be relatively fine-scaled as the area closures where also on a small-scale level, in contrast to the closures implemented in Chapter 2 for NSAS herring.

*Game-theory* – Results from Chapter 2 illustrated that FishRent is not a well-suited tool for game-theoretic approaches, which use mathematic multiobjective optimisation models to estimate strategic interactions between rational decision-makers. The strategies in such a game-theoretic model can be cooperative or noncooperative (Matsumoto and Szidarovszky, 2016). FishRent, however, only considers a single objective function, i.e. net profit, always assuming an ideal cooperation between all fleets. This became apparent when trying to incorporate a Brexit scenario, i.e. closing the UK EEZ to all fleets but the British and the EU EEZs to the UK fleet. In general, a full closure could not be implemented because the model could not find an optimal solution for the fleets fishing primarily in the UK waters (i.e. the Dutch, German, Danish fleets), in which most of the NSAS herring biomass occurs and the traditional fishing grounds are situated. Another test was therefore to close the EEZs in different intensities. However, closing the UK EEZ for the EU fleets by 95% and vice versa, the EU EEZs for the UK fleets by 95%, the UK was tagged along with the other fleets in a so-called prisoner's dilemma. It is basically a discrepancy between the individual and collective rationale, where decisions that may seem rational from an individual's point of view may not seem rational from the entities point of view exposed to the same situation (Rapoport, 1989). Hence, all individual's decisions affect all participants. The UK would have been expected to perform exceptionally well within their own EEZ in contrast to the EU fleets, which were still mostly excluded from fishing in their traditional fishing grounds. Instead, the model let the UK fleet fish outside their own EEZ, the same as what the EU fleets had to do, and therefore significantly increased total effort in order to maximise the overall net profit of all fleets, but considerably decreased the profit of the UK fleet. As this is extremely unlikely to happen in reality, we finally decided to exclude this scenario from Chapter 2 (Figure 1).

*Fish quality and price* - In general, it would be important to include spatial information about fish quality when increasing area accessibility. As already mentioned in Chapter 2, this could be done by assigning fish prices to the different areas but also depends on what data is available. A common technique in economics to predict such prices is the usage of a hedonic model. In such a model, market goods are treated as individual goods, which cannot be separately sold on a market. Therefore, the contribution of each good to the whole price is estimated by using regression models (Guillen and Maynou, 2014; Austen et al., 2019). The whole price would be the fish price, but this in turn depends on other factors such as biomass availability and quality, weather conditions, fuel price, effort, gear type used, catch time, vessels sizes etc. These attributes vary in season as well as space and the aim of using a hedonic model would be to estimate the contribution and prices of each attribute, therefore finally estimating the fish price in each season and area. These prices can then also be altered during model runs and effects of changes in market trends can be estimated (e.g. in case of a change in demand for certain products that differ in quality).

*FLBEIA* - Another bio-economic simulation software increasingly used in the ICES context is currently "FLBEIA". It has been specifically built to evaluate management strategies under a Management Strategy Evaluation (MSE) approach, integrating fleet dynamics, stock assessment methods and harvest control rules (Garcia et al., 2017). The advantage is the usage of the freely available software R as well as FLR packages, which are commonly used. FishRent, on the other hand, is operated by using the General Algebraic Modelling System (GAMS) and uses another, rather circuitous coding system. FLBEIA works in two blocks: 1) The operating model (OM), which simulates fishery dynamics with biological population and fleet interactions, and 2) The management procedure (MP), which includes a link between 1) and 2) as well as the assessment procedure and management advice (Garcia et al., 2017). In the OM module, catch and effort data as well as age-structure biological information can be incorporated. Moreover, the same disinvestment module as applied in FishRent is available. Interestingly, prices are formed dynamically depending on fleet and stocks size. As already discussed in this thesis, prices in FishRent are yet fixed and the assessment module is rather simple, although harvest control rules can be incorporated where applicable (e.g. Simons et al., 2015). FishRent, on the other hand, incorporates detailed information about economic parameters (e.g. specific costs/profit) that influence fleet behaviour other than effort and biomass availability. Apparently covariates influencing, for example, (dis-)investment can be added to FLBEIA, but they do not seem to be essential or are assumed to be constant (e.g. Sánchez et al., 2019). Besides, FLBEIA operates seasonally but not spatially, hence increasing changes in spatial distribution also said to result from warming waters, effecting fleet decisions and again in-turn biomass levels, cannot be considered (Garcia et al., 2017; Sánchez et al., 2019). As Chapter 2 showed, however, a spatial resolution is necessary when trying to estimate and explain seasonal effects. Both methods have their advantages, following different approaches. FishRent is primarily used on a fleet level (i.e. an entity of vessels sharing similar characteristics regardless of the target species) to estimate the optimal resource rent of fisheries systems, whereas FLBEIA tries to inform about consequences of different MSE frameworks on a metier level (i.e. a description of activity defined fishery and therefore target assemblage as well as vessel type; ICES, 2003; Jardim et al., 2013). Yet, a link or comparison between both could be of great importance when applying future MSE approaches and estimating effects on fleet behaviour/net profit as well as stocks.

**Future perspectives**

Several aspects would be important to continue and further develop in future studies: First, both biological and economic data should be updated, as already mentioned. Many things have changed during the time of this study. The German fleet, for example, sold one of their vessels and now only consist of three instead of four. This will probably reduce their capital costs in which annual depreciation is included and can in turn significantly affect outcomes. Although fixed costs may be reduced, the catch capacity also decreases. Therefore, the effort of the remaining effort may increase also rising variable costs, such as fuel and repair costs. This in turn can have a large effect on the fleet behaviour and might generate different patterns than observed in these chapters.

Moreover, new information concerning NEA mackerel and NSAS herring will become available, which should be incorporated. The attention should thereby also lie on how the assessment of NEA mackerel develops. It would be especially interesting if and, if yes, how the NEA mackerel biomass distribution will continue to change. In this perspective, information from the individual based model from Boyd et al. (2018/2020) could be used to estimate the biomass distribution in the summer feeding period. In their study, the model searches for the most profitable location of NEA mackerel considering energy budgets and detailed information about the life cycle (Boyd et al., 2018/2020). Upon an inquiry, the authors indicated a possible model expansion in the future to include the spawning area and season, which would be highly suitable as migration input information for FishRent. The upcoming Brexit (possibly to be completed in 2021) may be problematic concerning data access, especially economic parameters. Moreover, new fisheries agreements, as already observed between Norway and the UK, will be involved. In this agreement, fishing access and an exchange of quotas between the two coastal states is arranged and will be implemented from January 2021 (Norwegian Government, 2020). New agreements can in turn be tested with FishRent.

Additionally, other species (e.g. blue whiting (*Micromesistius poutassou*) and horse mackerel (*Trachurus trachurus*)) that are also targeted by the pelagic fleets could be added into the model, enabling the user to include more dynamics and alternatives for the fleets in case a fishery becomes unprofitable or when including area closures for a specific fishery. On the other hand, this would then further complicate the model and is highly dependent on the data availability. The pelagic freezer-trawler fleet, for example, also targets beaked redfish (*Sebastes mentella*) for which biological data is rather scarce (ICES, 2019b). However, including biological data of blue whiting and horse mackerel should be possible. As economic data of the corresponding fleets already exists, catch and effort data would additionally be needed but might be relatively easily be obtained from the STECF by now.

If the NEA mackerel stock continues to decline, as is currently the trend in the assessments as well as the simulations of this study, another consideration might be to close the major spawning grounds similar to what was performed in Chapter 2. The resolution of Chapter 3 should be adequate for such a NEA mackerel spawning ground closure implementation, although a major problem concerning area availability for the fleets might arise again (as was the case for Chapter 2). Another method might be needed to increase the accessibility to more areas for the fleets when closing significant zones. In this regard, an in-depth analysis on how catchability of pelagic fleets is influenced might be needed in order to assign appropriate values to areas where no underlying catch data exists. Finally, it would be important to include spatial information about fish quality when increasing area accessibility, which could be done with the already explained hedonic modelling technique.

## *CONCLUSION*

The work documented within this thesis has described the fleet structure of the European pelagic fishery targeting NEA mackerel and NSAS herring as well as the underlying data needed to parameterize the FishRent model and discussed associated problems. Moreover, different influences, ranging from economic over environmental to management strategies, affecting the fleet behaviour as well as the stock levels have been illustrated. The model showed good fits relative to observed biomass levels of both species. Applying different spatial resolutions highlighted the need for a relatively high resolution and the inclusion of seasons when trying to understand the fleet behaviour but when considering the general trend of pelagic stocks over time it might not be necessary. The results are in line with the common perspective that fish and fuel prices from target species as well as the spatial distribution of the resource are essential factors determining the simulated fleets' behaviour. An advantage of the model is the balance and feedback mechanism between economic and biological dynamics allowing the user to set up the model relative to data availability. Additionally, effects on different fleets, although having different homeports as well as different seasonal fishing preferences, can be tested at the same time, allowing for a relatively realistic consequence determination of management measures. In this perspective, the importance of revising the quota repartition key was highlighted and a method for a new quota assignment possibility was provided. Moreover, the thesis illustrated the consequence of continued overfishing or fishing according to ICES advice of the NEA mackerel stock and the resource dependence on management goals of different fishing nations. In general, the results do not project a positive future for the NEA mackerel and NSAS herring stocks accept for when reducing the fishing pressure to advice level. Outcomes also show that the fleets will find a way to adapt to single changes, although this will be more problematic for some than for others and can lead to further socio-economic consequences, such as the increase in unemployment. Yet, shocks and changes as described in this thesis may amplify, since they seldom appear separately. In this regard, future work should try to incorporate new data that also take into account other factors ranging from other target species to dynamic, possibly spatially resolved fish prices.

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## *ACKNOWLEDGEMENTS*

First of all, I would like to thank my supervisors Prof. Dr. Axel Temming and Dr. Katell Hamon for all of their help, guidance and support throughout this PhD. You provided so many ideas, showed me how to work as a scientist and to ask the right questions. Without you, I simply could not have finished this work!

Many thanks to the Thünen Institute of Sea Fisheries and the CERES project (Grant agreement No 678193) for providing financial and administrative support allowing me to travel, present my results at international conferences and to meet many new people with whom I enjoyed interesting discussions. In this perspective, I am also thanking Gerd Kraus and Nicole Hielscher for supporting and encouraging me to continue my work even during the most difficult time of this PhD. When I could not find a solution anymore, they could and I am most grateful for this. The same applies to my working group that includes Cornelia Kreiss, Jörg Berkenhagen, Ralf Döring, Tobias Lasner, Erik Sulanke, Leyre Goti, Simone Brüning, Lina-Marie Huber, Sarah Simons and Imke Edebohls (in no particular order). You listened to me and tried to find solutions that may help, but we could also just enjoy ourselves chatting. It is a diverse working group that provided a lot of insights into other topics, I learned a lot! Jörg Berkenhagen also provided part of the data and gave me a lot of advice on the economic structure of the fleets. Cornelia and I both worked within CERES. She shared a lot of information on how to work in projects and we enjoyed several project meetings together. Moreover, many thanks to Sarah Simons, who provided the initial scripts and model as well as commented on the Chapters and introduced me to the project and its processes at the beginning of the PhD. Many others have contributed to data provisions and advice about the fleet dynamics: Many thanks to the numerous researchers of the Data Collection Framework (DCF) for providing the economic data and their expert knowledge (in no particular order): Matt Elliott (MMO), Anna Ólafsdóttir (MRI), Arina Motova (Seafish), Josefine Egekvist (DTU Aqua), Kim Normark Andersen (DST), Jörg Berkenhagen and Torsten Schulze (TI-SF), Hans Gerritsen (Marine Institute IR) and Emmet Jackson (BIM). Also, many thanks are given to Anna Ólafsdóttir (MRI), Jens Ulleweit and Norbert Rohlf (both TI-SF) for plenty of information concerning the biology of NEA mackerel and herring. For a lot of feedback and new ideas many thanks are given to Martin Pastoors (PFA), Uwe Richter (Doggerbank Seefischerei GmbH) and the DCF Team at the Thünen (most of all Eckhard Leu, Finn Werner, Christian Schulte, Philipp Schweizer, Sakis Kroupis and Timo Meißner). It was a pleasure meeting and working with you! Many thanks to Miriam Püts, my PhD fellow, to whom I could always talk to and who always supported me.

We both had many ups and downs and I will totally miss our "Model-Horst"! Many thanks to Marc Taylor, Alexander Kempf and Bernhard Kühn for their modeling expertise (all TI-SF). Also many thanks to the Thünen Journal Club, who reviewed and critically commented on my Chapters, as well as Karsten Rätze, my uncle Franz-Walther Baathe and my mum Pia-Sibyll Rybicki, who also contributed in helping to conquer the GAMS software and the maths behind it.

I would like to thank my dearest friends Dominique Weilermann (with Iteag, the dog), Franziska Link and Núria Sánchez-Baizan for listening to me, sharing my problems, kicking me out of my thesis mania from now and then, and just being there whenever there was need. I hope we will be able to maintain our friendships although unfortunately being physically apart.

Last but not least I would like to thank my family, especially my parents Pia-Sibyll and Werner Rybicki, my aunt and uncle Baathe, my adoptive grandmother Lisa and my partner, Felix Demmin, for all the support they provided, never doubting me and always being there no matter what. I learned that this support cannot be taken for granted and I do count myself very lucky to have you by my side - unconditionally.

Nicht zuletzt möchte ich meiner Familie danken, vor allem meinen Eltern Pia-Sibyll und Werner Rybicki, meiner Tante und meinem Onkel Baathe (auch eine riesen Hilfe bzgl. der Programmierung!), meiner Adoptiv-Oma Lisa und meinem Partner, Felix Demmin. Sie haben mich immer unterstützt, nie an mir gezweifelt und waren immer für mich da, egal was passiert ist. Ich habe gelernt, dass diese Unterstützung nicht als selbstverständlich betrachtet werden kann und ich schätze mich sehr glücklich, Euch an meiner Seite zu haben – bedingungslos.

**Happiness can be found even in the darkest of times, if one only remembers to turn on the light.**

*J.K. Rowling*

## DECLARATION ON OATH

I hereby declare upon oath that I have written the present dissertation „ Evaluating the spatio-temporal impacts of environmental, political and economic changes on the stocks of Northeast Atlantic mackerel and North Sea herring and fisheries " independently and have not used further resources and aids than those stated.

## EIDESSTATTLICHE VERSICHERUNG

Hiermit erkläre ich an Eides statt, dass ich die vorliegende Dissertationsschrift mit dem Titel „Evaluating the spatio-temporal impacts of environmental, political and economic changes on the stocks of Northeast Atlantic mackerel and North Sea herring and fisheries" selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

S. Rybicki

Bremerhaven, 06th November 2020

Sandra Rybicki