

**A route into the unforeseeable -
Evaluating future perspectives of North Sea demersal
fisheries with bio-economic modeling and
management strategy analysis**

Dissertation

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

Department of Biology
University of Hamburg



Submitted by

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2026 in Hamburg, Germany

Declaration about personal contribution to manuscripts/publications in a cumulative thesis (please submit one form per manuscript/publication)

Candidate's name: Erik Sulanke

Manuscript (including all authors, title, and if applicable journal, year; mark all first authors with asterisk):

Ammending the European Fishing fleet segmentation based on machine learning and multivariate statistics
 Erik Sulanke*, Verena Rubel*, Jörg Berkenhagen, Matthias Bernreuther, Thorsten Stoeck, and Sarah Simons
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Detailed description of own contribution to this manuscript

Conceptualization and planning of project:

I conceptualized the multivariate approach to fleet segmentation. Jörg Berkenhagen, who wrote the original project proposal, provided feedback and ensured that the developed concepts were in line with the project objective. Together with Jörg Berkenhagen, I also planned the three online workshops, which generated knowledge and user feedback essential to the development of the alternative segmentation approach.

Method development:

I developed the multivariate segmentation scheme and transferred the entire method to a publicly available R-package. In addition, I aided the application of the machine learning algorithm to the fishing fleet dataset.

Data generation and analyses (including contribution to specific figures):

I conducted the application of the approach to the German fishing fleet data set and facilitated the data anonymization necessary to provide data for the machine learning algorithm. For the publication, I designed all figures on the aforementioned aspects, i.e., figures 1, 2, 6, and 7.

Writing and editing of manuscript:

I wrote the original draft of the manuscript in collaboration with Dr. Verena Rubel, who provided information on the statistical background of machine learning algorithms and their application in fisheries. Furthermore, I coordinated all editing and the revision process.

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In close collaboration with Dr. Sarah Simons, I conceptualized the modeling approach and the model version applied.

Method development:

Other authors developed all methods applied in the manuscript, as no novel methods were introduced.

Data generation and analyses (including contribution to specific figures):

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Writing and editing of manuscript:

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Method development:

Other authors developed all methods applied in the manuscript, as no novel methods were introduced.

Data generation and analyses (including contribution to specific figures):

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Writing and editing of manuscript:

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Writing and editing of manuscript:

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**How inappropriate to call this
planet Earth when it is clearly Ocean.**

- Sir Arthur Charles Clarke

Summary

The North Sea has one of the longest histories of extensive human use of all oceans of the world, and for generations, its fish stocks have been targeted by fleets of all adjacent nations. In recent years, some of its overexploited stocks have recovered, yet fleet sizes continue to decline, and many fleets are struggling to survive. Economic pressures such as surging fuel costs and dwindling prices for key target species, spatial competition with offshore energy production, marine conservation and other forms of use, and climate-driven ecosystem changes have significant effects on those fleets and call for new strategies in fisheries research and management. In this thesis, a holistic approach towards these pending issues is presented, covering some of the core areas necessary to comprehend the complexity of demersal North Sea fisheries: Data collection schemes, bio-economic modeling, species distribution changes, and alternative management approaches.

In the first chapter, a technical improvement of the EU's fisheries Data Collection Framework (DCF) is presented. The DCF is one of the pillars of the Common Fisheries Policy (CFP) of the EU, in which member states coordinate the collection and processing of all relevant fisheries data. One obligation of the member states active in the DCF is, therefore, the collection of socio-economic data of fisheries, a task requiring the separation of a nation's fishing fleet into fleet segments. Since the current DCF segmentation scheme is solely based on technical characteristics of the vessels, operational characteristics and fishing strategies are not well accounted for, hampering targeted management strategy evaluation and applicability of the collected data in research and management. In order to improve this process, an alternative approach to the segmentation of fishing fleets based on multivariate statistics and applying machine learning functions for automation was developed. To test the approach's efficiency, it was applied to two decades of German fishing fleet data. This analysis not only revealed distinct fishing strategies in accordance with fleets' operational reality and thus was better suited for further use, but it also resulted in fewer overall segments compared to the DCF approach, reducing workload for data collectors. To further assess the performance of the novel approach, biological stock health indicators were calculated for fleet segments formed by both segmentation schemes, demonstrating the DCF scheme's failure to detect fisheries relying on overexploited stocks or wrongfully characterizing segments as unsustainable. The novel approach was designed to be as transferable as possible, it includes highly precise automation, only encountering difficulties when fisheries had overlap in targeted stocks, and hence represents a valuable improvement to fishing fleet data collection, analysis, and management, which was demonstrated by several studies adapting and applying it for their respective case studies and its application in advisory work.

The alternative approach to fleet segmentation was also applied for identifying the fleets simulated in the spatially explicit simulation and optimization model FishRent, of which the results are presented in the second Chapter of this thesis. To assess the impact of climate-driven price and management strategy developments as well as different MSP scenarios, the profitability trajectories of three North Sea demersal fishing fleets from Germany, Norway, and the United Kingdom fishing for cod, saithe, and haddock were simulated. Fleet profitability increased in two of the three scenarios, with the most profound increase happening in a scenario focused on economic development, while the sustainable development scenario showed a less pronounced increase. In a scenario focused on national economies,

unsustainable fisheries management led to the overfishing of the valuable North Sea cod stock, resulting in the economic collapse of the dependent fisheries. Marine spatial planning had only minor effects on fleet profitability and spatial dynamics, yet effort concentration was distinct, caused by fuel price dynamics and lack of investment in technological development. The model revealed the intricate socio-economic dynamics of fishing fleet profitability and effort distribution, but also highlighted the central necessity of sustainable management and quota allocation for the long-term economic viability of fishing fleets.

For the third chapter, these socio-economic dynamics of North Sea demersal fisheries in times of rapid environmental change were further explored, utilizing the emergence of targeted squid fishing in the southern North Sea as a case study and providing its first scientific description. While the first part of the chapter focused on aggregated fleet data, illustrated the overall phenomenon, and identified management strategy gaps, the specific implications for the German North Sea mixed demersal fleet were analyzed in the second part. Despite being a very recent phenomenon with only two fishing seasons undertaken, squid shares in the revenues of the respective fleet surged to 21% in 2024. Spatiotemporal analysis of logbook data showed distinct fishing grounds in the southern North Sea and the eastern English Channel, and a pronounced fishing season in the winter months (October to March). Onboard sampling of a commercial squid trawler revealed strong exclusivity, as only one squid species, *Loligo vulgaris*, was present in the catches. The ecological reason for the species aggregating remains unknown, as feeding and spawning activity appear plausible, and further ecological research needs to be conducted. Meanwhile, specifically designed, multilateral management approaches need to be developed to safeguard the long-term economic and ecological sustainability of this emerging fishery.

In the fourth and final chapter, the role of alternative management strategies was discussed in the context of facilitating Blue Growth in fisheries. It is a common notion of most management frameworks that fisheries have no relevant potential for sustainable growth and are therefore neglected in most such strategies. In the chapter, the potential of supporting extensive growth in fisheries by implementing Community Development Quota (CDQ) systems and supporting small-scale fisheries is highlighted, counteracting consolidation and securing the livelihood of fishery-dependent communities. Therefore, the CDQ program of the Alaska pollock fishery served as an example, and potential benefits of such management approaches for several European fishing nations experiencing quota consolidation and declining small-scale fleets were discussed. This quota allocation scheme, in combination with other management measures presented in the chapter, could play a substantial role in securing the role of fisheries in the envisioned Blue Economy.

In conclusion, the presented thesis aimed to provide a holistic collection of insights and opportunities on how to improve fisheries data collection, analysis, and management to support socio-economic and ecological sustainability in unforeseeable times of rapid change. Even though its central findings have the potential to contribute to improvements in all of these fields, essential knowledge gaps and lacking management strategies were identified. Only through additional research, transdisciplinary approaches, and multilateral cooperation, the natural resources of the North Sea ecosystem, as well as the long-term economic viability of fisheries can be safeguarded.

Zusammenfassung

Kaum eine Meeresregion wird so intensiv durch den Menschen genutzt wie die Nordsee und seit Generationen werden ihre Fischbestände von Flotten aller Anrainerstaaten befischt. In den letzten Jahren haben sich einige überfischte Bestände erholt, doch viele Fischereiflotten kämpfen trotzdem ums Überleben. Ökonomische Belastungen wie steigende Treibstoffkosten und sinkende Preise für wichtige Zielarten, räumliche Konkurrenz durch Offshore-Energieerzeugung, Meeresschutz und andere Nutzungsformen sowie klimabedingte Veränderungen des Ökosystems haben erhebliche Auswirkungen auf die Fischerei und erfordern neue Strategien in Forschung und Management. In dieser Thesis werden Lösungsansätze für Probleme in einigen der Kernbereiche präsentiert, welche zum Verständnis der Komplexität in Fischereiforschung und -management notwendig sind: Datenerhebung, bioökonomische Modellierung, klimabedingte Veränderungen in der Verbreitung von Arten und alternative Managementansätze.

Im ersten Kapitel wird ein Ansatz zur Verbesserung des Datenerhebungsprogramms (DCF) der EU für die Fischerei vorgestellt. Der DCF ist einer der Grundpfeiler der Gemeinsamen Fischereipolitik (GFP), in dessen Rahmen die Mitgliedstaaten die Erhebung relevanter Fischereidaten koordinieren. Eine Verpflichtung der DCF-Mitgliedstaaten ist die Erhebung sozioökonomischer Flottendaten, wofür die Aufteilung der Fischereiflotten in Flottensegmente nötig ist. Da das derzeitige DCF-Segmentierungsschema auf den technischen Merkmalen der Fahrzeuge basiert, werden operative Charakteristiken und Fischereistrategien kaum berücksichtigt. Dies erschwert die Folgenabschätzung von Managementmaßnahmen und die Verwendung der erhobenen Daten in der Forschung erheblich. Um diesen Prozess zu verbessern, wurde ein alternativer Segmentierungsansatz entwickelt, der auf multivariater Statistik und Maschinellem Lernen basiert. Um die Effizienz des Ansatzes zu testen, wurde er auf Daten der deutschen Fischereiflotte angewendet. Diese beispielhafte Anwendung ergab Segmente, die nicht nur die operative Realität und Fischereistrategie besser widerspiegeln, auch wurde die Anzahl der Segmente verringert. Hierdurch würde der Arbeitsaufwand für die Datenerhebung reduziert werden. Die Berechnung biologischer Bestandsgesundheitsindikatoren zeigte, dass das DCF-Schema Fischereien, die wirtschaftlich auf überfischte Bestände angewiesen waren, nicht verlässlich erkennen konnte oder Segmente fälschlicherweise als nicht nachhaltig einstufte. Durch seinen Fokus auf Übertragbarkeit und seine hochpräzise Automatisierung, die nur bei tatsächlicher Überlappung von Fischereien ungenau arbeitete, stellt der neue Segmentierungsansatz eine wertvolle Verbesserung für die Datenerhebung, -analyse und das für Management von Fischereiflotten dar, was durch mehrere Studien, die ihn für ihre jeweiligen Forschungsfragen adaptierten, belegt wurde.

Der alternative Ansatz zur Flottensegmentierung wurde auch zur Identifizierung der Flotten angewendet, die im bio-ökonomischen Flottenmodell FishRent simuliert wurden, dessen Ergebnisse im zweiten Kapitel dieser Arbeit vorgestellt werden. Um die Auswirkungen klimabedingter Preis- und Managementstrategie-Entwicklungen sowie verschiedener MSP-Szenarien zu bewerten, wurde die Profitabilitätsentwicklung von drei Grundfischereiflotten simuliert. Die Profitabilität der Flotten stieg in zwei der drei Szenarien, wobei der stärkste Anstieg in dem auf wirtschaftliche Entwicklung ausgerichteten Szenario zu verzeichnen war, während das Szenario der nachhaltigen Entwicklung einen weniger ausgeprägten Anstieg zeigte. In einem von nationaler Wirtschaft und geringer internationaler

Kooperation geprägten Szenario führte eine nicht nachhaltige Bewirtschaftungsstrategie zur Überfischung des Kabeljaubestands, woraufhin die von ihm abhängigen Fischereien zusammenbrachen. Marine Raumentwicklung hatte geringe Auswirkungen auf die Profitabilität und die räumliche Dynamik, trotzdem waren deutliche Konzentrationseffekte des Fischereiaufwands zu beobachten, verursacht durch die Entwicklung der Treibstoffpreise und mangelnde technologische Innovation. Das Modell zeigte die komplexen sozioökonomischen Dynamiken von Fischereiflotten und Fischereiaufwandsverteilung auf, hob aber auch die zentrale Bedeutung einer nachhaltigen Bewirtschaftung für die langfristige Wirtschaftlichkeit von Fischereiflotten hervor.

Im dritten Kapitel dieser Arbeit wurde die Veränderungsdynamik der Nordseefischerei tiefergehend untersucht, wofür die neu entstandene gezielte Kalmarfischerei als Fallstudie diente. Während sich der erste Teil des Kapitels auf aggregierte Fischereidaten und das Gesamtphänomen konzentrierte und Verbesserungspotentiale im Management identifizierte, wurden im zweiten Teil spezifische Implikationen für die deutsche gemischte Grundfischereiflotte analysiert. Obwohl es sich um ein neues Phänomen handelt, stieg der Anteil von Kalmaren am Gesamterlös der Flotte im Jahr 2024 auf 21% an. Die räumlich-zeitliche Analyse von Logbuchdaten ermöglichte die Identifikation klarer Fanggründe sowie einer ausgeprägten Fischereisaison in den Wintermonaten (Oktober bis März), während in der Beprobung eines kommerziellen Kalmar-Trawlers eine starke Konzentration auf eine einzelne Kalmarart, *Loligo vulgaris*, festgestellt wurde. Die Gründe für die Aggregation dieser Art sind noch ungeklärt, da Indikationen sowohl für eine Fraßaggregation als auch für Laichaktivität vorliegen. Weitere ökologische Untersuchungen müssen durchgeführt und multilaterale Managementansätze entwickelt werden, um langfristig die wirtschaftliche und ökologische Nachhaltigkeit dieser aufstrebenden Fischerei zu gewährleisten.

Das vierte Kapitel behandelt die Rolle alternativer Managementstrategien im Kontext des Blue-Growth-Konzepts und dessen Bedeutung für die Fischerei. Üblicherweise gehen Strategiekonzepte der Blue Economy davon aus, dass Fischerei kein Potenzial für nachhaltiges Wachstum hat, und vernachlässigen sie. In diesem Kapitel wurde das Potenzial der Förderung eines extensiven Wachstums in der Fischerei durch die Einführung von gemeinschaftlicher Quotenverwaltung und die Unterstützung der kleinen Küstenfischerei untersucht, wodurch Konsolidierung entgegengewirkt und die Lebensgrundlage der von der Fischerei abhängigen Gemeinden gesichert werden kann. Als Beispiel diente das CDQ-Programm der Alaska-Seelachs-Fischerei, und es wurden die potenziellen Vorteile dieses Ansatzes für europäische Fischereinationen diskutiert.

Die im Kapitel vorgestellten Managementmaßnahmen können eine wesentliche Rolle bei der Sicherung der Rolle der Fischerei in der angestrebten blauen Bioökonomie spielen. Die vorliegende Thesis hatte zum Ziel, in einem ganzheitlichen Ansatz Verbesserungsmöglichkeiten in der Datenerhebung, der Analyse und im Management zu generieren und wichtige Erkenntnisse zu den sozio-ökonomischen Auswirkungen des Klimawandels und weiterer belastender Faktoren auf die Fischerei zu generieren. Die Ergebnisse haben das Potenzial, zu Verbesserungen in all diesen Bereichen beizutragen, allerdings wurden auch wesentliche Wissenslücken und fehlende Managementstrategien identifiziert. Nur durch zusätzliche Forschung, transdisziplinäre Ansätze und multilaterale Zusammenarbeit können die natürlichen Ressourcen des Ökosystems Nordsee und die langfristige wirtschaftliche Lebensfähigkeit der Fischerei gesichert werden.

Table of contents

Introduction

Fisheries under pressure in a time of rapid change

The North Sea is one of the most intensively used marine regions of the world. For centuries, its shorelines have been densely populated, its sea routes frequently traveled, and its fish stocks heavily fished (see Fig. 1). It was in the North Sea, where the industrialization of fisheries started, and from where distant-water trawlers emerged first in search of new fish stocks to exploit, as the North Sea was also one of the first areas facing the consequences of overfishing. The onsets of overfishing and the use of destructive fishing techniques prompted scientists and managers to gather and agree on common, sustainable harvesting strategies as early as 1894 (Heincke, 1894). Over a century later, the collective efforts of researchers, particularly the International Council for the Exploration of the Sea (ICES), managers, and fishermen have started to show effect, as numerous commercially used fish stocks have recovered and are currently within safe biological limits (ICES, 2024). Yet, North Sea fisheries are struggling for economic viability. In particular, coastal fleets of all kinds exhibit a sustained decline in both capacity and economic performance (Pascual-Fernández et al., 2020). The reasons for this decline are manifold, and they can only be explained by considering not only the state of the targeted fish stocks and the marine environment, but also the economic and societal aspects of fisheries.

After the Second World War, which halted most fishing operations due to the deployment of all available sailors and vessels in the conflict, fisheries in the North Sea were reestablished, and fleet sizes and catches increased dramatically within a few years. In addition, more powerful vessels and the availability of novel technologies, especially echo sounding for fish swarm localization, increased the catch efficiency of the vessels, while modernized cooling systems allowed them to stay at sea longer and travel further (Dierks et al., 1961; Engelhard, 2008). The resulting increase in fishing pressure was too severe to be compensated for by the target stocks, leading to the sequential collapse of several key fisheries. Herring (*Clupea harengus*), one of the major target species of North Sea fisheries for centuries, which facilitated the rise of major coastal cities and was the economic backbone of Dutch and German fisheries. The stock yielded 1.2 million tons in the 1960s, but collapsed just ten years later, leading to a complete fishing ban on North Sea herring being implemented in 1977 (Dickey-Collas et al., 2010). The ban lasted for six years and allowed the stock to recover to a size suitable for commercial exploitation, but it has not returned to historic spawning stock biomass levels. Meanwhile, fleets profited from the so-called “Gadoid outburst”, a period of strong recruitment in several gadoid fish species like cod (*Gadus morhua*), saithe (*Pollachius virens*), and haddock (*Melanogrammus aeglefinus*). During this period, colder temperatures, especially in the winter months, led to a substantial shift in the plankton community, particularly an increase in *Calanus* copepods, which are a preferred prey item for juvenile gadoids (Hislop, 1996; Beaugrand et al., 2003). This increase in prey availability transferred to larger spawning stocks, resulting in substantial gains in demersal fleet yields. However, these stocks ultimately proved unable to sustain the persistent fishing pressure. North Sea haddock catches reached their maximum in the

1. Introduction	1
2. Chapter I	12
<i>Improvements in data collection to facilitate realistic fishing fleet models</i>	
3. Chapter II	30
<i>A bio-economic modeling approach to simulate the impact of climate change on fisheries</i>	
4. Chapter III	48
<i>Species redistribution and its economic implications: Squid in the southern North Sea as a case study</i>	
<i>Value and volatility of squid as a fisheries resource in the North Sea and adjacent waters – starting point for a sustainable management</i>	50
<i>First description of the emergence of targeted squid fisheries in the German North Sea demersal trawl fleet</i>	56
5. Chapter IV	67
<i>Fisheries in the Blue Economy and the potential of alternative management measures</i>	
6. Discussion & Conclusion	92
<i>Discussion</i>	94
<i>Conclusion</i>	105
7. Affidavit	108
8. Acknowledgements	109
9. References	110

mid-1970s at approximately 500,000t, saithe peaked around the same time at 400,000t, and North Sea cod catches peaked a final time in 1982 (ICES, 2025a).

Commercially valuable flatfish species, particularly plaice (*Pleuronectes platessa*) and sole (*Solea solea*), exhibited similar patterns of overexploitation and decline. Sole catches were highest in the late 1960s and early 90s, following years of extraordinarily strong recruitment, at approximately 30,000t, which is a rather low tonnage compared to the aforementioned species. Yet sole is one of the most valuable fish species of the region and a key driver of fleet profitability (STECF, 2024). The particularly fuel-intensive sole fishery, which uses heavy beam trawls, is highly sensitive to fuel price developments and was therefore designated as a trial fishery for fuel-saving alternative fishing gear, known as the pulse trawl. This variation of

the beam trawl utilizes electromagnetic pulses to startle demersal species, significantly reducing seafloor contact and, consequently, environmental damage, as well as fuel consumption (Schram et al., 2022). Despite scientific evidence of these advantages, campaigns conducted by a coalition of organized artisanal fishermen and environmental NGOs successfully contested the use of the pulse trawl, leading to its ban being passed by the European Commission in 2019 (Kraan et al., 2020). This ban allowed for a transition phase until July 2021, after which approximately half of the Dutch sole trawlers were decommissioned, as the fuel price increase, caused by Russia's invasion of Ukraine, did not allow for the profitable operation of conventional heavy sole beam trawls (Hamon et al., 2023). This, however, had a positive influence on the North Sea sole stock, which faced critically high levels of fishing mortality for years, but has shown strong signs of recovery after the ban had been imposed (ICES, 2025d). The other major commercial flatfish species of the North Sea is plaice, and its fishing mortality had a similarly positive development recently, yet for entirely different reasons. After two decades of exceeding fishing pressure, plaice catches accounted for nearly 180,000t in 1989, with approximately the same amount being discarded (ICES, 2025c). By 1995, ICES advised a significant reduction in fishing mortality, and total allowable catches were lowered in accordance. In the same year, the marine protected area for

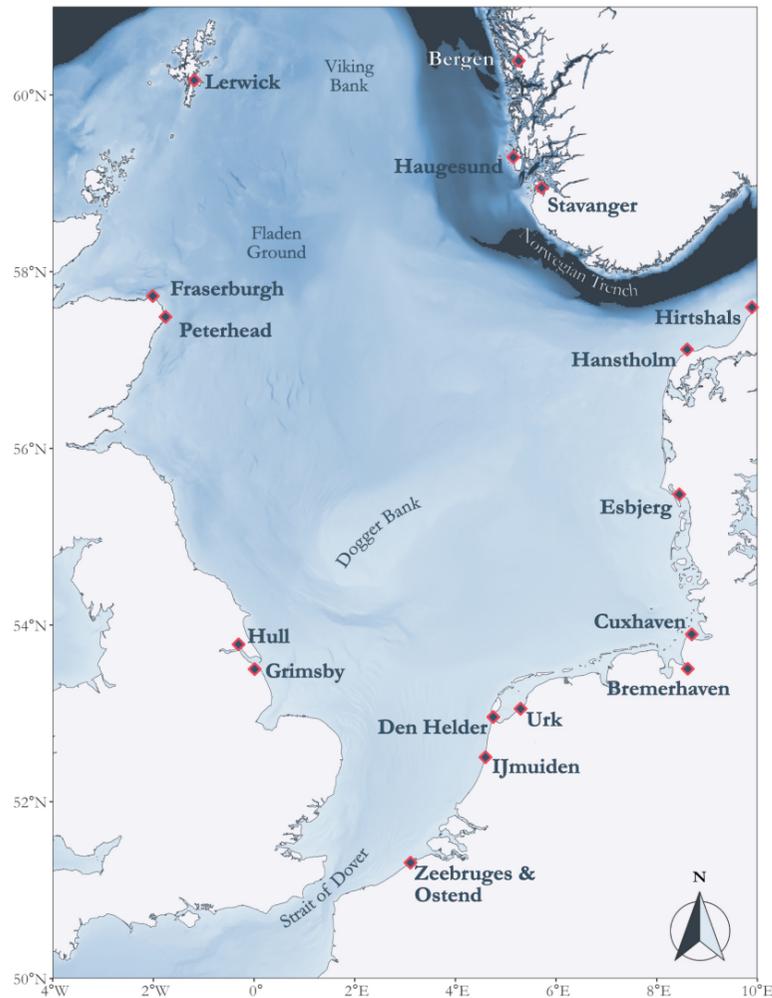


Fig.1: Map of the Greater North Sea Region. Relevant fishing ports, current and historic, are depicted, as well as geomorphological features relevant to fisheries.

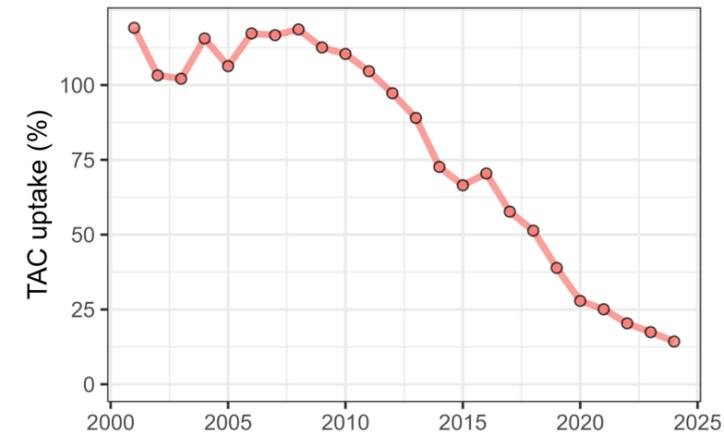


Fig.2: Annual TAC-uptake of the North Sea plaice stock (ple.27.420) in percent. Source: ICES, 2025c.

2., Pastoors et al., 2000; Beare et al., 2013; Amelot and Hintzen, 2022). This is mainly due to the large, marketable plaice shifting towards deeper waters in the northwestern North Sea, making their pursuit unprofitable, as the import of Pacific flatfish species as substitutes fulfills most market demands (Neerlandia, 2022).

Price dynamics like the described price decline of North Sea plaice are typical in seafood products, which are among the most traded commodities, with Europe being a central hub of trade and one of the biggest seafood importers in the world (Paquette and Lem, 2008; Wilf Swartz et al., 2010; FAO, 2024b). The globalization of seafood trade has shifted market dynamics and affected prices, as domestic products have to compete with a steady supply of imports. For example, the fishery for Alaska pollack (*Gadus chalcogrammus*), a gadoid species from the northern Pacific, has become the single largest fishery for human consumption, setting a price threshold for easily palatable whitefish (Nielsen et al., 2009). Supply shortages caused by Russia's War in Ukraine are increasingly compensated for using *Pangasius (Pangasianodon hypophthalmus)* from aquaculture production and not by comparable whitefish species from domestic fisheries, like plaice, whiting, or haddock. Because of their relatively higher production costs, demersal fisheries of the North Sea are increasingly relying on high-priced species like sole, turbot (*Psetta maxima*), or Norway lobster (*Nephrops norvegicus*). The latter is a decapod crustacean with substantial market value, making it the commercially most important crustacean of European fisheries (STECF, 2024). It is a particularly interesting case, as Norway lobsters are specifically bound to benthic habitats consisting of at least 40% clay and silt (Chapman and Rice, 1971; Bailey et al., 1995). Therefore, the distribution of the species is fragmented into more than 30 populations over Europe, being assessed separately by ICES. The next section describes how the restriction of this species to a certain habitat type led to it being a stress test in Marine Spatial Planning (MSP), a form of marine governance gaining importance in the past decade.

juvenile plaice along the Wadden Sea coast ("Plaice box"), established in 1989, was extended from the first and third quarters to the full year, limiting the maximum engine power of all fishing vessels operating in the area to 221kW (Amelot and Hintzen, 2022). After years of successful recovery, the plaice stock has predominantly been within safe biological limits since 2008, but in the most recent years, quota utilization dropped drastically, falling to 14% of the quota being landed as catches in 2024 (see Fig.

Marine Spatial Planning – Endless Ocean running out of space

With the rapid increase in demand for climate-friendly offshore energy production and the simultaneous momentum gained by conservation efforts, especially in the form of Marine Protected Areas (MPAs), the perspective of space in the marine realm has drastically changed. Once serving as the exemplary symbol of openness and endlessness, oceans have become a matter of bargaining rather than a metaphor for vastness. This is especially true for marginal seas like the North Sea, which are fully covered by the Exclusive Economic Zones (EEZs) of coastal states. The German Bight, where one of the world's busiest shipping routes connects the port of Hamburg and the Kiel Canal with global trade routes, was one of the first areas of the North Sea, where the accumulating claims of offshore wind farms (OWFs), conservation, fisheries, defensive concerns, and pipeline and cable building could not be met without a designated maritime spatial plan. The first version of this plan was passed in 2009 and did not include any prioritization of fishing grounds, sparking protests in the fishing communities, where coastal fishing is commonly a patrilineal tradition and rooted in coastal folks' identity (Döring et al., 2020). Other coastal states of the North Sea launched similar initiatives. The Netherlands released a maritime spatial plan in the same year, and the United Kingdom (UK) followed in 2011, after testing a regional maritime spatial plan for the Shetland Islands as early as 2007. The remaining states adopted MSP programs soon after – Belgium in 2014, Denmark in 2021, and Norway in 2024 (with regard to the North Sea, older MSP programs exist for other Norwegian waters). However, fisheries priority areas were still a rarity in the planning efforts, and only in 2021, Germany adopted an updated maritime

spatial plan (see Fig. 3), which included a fisheries priority area for the described Nephrops fishery, with the habitat specificity of the target species being the central argument (Letschert et al., 2021). In light of these planning processes and the ongoing expansion of OWFs and their related infrastructure, research on the implications for fisheries is a steadily developing field harnessing approaches from various disciplines. On the larger, hydrodynamic scale, the effect of OWFs on stratification and upwelling is rather localized, and ecosystem-wide impacts are considered unlikely (Schultze et al., 2020). On the other hand, the construction of OWFs in deeper, seasonally stratified waters is just beginning to become feasible. In these waters, which exhibit considerable oceanographic differences from well-mixed coastal waters,

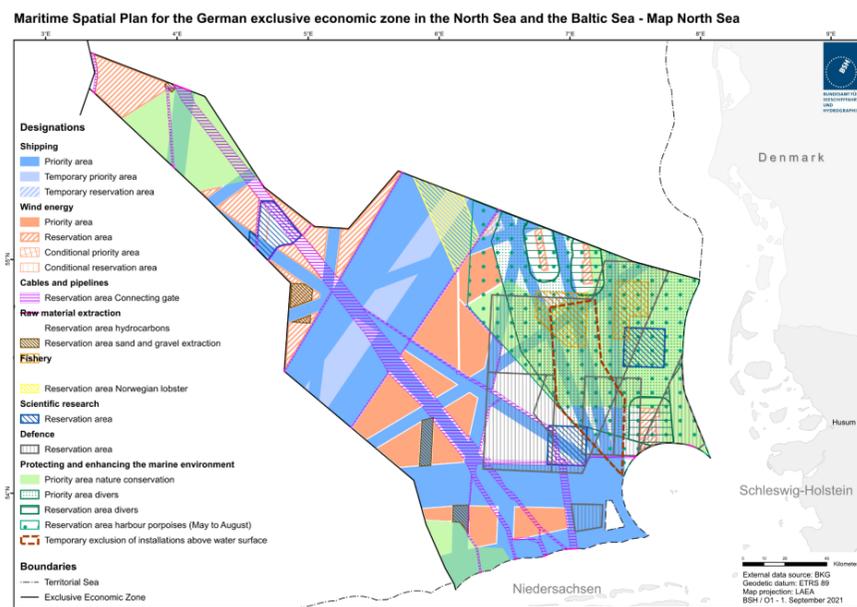


Fig.3.: Second Maritime Spatial Plan of the German EEZ in the German Bight. Source: German Federal Maritime and Hydrographic Agency (BSH).

major changes in hydrodynamic processes are, theoretically, possible. More localized zoological research on demersal fish assemblages in OWFs found increases in abundances, for example, for cod (Werner et al., 2024) and plaice, the latter also showing high site fidelity (Buyse, Backer and Hostens, 2023; Buyse and Reubens et al., 2023). Macrozoobenthos such as brown crab (*Cancer pagurus*) also showed increased abundances in proximity to OWFs, especially with regard to juvenile individuals, indicating a nursery area (Stelzenmüller et al., 2021; Tonk and Rozemeijer, 2022). These abundance increases are, however, highly dependent on the foundation type of the installation and cannot be generalized (Werner et al., 2024). Given these possible ecological effects, OWFs need to be considered in marine conservation and restoration. They are serving as artificial reefs and, effectively, as fisheries exclusion zones on the one hand, yet they also have direct and measurable impacts on marine organisms and the environment. During their construction period, massive underwater noise occurs, proven to deter marine mammals, even though this effect appears to be temporary (Brandt et al., 2018). The use of sacrificial anodes and antifouling on the installations leads to considerable chemical emissions (Hengstmann et al., 2025), possibly impairing food safety of organisms cultivated inside OWFs, as co-design concepts have suggested (Maar et al., 2023). At least in the current German jurisdiction, OWFs are considered as their own compensation areas, as they exclude fisheries, but this might not hold up in the light of the EU's '30 by 30' biodiversity strategy, aiming to protect 30% of its marine areas, especially those of high biodiversity or climate resilience value, by 2030 (EU, 2020). The UK, even though no longer a part of the European Union and its conservation strategies, is still setting and enforcing similarly ambitious marine protection goals. Yet, if and under what circumstances MPAs, like they are outlined in such strategies, have a positive effect on fish populations is highly debated in the scientific community. Costello et al. (2024), for example, found no evidence of net costs of no-take MPAs for fisheries and see evidence of economic benefits due to increased productivity, while Sala and Giakoumi (2018) identify them to be the best tool to restore depleted fish stock biomass. Lester et al. (2009) and Halpern et al. (2009) highlight the necessity of connectivity between protected areas and emphasize placement to be more influential for their effectiveness than size. On the contrary, Hilborn et al. (2025) stress that spillover of MPAs is predominantly evident in small coastal MPAs that were subject to intense fishing pressure before closing and cannot be identified as a general benefit of protected areas. Especially with regard to fisheries resources, Hilborn (2018) highlights science-based and well-enforced fisheries regulations and catch limits to be the central tool for ensuring sustainability. The North Sea offers a striking example of the complex dynamics of effective MPA design and management strategy, as the aforementioned 'Plaice box', a coastal area in which engine capacity of trawlers is limited to protect juvenile plaice established in 1989, has been extensively studied. It is widely considered to have become ineffective for protecting plaice biomass, as the plaice stock has shifted northwestwards into deeper waters (van Keeken et al., 2007; Engelhard et al., 2011; Freitas et al., 2012; Dutz et al., 2016; Støttrup et al., 2017). Yet, the stock is well within healthy limits of biomass and productivity, as described above. Climate change and the subsequent changes in the marine ecosystem will continue to challenge spatial protection approaches, and scientists have called for the implementation of mobile, i.e., spatially flexible, protected areas, especially for the high seas (Maxwell et al., 2020). Design, placement, and effective regulations of MPAs are a subject of ongoing scientific debate, especially with regard to the effects of fishing effort displacement and effort concentration effects. Given the complexity of the topic in combination with the rapid development of the sector, scientific evaluation of MSP has become one of the most common tasks

in scientific advisory work. Management strategy evaluation of spatial management measures like MPAs requires sophisticated approaches accounting for spatiotemporal dynamics, often achieved by applying spatially explicit models. These models are, in turn, dependent on detailed socio-economic fleet data. As the foundation of each model, the structure, quality, and robustness of these socio-economic datasets are crucial for generating conclusive model results. Yet, given the heterogeneity and complexity of fisheries, the structure of these datasets is a major challenge in fisheries data collection.

Meaningful fishing fleet data and the difficulties in obtaining it

In order to collect fisheries data in a structured and holistic manner, officials and researchers need to develop a detailed common understanding of the composition, operational scale, and fishing strategies of the respective fishing fleets. This requires clear terminology and well-defined sampling strata, a prerequisite that is unfortunately not met when comparing terms used by different management bodies. In the European case, ICES is one of the main advisory bodies of the European Union (EU). According to them, ‘fishery’ is defined as "...a group of vessel voyages targeting the same (assemblage of) species and/or stocks, using similar gear, during the same period of the year and within the same area (e.g., the Dutch flatfish-directed beam trawl fishery in the North Sea)..." (ICES, 2003). This definition implies a fleet segmentation on a capacity, effort, gear, and target assemblage level, which, applied on an activity basis, is highly specific and likely to create small segments of fisheries within a fleet. On the contrary, the European Fisheries Data Collection framework (DCF), which coordinates and conducts the collection and analysis of fisheries data of all EU member states, does not offer a definition for the term ‘fishery’, but does define the term ‘fleet segment’ as follows: "...‘segment’ means a group of vessels as homogeneous as possible in terms of physical characteristics and of use of fishing gear resulting from a partition of the segments contained in the fourth multiannual guidance programme (MAGP IV)’ (EU, 2001). The Food and Agriculture Organization (FAO) of the United Nations recommends grouping vessels which are ‘...similar, by size and gear’ (FAO, 2024a). On the regional scale of the North Sea, non-EU third countries Norway and the United Kingdom follow hybrid clustering approaches, grouping vessels based on capacity and gear used, as well as on the target assemblage. While Norwegian Authorities do not provide a publicly available definition of a fleet segment, the UK’s seafood industry authority, Seafish, states that ‘...each fleet segment has a set of mutually exclusive criteria that define which vessels are included in it for each year. Every single active vessel will fit into only one segment each year. Criteria are based on the physical characteristics of the vessels, activity level, the gear used, species targeted, and areas fished.’ (Seafish, 2025).

This heterogeneity in fleet segment definitions leads to data sets being essentially incompatible in scientific analyses. By the principles of such fleet segmentations, a vessel is assigned to one segment or another. Fisheries management measures, like funding, restrictions, or quota allocation, are often linked to these segments. Hence, the principles of segmentation can determine whether a vessel is subject to certain measures or not. More than 20 years after the implementation of the DCF, scientists stress that

there is still no satisfactory framework to give scientific advice on the level of specific fisheries in terms of sustainability or economic performance (STECF, 2023). However, it remains a central issue for the European advisory bodies to assess the impact of fisheries management measures on certain fisheries in order to support the Common Fisheries Policy (CFP). In reality, vessels with similar technical parameters, hence grouped together in the DCF’s segmentation scheme, often exert very different fisheries that do not correspond in terms of catch composition, fishing activity, and cost structure.

Comparing these different segmentation approaches reveals the need for a method that serves the needs of all aforementioned bodies, and that can be applied in a homogeneous manner, on the basis of available information. The issue not only severely hampers adequate management measures and funding allocation, but also contradicts a central requirement of many bio-economic models of fisheries. In the first chapter, a clustering-based and machine-learning-enhanced approach is presented to address it. It was also used for defining the fleets included in the bio-economic model FishRent, which is presented in the second chapter of this thesis. Bio-economic models hold the potential to be among the most effective tools of management strategy evaluation (MSE), yet they require detailed data sets of fishing fleet segments that are defined consistently and are suited for the intended purpose.

Bio-economic modeling as a predictive tool in fisheries research

For many years, modeling as a prediction and evaluation tool was mainly conducted with respect to the stock status and ecology of harvested resources (Prellezo et al., 2012). These approaches, however, were often insufficient to reproduce the practical reality of fisheries, where a multitude of factors and variables influence the profitability of fishing fleets and the behavior of fishers. Economic performance of fishing fleets is more than a mere function of resource availability, and in the past decades, fisheries scientists have gone to great lengths to develop models that combine the biological features with socio-economic characteristics of fishing fleets. In this thesis, such models will be referred to as ‘bio-economic’ models, even though this term is not sharply delineated and not all the models mentioned describe themselves as such. A basic distinctive criterion of bio-economic models in fisheries is the distinction between simulation models and optimization models. Simulation models determine likely pathways of economic performance and, sometimes, fishers’ behaviour, e.g., with respect to spatial distribution. In optimization models, parameters and variables are adjusted to achieve an optimal result, e.g., in fleet profitability (Salz et al., 2011; Prellezo et al., 2012; Simons, 2014). This optimization can be performed stepwise or partitioned, or it can be set as the overarching goal of the simulation run, e.g., optimal profit over the time series (Frost et al., 2013). Yet again, the distinction between simulation models and optimization models is not absolute, as many simulation models contain optimization functions, which are commonly referred to as objective function of the respective model (Salz et al., 2011). In addition to the described differences in the model objective, bio-economic models, although mostly similar in structure, can be further differentiated by several characteristics in their functionality, namely the following. Most closely linked to the model objective is the model orientation, in which input-regulated, output-regulated, and

input-output-regulated models are distinguished (Prellezo et al., 2012). Input-regulated models are strictly regulated by factors obtained from outside the modeling framework, which are referred to as exogenous factors. Output-regulated models achieve their objective by modifying their internal set of variables, the endogenous factors, to match predetermined target values. Input-output-regulated models, which are the most complex of bio-economic models, are regulated by both exogenous and endogenous factors, i.e., they modify the internal modeling framework to achieve a given target objective while they are influenced by exogenous factors. Another important model characteristic is stochasticity. The modeling framework can contain stochastic elements of statistical uncertainty for at least a part of the included variables, while deterministic models do not include such features. Within these basic variations of functionality, an enormous diversity of spatial and temporal scale, system complexity, and degree of detail, both in terms of biological features and socio-economic characteristics, exists. From single estuary systems to distant-water fisheries in international waters and on scales from days to years (Bartelings et al., 2015; Dorleta Garcia et al., 2017; Nielsen et al., 2018; Kvamsdal et al., 2020; Rybicki et al., 2020; Rybicki et al., 2021), bio-economic models have become an essential tool of fisheries research, MSE, and advisory work. The most recent addition to the complexity of bio-economic models has been the adaptation of agent-based or individual-based modeling approaches for bio-economic research questions. The terms agent-based and individual-based are commonly used interchangeably and refer to the same basic principle of modeling. In contrast to other described model frameworks, agent-based models are defined by a fundamental decision theory in the form of a basic ruleset, by which the individual agents, be it, in the case of fisheries, individual vessels, fleets, or entire nations' fisheries, interact with the modeling environment (Haase et al., 2023; Letschert, 2024). While these models present a compelling opportunity to adapt the dimension of behavior, learning, and interaction for bio-economic models, their current state lacks several important aspects. Especially the influence of environmental factors of the model, and particularly on the decision-making of the agents, is virtually absent in available fisheries ABM approaches (Haase et al., 2023). Yet, especially in the North Sea, where the consequences of anthropogenic climate change are exceptionally strong, this interaction is of particular importance.

Impacts of climate change on species distribution, fishing strategies, and fleet economy

Being a shallow, semi-enclosed marginal sea, the North Sea is particularly vulnerable to the effects of climate change and has been proven to warm faster than the adjacent open Atlantic Ocean (Colijn and Quante, 2016). The rapid warming has caused cascading effects through the ecosystem. Arguably, the biggest long-term effect it will have on the North Sea ecosystem as a whole and the fisheries depending on it is the shift in species distribution, leading to a profound alteration of the species assemblage. Some of the described central target species of North Sea fisheries have undergone striking distribution shifts with serious economic impacts. Cod has become virtually absent in the southern North Sea, where one of its genetically distinct substocks was critically decimated by severe fishing pressure, while a series of

warm, windy winters drove larval distribution northward (Hutchinson et al., 2003; Rindorf and Lewy, 2006). The settling individuals stayed in the northern part of the North Sea, a finding also supported by the limited response of individual cod to thermal stress found in tagging studies (Neat and Righton, 2007). This combination of warming seas and excessive fishing pressure has led to a distribution almost opposite to the 20th century (Engelhard et al., 2014) and a regime shift in the southern North Sea, which is likely to be permanent (Cecapoli et al., 2023). Plaice, another major target species of demersal fisheries, has exhibited a similar shift, showing a deepening and northward shift (Dulvy et al., 2008). Even though early laboratory studies on temperature effects found no correlation with mortality (van der Veer et al., 2009) or growth (Rijnsdorp, 1994), modeling revealed a negative correlation of plaice biomass and sea surface temperature (SST) in the Bay of Biscay (Hermant et al., 2010) and potential disruptions of spawning ground and nursery connectivity due to altered current patterns (Hufnagl et al., 2013). This change has critical implications, as plaice displayed extremely high spawning ground fidelity (Hunter et al., 2003). As described in section 1.1, the northward shift of the plaice stock also had economic consequences, as the necessary steaming distance to fishing grounds with abundant plaice in marketable sizes has become too long and the quota for one of the former most important fish stocks in the North Sea is now remarkably underutilized (ICES, 2025c). Yet, not all commercially important species can adapt to climate change by shifting their distribution. Nephrops is extremely restricted in its suitable habitat, but potentially highly vulnerable to the effects of climate change, as levels of ocean acidification expected to be present in 2100 have been shown to impair its immune function severely (Hernroth et al., 2012). In addition, temperature changes affect larval mortality and larval stage duration, possibly leading to mismatches with suitable prey organisms (Wood et al., 2015). If climate change makes parts of the North Sea uninhabitable for Nephrops, North Sea demersal fisheries would lose their currently most valuable target species, accounting for €66M revenues for EU and UK fisheries in 2023 alone (STECF, 2023; Seafish, 2025).

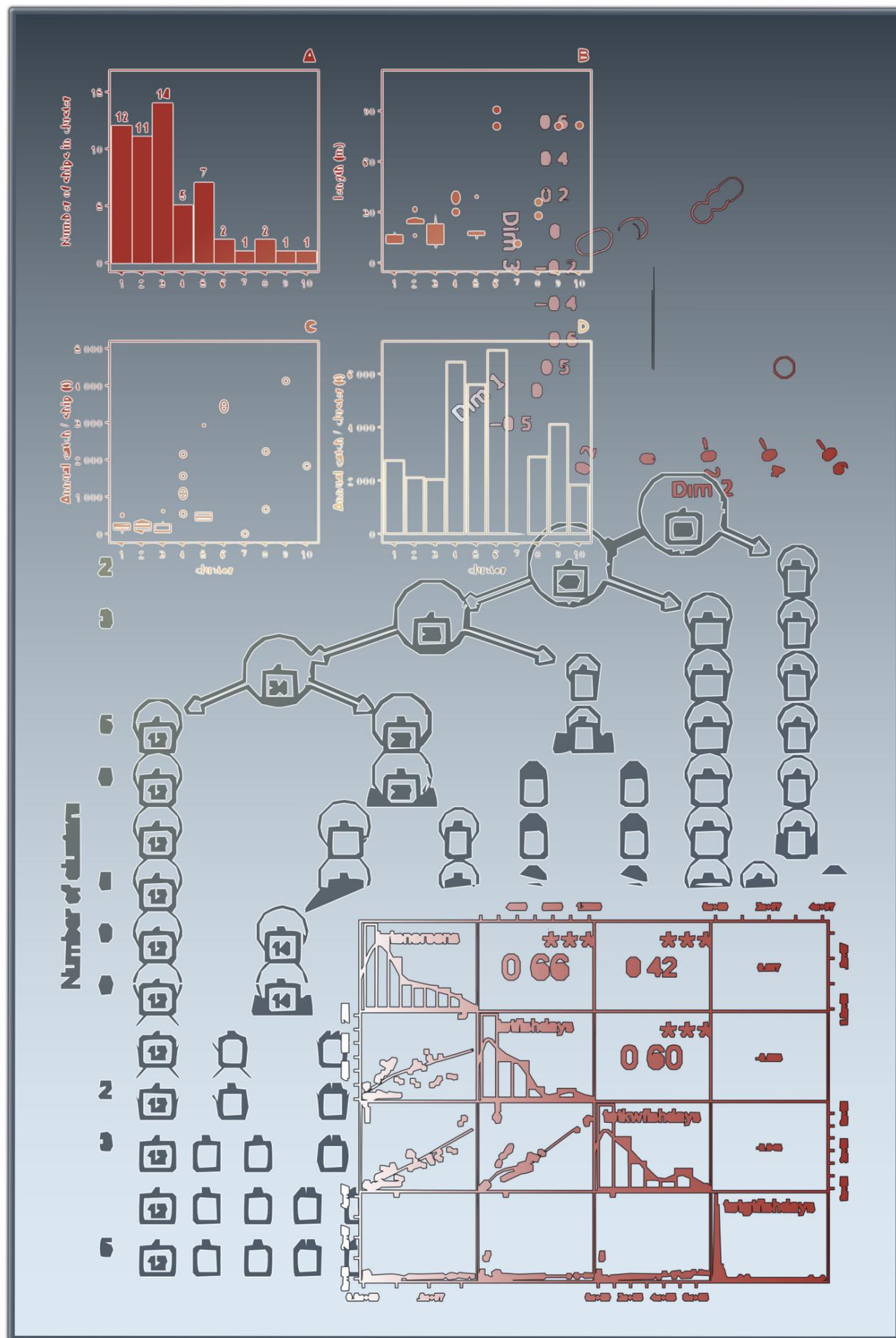
With ongoing warming, the North Sea becomes not only an unfavorable habitat for many boreal species, but also sees a steady increase in the occurrence and abundance of Lusitanian species (Jones et al., 2023) like mullets (*Mullus surmuletus* and *Mullus barbatus*), anchovies (*Engraulis encrasicolus*), hake (*Merluccius merluccius*), and several squid species (Oesterwind et al., 2022). Many of these species are highly valuable target species of fisheries with established regional and global markets, and might therefore become an economic opportunity for established demersal fisheries. Yet, the arrival of these new species poses a twofold challenge for fisheries management. If the species are managed by TACs in EU waters, they fall under the European quota systems of relative stability. This system grants a fixed share of the decided TAC to the European member states, which is based on catches obtained during a reference period between 1973 and 1978 (Hoefnagel et al., 2015). This period coincided with the gadoid outburst caused by a series of cold winters (Hislop, 1996) and therefore reflects environmental conditions significantly different from the present. Most North Sea fisheries hold no or only very little quota for Lusitanian species, and if they don't find partners willing to swap quota (a relief mechanism possible under European law, which is also continued with the UK after Brexit), they cannot engage in fisheries targeting these species. Hake became a striking example of this phenomenon, as the Northern Hake stock showed massive biomass increases in the North Sea between 2010 and 2020, making it a 'choke-species' for mixed demersal fisheries targeting saithe, cod, and haddock. These fisheries had to cease

operations as they had no access to hake quota, even though the quotas for their target species were not fully fished out, leading to severe economic losses (Cormon et al., 2014). If the newly arriving species are, however, not managed by TACs in the European system, the risk of unsustainable fishing practices is high, as they can be freely targeted with minimal restrictions. The emergence of squid fisheries in the southern North Sea is a striking example of the latter. It is covered extensively in the third chapter of this thesis. Regardless of the respective species being TAC-managed or not, including climate-induced shifts in species distribution and marine ecosystems in fisheries management is a major challenge. Moreover, it needs to be contextualized with other economic demands and political strategies, in which the oceans are increasingly viewed as the foundation of a thriving 'Blue Economy'.

Management of fisheries in the context of Blue Economy & Blue Growth

Following the vision of the European Green Growth strategy and given the sense of urgency arising from the acceleration of MSP programs, the United Nations coined the terms 'Blue Economy' and 'Blue Growth' in the context of the United Nations Conference on Sustainable Development (Rio +20) in 2012 (Lee et al., 2020). In the following years, the concept of a Blue Economy, although only loosely defined, gained momentum in research and management. The World Bank defines Blue Economy as 'sustainable use of ocean resources for economic growth, improved livelihoods, and jobs while preserving the health of the ocean ecosystem', while the EU utilizes the term to summarize '[a]ll economic activities related to oceans, seas and coasts. It covers a wide range of interlinked established and emerging sectors.' These highly broad and unspecific definitions illustrate how the term is rather conceptual and reflects the general idea of reshaping ocean governance. Given the decade-long stagnation of global capture fisheries output (FAO, 2024b), the decline of catches obtained by the EU fishing fleet, and the competition for marine space illustrated above, developing such a strategy on a supranational level is a reasonable and contemporary yet very challenging endeavor. The EU approached it by defining five core areas with the highest potential for Blue Growth, i.e., economic growth in line with the Blue Economy principles of sustainability, circularity, and carbon-emission reduction: 1) maritime tourism, 2) marine biotechnology, 3) renewable energy, 4) aquaculture, and 5) ocean mining. Additional sectors deemed crucial for the Blue Economy, but regarded as having limited growth potential, are shipbuilding and ship repair, maritime transport (cargo and ferry), fisheries, and offshore oil and gas (EU, 2019). From a scientific point of view, developing structured approaches for sustainable development and identifying priority areas is highly desirable, but fisheries scientists are nonetheless very critical of the fact that fisheries are deemed to have no Blue Growth potential and no priority in most Blue Economy approaches. Practical implications of balanced Blue Growth approaches for fisheries remain widely unclear (Soma et al., 2018). The impacts of growth strategies focusing on heavily industrialized sectors on small-scale fisheries and the coastal communities they are embedded in are often overlooked (Das, 2022). Moreover, marine social sciences are an emerging field, and we are just beginning to understand the social role fisheries play in coastal communities, but these communities could perish in the process of 'ocean-grabbing' linked to Blue

Growth, which some authors are apprehensive of (Brent et al., 2020). Other research highlights the necessity to maintain structured, continuous stakeholder involvement processes (Burgess et al., 2018) or emphasize the potential for extensive Blue Growth in fisheries by adding value and not catch quantity through certification and innovative products (Boonstra et al., 2018; Das, 2022). In the fourth chapter of this thesis, selected fisheries management approaches will be put in the context of the European Blue Economy framework to critically discuss the role fisheries can have in it in the future.



I. Improvements in data collection to facilitate realistic fishing fleet models



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Amending the European fishing fleet segmentation based on machine learning and multivariate statistics

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ABSTRACT

Considering the critical issue of overexploited stocks due to overfishing, the EU's Data Collection Framework (DCF) was established. Within the DCF, member states collect and analyze data relevant to sustainable fisheries management. To evaluate the status of fisheries, it is necessary to categorize fishing fleets into fleet segments. However, the current DCF segmentation is primarily based on technical vessel parameters, such as vessel length and predominant fishing gear, which often do not accurately represent the fishing activities of the vessels. To address this, we developed an alternative fleet segmentation approach that provides a more realistic overview of fishing activities. This approach utilizes multivariate statistics and is coupled with machine learning techniques for automatization. Applying this approach to two decades of German fisheries data resulted in a data set with fewer segments compared to the DCF approach, which represented the actual fishing strategies more closely. The comparison of biological stock health indicators calculated for both the current and the novel segmentation schemes revealed that the current scheme often misses signs of segments relying on overexploited stocks. The machine learning technique applied showed high classification accuracy, with misclassifications being rare and only occurring in segments with overlapping catch composition. Since machine learning enables almost perfect allocation to the revised segments, we expect a successful implementation of this protocol for future fleet segmentation. This approach is highly suitable for data collection and analysis procedures and can serve as a standard tool. Therefore, this novel approach can contribute to the improvement of fishing fleet analyses and policy advice for better fisheries management.

1. Introduction

Fisheries are facing a period of global upheaval. Decades of industrialized fishing have extensively exploited the world's oceans, leading many fish stocks to critical depletion levels or placing them in slow recovery phases (FAO, 2024). Moreover, the impacts of climate change on marine ecosystems are becoming increasingly evident, bearing considerable challenges for fisheries management (Miles, 2011). Changes such as rising sea temperatures, ocean acidification, and shifts in ocean circulation patterns, which are disrupting fish populations, altering habitats, and unsettling the balance of ecosystems (Brierley and Kingsford, 2009). Many commercially important fish species are migrating in response to new temperature regimes, causing noticeable distribution shifts on a global scale (Cheung et al., 2010).

Effective fisheries management plays a crucial role in addressing

these emerging challenges by implementing adaptive measures in response to changing environmental conditions (Burden and Fujita, 2019). Key strategies include setting sustainable catch limits, modifying fishing gear, and adopting ecosystem-based approaches. By integrating both ecological and socio-economic considerations, fisheries management can develop balanced strategies that support the recovery and sustainability of fish stocks, protect marine environments, and safeguard the livelihoods of fishing communities (Frost and Andersen, 2006; Gaines et al., 2018; Gourlie, 2017). To make informed decisions, it is vital to assess the impact of these management strategies, ensuring they effectively balance the diverse needs of society, economies, and ecosystems (Thorpe et al., 2016). Impact assessments provide a systematic method for evaluating the potential outcomes of management options on fish stock health, the economic viability of the fishing industry, and the cost-effectiveness of management measures (Propst and Gavrilis,

E. Sulanke et al.

1987).

A crucial element in these assessments is the collection of comprehensive and detailed fisheries data. Within the European Union, the Fisheries Data Collection Framework (DCF) provides a robust system for gathering, managing, and analyzing biological, environmental, social, technical, and economic data related to fisheries and aquaculture activities in EU waters (Dörner et al., 2018). This framework mandates the reporting of essential information by fisheries stakeholders, including data on catches, landings, effort, and fleet structure. The DCF emphasizes the importance of data quality, promotes integrated data management, and supports scientific evaluations of fish stocks and the economic performance of fishing fleets. This data-driven approach is central to the success of the Common Fisheries Policy (CFP), ensuring that European fisheries resources are managed sustainably through informed decision-making (Barkai et al., 2010; Simmonds et al., 2011).

The aggregated groups for which e.g. fleet economic data are to be provided are called fleet segments. In the data assessment, the DCF fleets are partitioned based on dominant fishing gear type (see Table 1), vessel size categories (see Table 2), and area of operation (see Annex Table A1). However, the current segmentation lacks components related to stock or catch profiles (European Commission, 2021). There are many states and organizations worldwide collecting fisheries data and aggregating vessels into fleet segments (although the nomenclature differs), and most of them apply technical characteristics of vessels for this purpose, e.g., the Food and Agricultural Organisation (FAO). Adding fishery-based or stock-based aspects to the segmentation schemes is less common. Nonetheless, this approach is more frequently adopted at national or regional levels, such as in the US North Pacific fisheries (Witherell et al., 2012), the United Kingdom (Seafish, 2023), or Norway (Fiskeridirektoratet, 2021).

The current fleet segmentation under the EU fisheries Data Collection Framework (DCF) is based on technical characteristics and thus lacks a closer link to fisheries or even fish stocks. This shortfall hinders guidance on sustainability and economic efficiency across individual fisheries (STECF, 2022).

While it is straightforward, it lacks the detail needed to accurately represent the diversity of fisheries in European waters (Guyader et al., 2013). For instance, Pawson et al. (2008) and García-Flórez et al. (2014) both emphasize the need for clear definitions and segmentation of recreational and artisanal fisheries, respectively. Lloret et al. (2018) underscores the evolving nature of small-scale coastal fisheries, influenced by factors such as the expansion of recreational fishing and the adoption of more mechanized techniques. These studies collectively emphasize the need for a more nuanced understanding of the European fishing fleet, recognizing the unique characteristics of each segment.

In addition, the DCF segmentation scheme groups vessels with similar technical features, yet these vessels may engage in distinctly

Table 1

DCF gear codes, corresponding gears, classification, and activity category of all gear classes relevant to the German fleet.

gear code	activity category	Description	Category
DFN	Passive gears	Drift and/or fixed netters	Nets
DRB	Mobile gears	Dredgers	Dredges
DTS	Mobile gears	Demersal trawlers and/or demersal seiners	Trawls
FPO	Passive gears	Vessels using pots and/or traps	Traps
FPO	Passive gears	Uncovered fixed pound nets	Traps
PGO	Passive gears	Vessels using other passive gears	Other
TBB	Mobile gears	Beam trawlers	Trawls
TM	Mobile gears	Pelagic trawlers	Trawls
PG	Passive gears	Vessels under 12 m length using miscellaneous passive gears	Nets, hooks and traps

Table 2

DCF vessel length classes as applied in all European fleets except for Mediterranean fleets. Depicted are the official DCF length class codes, the corresponding vessel length range and the prevalence of the length class in the German fishing fleet. The prevalence is given in minimum and maximum percentage of the segment in relation to the entire fleet with regard to the number of vessels and the gross tonnage for the years 2002–2022.

Vessel length class	Vessel length [m]	Share of German fishing fleet 2002–2022 (%)	
		number of vessels	gross tonnage
VL0010	0 – 10	64.17 – 69.30	2.03 – 3.36
VL1012	10 – 12	5.87 – 7.33	1.17 – 1.99
VL1218	12 – 18	12.42 – 17.02	6.46 – 11.31
VL1824	18 – 24	6.64 – 9.03	8.51 – 13.43
VL2440	24 – 40	2.03 – 3.93	9.11 – 17.68
VL40XX	> 40	0.87 – 2.02	53.69 – 72.69

different fisheries with differing catch compositions, fishing practices, and cost structures. The German demersal trawl fleets operating in the Baltic Sea and the North Sea are good examples of this. These vessels are technically similar and thus belong to the same DCF segment, but they target different species and exhibit variations in fishing practices. Not only do they fish on entirely different fishing grounds, but they also considerably differ in the time necessary to reach these fishing grounds. The time a vessel spends reaching fishing locations is commonly referred to as 'steaming time'. Conversely, vessels performing the same fishery may have remarkable differences in technical characteristics, such as vessel length, and consequently are assigned to different segments. For instance, the German brown shrimp fishery, which includes beam trawlers ranging from 10 to 24 m, is segmented into different DCF segments: TBBVL1012, TBBVL1218, TBBVL1824 (Goti-Aralucea et al., 2021).

Thus, the current generalized fleet segmentation employed by DCF does not provide the detailed information required to fully comprehend the diverse fishing practices throughout European waters. This mismatch between fleet segmentation and actual fishing practices can lead to suboptimal fisheries management (Dépalle et al., 2020; Poos et al., 2010), especially as many fisheries management measures, including financial support, regulations, and quota allocations, are often linked to DCF segments (Branch et al., 2006; Moura et al., 2016; Ulrich et al., 2012). Consequently, fleet segmentation plays a pivotal role in deciding which management measures are applied to specific vessels, impacting the effectiveness of these initiatives in achieving sustainable fishing practices.

Moreover, the International Council for the Exploration of the Sea (ICES) as key advisory body for the European Union, defines fisheries as " [...] a group of vessel voyages targeting the same (assemblage of) species and/or stocks, using similar gear, during the same period of the year and within the same area (e.g., the Dutch flatfish-directed beam trawl fishery in the North Sea) [...] " (ICES, 2003). This definition suggests a more detailed fleet segmentation than that used by the DCF, highlighting a major granularity gap between ICES and DCF fisheries data systems. Because of this mismatch, ICES encounters difficulties to fully incorporate economic fleet structures and dynamics into its predominantly biological advice (ICES, 2024; Smit, 1996). Since fishing measures will affect fishers' behavior and subsequently affect fleet dynamics and fish stock development, it is crucial to consider detailed fleet data when evaluating fisheries management measures (Li et al., 2021; Branch et al., 2006; Salas and Gaertner, 2004).

To improve accuracy in fisheries management, an innovative fleet segmentation approach based on multivariate statistics has been developed that more closely aligns with the actual activities of fleets. Multivariate statistics have been commonly used in fisheries research to identify target fisheries since the general availability of high-power computers enabled researchers to analyze the necessary, large datasets (Lewy, 1994; Rogers and Pikitch, 1992). Often originating in community

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ecology (Faith et al., 1987), they are excellent tools for such analyses. The analysis of a species community, specifically of species diversity and abundance, resembles the analysis of a fisheries catch profile in nearly every aspect. Yet, to our best knowledge, the multivariate approaches used in fishing fleet analysis were primarily applied to specific fisheries or fleets (Holley and Marchal, 2004; Jiménez et al., 2004; Lewy, 1994; Murawski et al., 1983; Natale et al., 2015; Pelletier and Ferraris, 2000; Pilar-Fonseca et al., 2009) and were not designed with regard to transferability and mechanistic consistency. In addition, they were not paired with contemporary techniques of machine learning, which can boost the applicability and effectiveness of such approaches.

This method enhances the consistency of catch data and cost structures. To facilitate the segmentation procedure, a machine learning-based automation process using a random forest algorithm has been employed. Random forest algorithms have been increasingly applied in marine and fisheries research to a variety of research questions. Early, their general applicability in ecology was highlighted (Cutler et al., 2007). Random forest algorithms have since been used in marine ecology to forecast species abundances (Baba and Matsuishi, 2015), model the distribution of rare species (Garcia et al., 2022), analyze population structures (Berio et al., 2022; Zhang et al., 2016) and classify species based on echosounder data (Rousseau et al., 2022). Current efforts are underway to even incorporate new applications of random forest algorithms for autonomous biomonitoring into legislation (Cordier et al., 2018). In fisheries research, the variety of applications is similarly widespread, as random forest algorithms were applied for analyses of spatial use patterns (Behivoke et al., 2021; Joo et al., 2013), harvest control rules (Van Poorten et al., 2013), and bycatch misreporting (Lennert-Cody and Berk, 2007). Even on the economic side of fisheries research, business risk assessment can be conducted by applying random forest algorithms (Sethi et al., 2012). As highlighted by Cutler et al. (2007), these algorithms inherit several crucial advantages over other classification methods, most notably achieving very high classification accuracies. Further advantages include the ability to account for interactions of predictor variables and the robust identification of variable importance (Cutler et al., 2007). Also, the random forest algorithm is capable of performing accurate classification as well as regression tasks, which makes it suitable for a variety of disciplines and problems (Breiman, 2001).

Equipped with a training dataset, this method can efficiently segment and analyze extensive fisheries data spanning multiple decades. This advancement not only allows the user-friendly creation of fleet segments for management and advisory purposes but also reduces the workload for individual data collectors within the DCF.

2. Material and methods

The is divided in the three major sections, which are

- 1) the method description and statistical background of the alternative fleet segmentation approach based on multivariate statistics;
- 2) the description of the random forest algorithm which was applied for automatically assigning alternative segments; and
- 3) the calculation of balance indicators for the evaluation of the alternative segments.

They are structured as follows:

Section 2.1. and its sub-sections describe the data basis and preparation for the clustering approach; Section 2.2. describes the application of the clustering approach and the formation of alternative fleet segments. In Section 2.3., the random forest machine learning approach is described, divided into sub-sections for data preparation (2.3.1.) and model application (2.3.2.). In the last Section 2.4., the theoretical framework and calculation of the applied balance indicators used for evaluation are described.

2.1. Clustering – data preparation

The newly developed fleet segmentation approach focuses on a detailed analysis of the catch composition for individual fishing vessels within the German fishing fleet from 2002 to 2020. This analysis incorporates landed catch weights, fishing effort, and vessel characteristics such as length, tonnage, and engine power, which were linked to the landings data set.

2.1.1. Step 1: data segregation by gear classes

Initially, the dataset was categorized by gear classes (Table 1). From the logbooks, the average trip duration and annual fishing effort were calculated and then used to assign the predominant fishing gear to each vessel based on the highest percentage of annual usage. For small-scale coastal vessels without logbooks, estimates were derived from monthly reports and assigned to a designated gear type labeled "PG".

2.1.2. Step 2: allocation of catches to stocks

Catches were then allocated to stocks (i.e. fractions of species inhabiting defined geographic areas) according to species and catch location, using species definitions from ICES, ICCAT (International Commission for the Conservation of Atlantic Tunas), and GFCM (General Fisheries Commission of the Mediterranean). For areas lacking specific official stock descriptions, 'pseudo-stocks' were created based on the combination of species codes from ICES (ICES, 1979) and FAO fishing areas (FAO, 2020). These are not officially defined stocks, yet, they are necessary combinations of species information and geographic areas to create a homogeneous data set.

2.1.3. Step 3: calculation of sock shares

The share of each stock in the total annual catch was calculated using catch weight as a reliable variable due to its importance for stock management (Davie and Lordan, 2011). Catch value was excluded from consideration due to considerable fluctuations in market prices (Goti-Aralucea et al., 2021). Stocks contributing less than 5 % to a vessel's total catch were excluded to minimize distortions in the analysis, as they inflate the time needed by the grouping algorithm and inherit the risk of over-separation without adding any relevant information. The 5 % threshold was set and tested by fishing fleet data experts in three fleet segmentation workshops held prior to the preparation of this article (RCG ECON, 2023, 2022 & 2021).

2.2. Clustering – model application

Based on the stock shares and the major fishing gear, vessels were then pre-separated, and a distance matrix was calculated using a metric conversion of the Bray-Curtis-Dissimilarity Bray and Curtis, (1957), included in *vegan* R-Package, version 2.6–4, (Oksanen, 2009) to analyze the number of potential fleet segments.

The Bray-Curtis dissimilarity D between the two catch profiles j and k is computed as

$$D_{jk} = 1 - \frac{2 \cdot \sum_{i=1}^p \min(y_{ij}, y_{ik})}{\sum_{i=1}^p (y_{ij} + y_{ik})}$$

Where p is the number of stocks occurring in both catch profiles and $\sum_{i=1}^p \min(y_{ij}, y_{ik})$ is the sum of lesser shares of each stock on the total catch if it occurs in both catch profiles. The metric conversion M of the Bray-Curtis-Dissimilarity D is then computed as

$$M = \frac{2D}{(1 + D)}$$

The chosen distance measure for clustering adheres to the three axiomatic principles of metrics - positive definiteness (i.e., the distance

between two points is always positive), symmetry (i.e., the distance between point x and point y always equals the distance between y and x), and triangle inequality (the sum of any two sides of a triangle formed by the points x , y , and z is always greater than the third side) (Burago et al., 2001). This adherence ensures robustness in post-hoc analysis and cluster validation, as metric distances allow for the application of a larger variety of methods which are also easier to interpret than non-metric methods, e.g., multi-dimensional scaling (MDS) versus non-metric multi-dimensional scaling (NMDS) (Borg and Groenen, 2007; Legendre and Legendre, 2012). Employing the distance matrix, which reflects the stock proportions from each vessel's total catch, hierarchical agglomerative clustering (HAC) is used. HAC starts by treating each vessel as an individual cluster and progressively merges them into larger clusters using the UPGMA ("Unweighted Pair-Group Method using arithmetic Averages") algorithm.

The selection of UPGMA as the optimal fusion algorithm was based on its ability to maintain a high cophenetic correlation, which is the linear correlation coefficient between the original distance matrix and the clustering result (Sneath and Sokal, 1973). A high cophenetic correlation signifies a good reflection of the underlying data by the clustering result, underscoring the method's efficacy. In UPGMA, the distance between a single object and a cluster is calculated as the average of distances between the object and every member of the group (Sokal, 1958). This method is noted for its effective algorithm that accurately determines distances during the clustering process, enhancing the precision and relevance of the analysis.

$$d_{(AB)X} = \frac{1}{2}(d_{AX} + d_{BX})$$

In the clustering process, clusters are denoted by exemplary labels such as A and B, which merge into a resultant cluster X with computed distance d . Determining the ideal number of clusters within the data set by applying the described procedure is challenging. To address this, a combination of indices was used, including the silhouette coefficient (Rousseeuw, 1987), the Mantel correlation (Borcard et al., 2011), and the SD index (Halkidi et al., 2000). The silhouette coefficient and the SD index are indicators based on the compactness and separation of clusters, and therefore evaluate the quality of the clustering result (Rousseeuw, 1987; Halkidi et al., 2000), whereas the Mantel correlation between the original distance matrix and the binary partition matrices of

the clustering procedures evaluates the quality of the clustering result with respect to the original data (Borcard et al., 2011). Even though applying these indicators leads to selecting an appropriate number of clusters, not all clusters accurately represented distinct fleet segments, with some being amalgamated based on similarities in vessel length, catch composition, annual landed weight, and the Herfindahl-Hirschman index (HHI) of catch composition (Rhoades, 1993).

The HHI is a widely used economic index that measures the level of competition or concentration within an industry. It ranges from 0 to 1, where 1 indicates complete concentration while lower values indicate greater competition. Applied to our fisheries data, high HHI values near 1 suggest strong concentration of a fishery on a specific stock, whereas lower values indicate fisheries with a diverse catch composition. This nuanced application of the HHI helps understanding the degree of stock concentration within different fleet segments, facilitating more targeted and effective management strategies.

The process for determining the optimal number of clusters involves iterative loops to ensure accuracy, as shown in the flowchart (Fig. 1). Specific guidelines for applying the previously mentioned tests, selecting the appropriate number of clusters, and merging them are outlined in the user manual of the R-package *FleetSegmentation* (Sulanke, 2021). The clustering procedure segments each gear class dataset by reference year, ultimately producing a comprehensively segmented fleet dataset that spans two decades.

2.3. Random forest approach

2.3.1. Random forest – data preparation

Before deploying machine learning techniques, Principal Component Analysis (PCA) and correlation analysis were performed using the *prcomp* and *cor* functions from the *stats* package (R Core Team, 2024). PCA was chosen primarily for its ability to reduce the dimensionality of the dataset, thereby simplifying the subsequent analysis while retaining most of the variance present in the original data (Jolliffe and Cadima, 2016). This reduction in dimensionality helps in mitigating issues related to multicollinearity, where highly correlated variables can distort model predictions and make the model less interpretable. Additionally, PCA aids in noise reduction by focusing on principal components that capture significant variance, thus filtering out less informative aspects of the data (James et al., 2013). This process

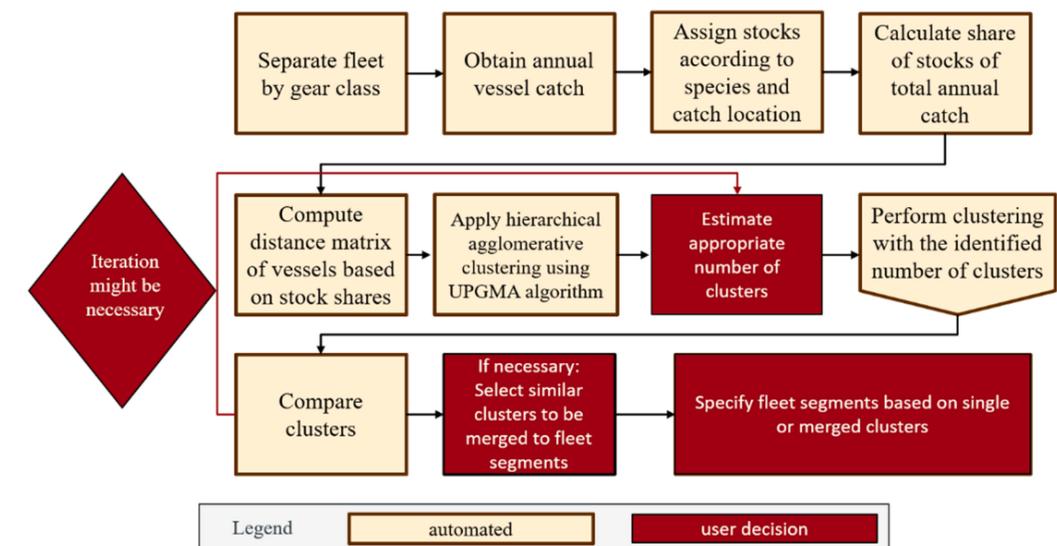


Fig. 1. Stepwise flowchart of the developed fleet segmentation approach. Dark sections highlight critical decision points for using the functions in the associated R package.

enhances the robustness and performance of the random forest model by ensuring it is trained on the most relevant features. Variables with <5 % contribution to distinguishing fishing fleet segments and those highly correlated (>0.9 correlation coefficient) were excluded, resulting in 130,441 observations and 5 explanatory variables, including fleet segment categorization. This dataset was randomly split into a 70:30 learning-testing ratio iteratively.

2.3.2. Random forest – model application

A Random Forest (RF) model (Breiman, 2001) was applied to the learning dataset using the *randomForest* package (Liaw and Wiener, 2002) with default tuning parameters for laymen applicability. The RF model predicted fleet segments for the testing dataset, and the results were compared to the alternative segments. Confusion matrices were generated to identify and quantify misclassifications. Accuracy, Cohens kappa values, and variable importance measures were determined. The entire process was repeated in a 10-fold cross-validation, averaging measures across bootstrapped models.

2.4. Balance indicators

To assess the improvements made by implementing the alternative segmentation approach, both in terms of relevance and effectiveness for fisheries' operational profiles, a suite of both established and novel indicators was used.

1. Cumulative Share Analysis: The cumulative share of segments on the total catch of fish stocks was calculated, by calculating the shares of the fleet segments under both the DCF and novel segmentation schemes on the total harvest of given stocks and then aggregating these shares. The cumulative shares were subsequently analyzed graphically.
2. Stocks Targeted by Each Segment: The number of stocks targeted by each segment under both the novel and the DCF segmentation schemes was calculated. In this part of the analysis, only stocks that were harvested by more than one segment in at least one segmentation approach were considered. Additionally, a stock had to account for at least 5 % of a segment's total catch to be classified as targeted.
3. Sustainable Harvest Indicator (SHI): The SHI was calculated for all segments under both segmentation schemes. It quantifies the reliance of fleet segments on potentially overfished stocks, taking into account the health of the targeted stock as well as the fleet economics. This well-established indicator is an integral part of an annual fishing fleet report of the STECF, in which the balance between the fishing capacity and the fishing opportunities in the EU fishing fleet is assessed (STECF, 2024). It is calculated based on the ratio between fishing mortality (F) and fishing mortality linked to maximum sustainable yield (FMSY), where values above 1 ($F / FMSY > 1$) signify excessive economic reliance on vulnerable stocks. The economic reliance is derived from the landing values. A detailed description and discussion of the SHI methodology can be found in the corresponding communication of the European Union (European Commission, 2014).
4. Stocks at Risk (SAR): The number of SAR for each segment under both segmentation schemes was determined. SAR accounts for the number of stocks at low biological levels of biomass or productivity that are economically important to the respective fleet segment or where the fleet segment significantly contributes to the overall fishing pressure on the stock. Like the SHI, it is a commonly used indicator of the STECF (STECF, 2024). To be considered as an SAR under the official definition of STECF, a stock must meet at least one criterion in each of two categories: 1) It must be assessed as being below biological limits (B lim); subject to advice to close the fishery or reduce fishing pressure; part of a regulation requiring catch and release; or listed by IUCN or CITES. 2) It must constitute 10 % or

more of the catches by the fleet segment or the fleet segment must harvest 10 % or more of the total catches of the stock.

These indicators collectively provide a comprehensive evaluation of how well fisheries are in line with their fishing opportunities, how reliant they are on stocks having a risk of being overfished and of how well these fisheries are represented by the underlying fleet segmentation approach. Therefore, they were chosen to illustrate how the new segmentation approach aligns with the operational realities and conservation objectives of fisheries, facilitating more informed management decisions.

3. Results

In the analysis of the German fishing fleet from 2002 to 2020, fifteen distinct fleet segments were identified, consisting of 2328 individual vessels across five different gear classes. Except for 2002, all identified segments were consistently present throughout the years. The analysis revealed a mix of multi-species fisheries, predominantly targeting various demersal fish assemblages, alongside single-species fisheries focused on demersal and pelagic fish, crustaceans, and bivalves. The structure of these fleet segments aligns with expert statements of the German fishing fleet structure, which were collected before the analysis. A comprehensive overview of all identified fleet segments, the number of vessels in each, and the type of fisheries performed in the reference year of 2018 is presented in Appendix Table A2. Fig. 2 illustrates the relationship of DCF segments and alternative segments by displaying the number of vessels per segment in the respective segmentation approaches as well as the relationship between segments formed in both segmentation approaches. The details of the fleet segments formed applying the alternative approach and their relation to the DCF segments will be described in the following sections, which are structured as follows. Sections 3.1 and 3.2 comprehensively describe the new fleet segments formed using the alternative approach; Sections 3.3 and 3.4 contain the results of the application of the random forest algorithm; and Sections 3.5, 3.6, and 3.7 relate the alternative segments to the DCF segments and describe the result of the evaluation based on the balance indicators.

3.1. Small-scale and specialized fisheries

Small-scale coastal fisheries, which comprised about 70 % of the vessels in the dataset, displayed a wide range of catch profiles due to their part-time or subsistence nature. Despite their operational diversity, these vessels are often similar in cost structure, justifying their categorization into a single fleet segment labeled as "Small-scale passive gear fishery" for vessels using passive gear and less than 12 m in length.

However, few vessels under 12 m, actively engaged in the brown shrimp fishery but initially misclassified due to missing gear information, were reassigned to "Brown shrimp fishery". This segment includes the majority of beam trawlers (gear code TBB), and is noted for being the largest and, in terms of revenue, most valuable coastal fishery in the German fleet, accounting for about 18 % of the vessels annually.

Another small group of beam trawlers targeted plaice (*Pleuronectes platessa*) and sole (*Solea solea*), with sole being the more lucrative species. This segment was designated as "Sole fishery". The remainder of beam trawlers participated in the "Blue mussel fishery", involving the capture of seed mussels (*Mytilus edulis*) for cultivation. This "Blue mussel fishery" also contained all vessels using dredges (DRB).

3.2. Larger and diverse gear classes

Vessels longer than 12 m using passive gears – such as pots and traps (FPO), drift and fixed nets (DFN), and hools (HOK) – were grouped into a single gear class, representing a smaller fraction (1–2 % annually) of the fleet.

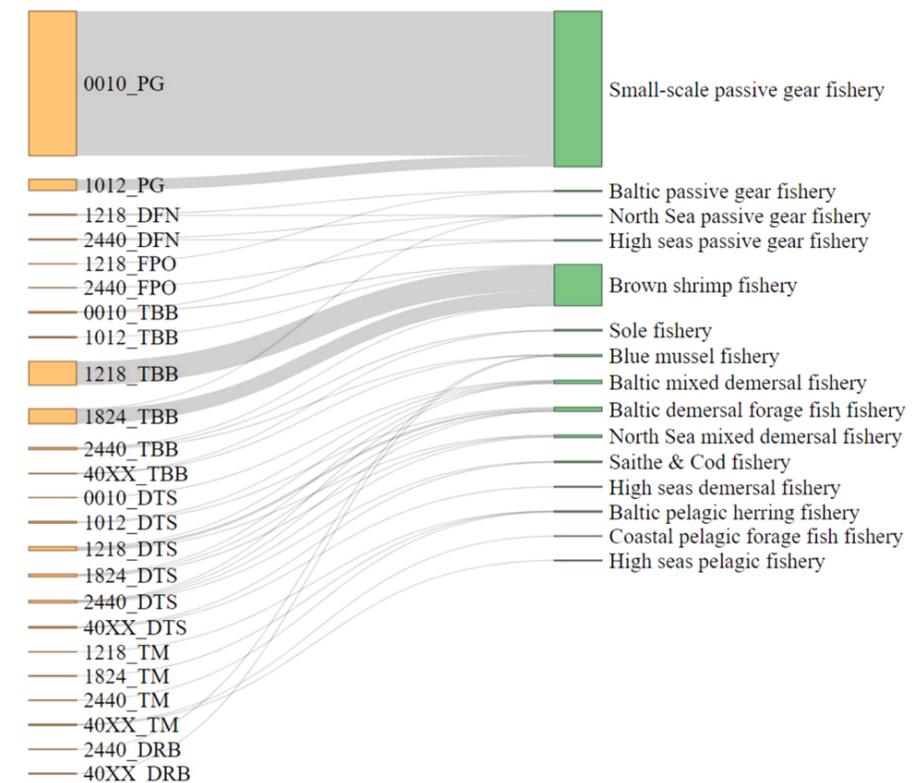


Fig. 2. Sankey flowchart of the vessels in the German fishing fleet in 2018 classified according to DCF segmentation approach (left, orange) and the alternative segmentation approach (green, right). The width of the rectangles and links is proportional to the segment size.

The demersal trawlers and seiners (DTS) represented the most diverse gear class, distinguishing five specific fisheries. Two of those were in the Baltic Sea: one primarily targeting herring (*Clupea harengus*) and another mixed fishery for plaice (*Platichthys spp.*), flounder (*Platichthys spp.*), dab (*Limanda limanda*), and cod (*Gadus morhua*). In the North Sea, one fishery mainly targeted saithe (*Pollachius virens*) and cod, and another is a mixed fishery for plaice, sole, and Norway lobster (*Nephrops norvegicus*). The fifth is the high seas demersal fishery operating Svalbard and Greenland, targeting Greenland halibut (*Reinhardtius hippoglossoides*), cod, and redfish (*Sebastes spp.*).

The midwater trawlers (TM) also showed diverse activities, with one segment comprising smaller vessels (<25 m) in the Baltic Sea catching herring and sprat (*Sprattus sprattus*), while a second included larger vessels (~40 m) in the North Sea targeting the same stocks, but also sprat and sandeel (*Ammodytes spp.*). The last segment encompassed the largest vessels (80–120 m) of the fleet, operating in international waters targeting pelagic species like mackerel (*Scomber scombrus*), herring, blue whiting (*Micromesistius poutassou*), and Chilean jack mackerel (*Trachurus murphyi*) in the Northeast Atlantic, as well as of the coast of West Africa and in the Southern Pacific.

Overall, the novel approach to fleet segmentation reduced the number of fleet segments from 24 to 15, with 65 % of DCF segments containing vessels from two or more identified novel fleet segments, demonstrating more nuanced and efficient categorization reflective of operational realities.

3.3. PCA analysis and RF model implementation

The PCA (Fig. 3) of the data set resulted in 69.1 % of the variance explained. Especially the variables 'Vessel length', 'Gross tonnage', 'Engine power', and 'Mean trip length' had a large contribution to

dimension 1, while 'Gear type', 'Target assemblage ID', and 'Mean trip length' explained the separation of the observations along dimension 2 (see Fig. 3). The contribution of 'Catch weight' to the variance was minimal, accounting for less than 5 % across both dimensions combined.

Closely spaced directional PCA vectors of the variables 'Vessel length', 'Gross tonnage', and 'Engine power' already indicated a feature correlation which was confirmed in a subsequent correlation analysis (see Fig. 3). The correlation coefficient for all possible parameter combinations yielded between 0.9 and 0.96. Since the contribution of the parameter 'Vessel length' (contrib.=13.6) to the PCA dimensions exceeded the contribution of "Gross tonnage" (contrib.=13.3) and "Engine power" (contrib.=13.5), the highly correlating features 'Gross tonnage' and 'Engine power' were omitted for downstream analysis to streamline the dataset and focus on the most influential parameters.

Hence, in addition to the reference label of fishing fleet segment, four explanatory variables have met the previously set conditions and were therefore used for RF model construction: i) 'Vessel length' (approx. 3.5–130 m), ii) 'Mean trip time' (approx. 30 mins-3.5 months), iii) 'Gear type' (6 different gear types) and iv) 'Target assemblage ID' (14 different IDs) (see Fig. 4). The RF models were able to correctly characterize the fishing fleet segments in 99.18 percent of the observations in the testing dataset (see Fig. 5). On average, the calculated kappa value was 0.98, indicating a "perfect agreement" between prediction and reference (Landis and Koch, 1977).

3.4. Error analysis and variable importance

Fishing fleet segment classification errors were most frequent in the segments 'G_7' (class error = 7.1 %), 'F_6' (class error= 3.2 %), 'I_9' (class error= 3.1 %) and 'C_3' (class error= 2.7 %). For all other fishing fleet segment classifications, the error rate was <1.5 %. For the

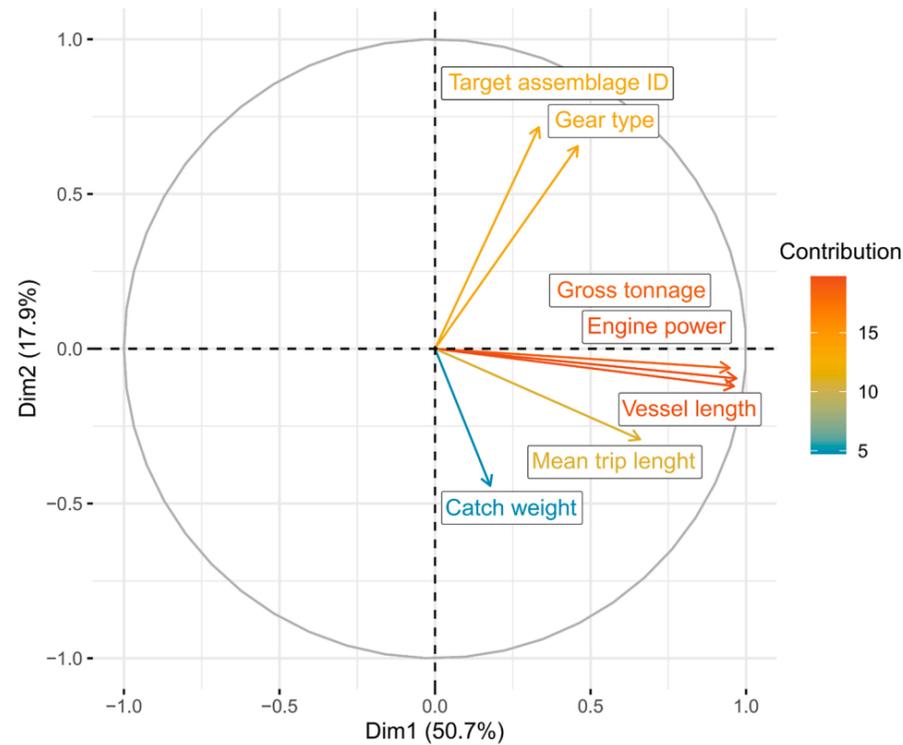


Fig. 3. Relative contribution of labels to separation of observations among the two most discriminant PCA axis. Directions of the vectors indicate the axis to which the factor contributes the most. The color coding shows the total relative contribution of the respective factor.

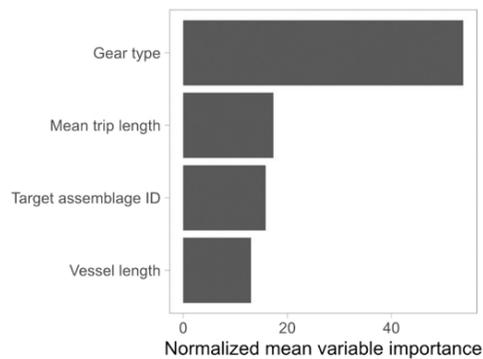


Fig. 4. Variable importance scores of the random forest, based on mean decrease in accuracy and averaged from the ten cross-validation runs, scaled to a total of 100.

prediction of five fishing fleet segments ('E_5', 'K_11', 'L_12', 'M_13', 'N_14'), an error rate of zero was achieved, meaning that in all ten bootstrap models, no single observation was assigned to an incorrect fishing fleet segment. To determine variable contribution to the RF model, variable importance measures for each feature were averaged over the ten bootstrapped models. Overall, the feature 'Gear type' was detected to be the most important variable to enable correct classifications of fishing fleet segments. The features 'Mean trip length', 'Target assemblage ID', and 'Vessel length' contributed in descending order to correct classifications. We found that G_7 and I_9 as well as F_6 and C_3 have overlaps in their catch composition with some vessels regularly switching between the respective fisheries. Therefore, the classification error is the result of an actual overlap in fishing strategies in a part of the

fleet and not due to a mechanistic problem or a data issue. However, they are not the only fleet segments with overlapping catch profiles present in the data set. Those remaining segments with overlapping catch profiles had, as mentioned, very low classification errors. All segments with zero classification errors are comprised of vessels with unique combinations of technical features and catch profiles with little to no overlap with other segments.

3.5. Homogeneity of fleet segments

Fleet segments are intended to reflect and facilitate management related to fisheries and stock assessments. To compare the homogeneity of segments in relation to fisheries and stocks four specific metrics have been employed: The SHI and SAR indicators, the analysis of the number of stocks exploited per segment, and the number of segments exploiting each stock. A full overview of the calculated SHI indicators and SARs can be found in Appendix Table A3.

Multiple cases where vessels from two or more alternative segments with considerably different SHIs and/or SARs were present within a single DCF segment were detected. For example, three demersal trawler length classes (DTS VL1218, DTS VL 1824, DTS VL 2440) encompassed vessels from several alternative fleet segments. Notably, the Baltic mixed demersal and Baltic demersal forage fish (e.g., herring *Clupea harengus* or sprat *Sprattus sprattus*), along with the North Sea mixed demersal fishery, were present across all these DCF segments. The SHIs for the Baltic fisheries were similar (1.85 and 1.81) and generally higher than those of the corresponding DCF segments, whereas the North Sea mixed demersal fishery displayed a lower SHI of 1.18.

3.6. Challenges with DCF segmentation

The analysis highlights issues with the DCF segmentation, such as the non-detection and misestimation of SHIs and SARs. For instance, the

		Prediction														
		A_1	B_2	C_3	D_4	E_5	F_6	G_7	H_8	I_9	J_10	K_11	L_12	M_13	N_14	O_15
Reference	A_1	99.4	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0
	B_2	0.01	98.597	0.103	0.118	0	0	0.002	0	0.018	0.004	0	0	0	0	1.148
	C_3	0	2.092	97.259	0.022	0	0.627	0	0	0	0	0	0	0	0	0
	D_4	0	0.828	0.023	99.149	0	0	0	0	0	0	0	0	0	0	0
	E_5	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0
	F_6	0	0.664	2.415	0	0.091	96.83	0	0	0	0	0	0	0	0	0
	G_7	0	0.105	0	0	0	0	92.866	0.061	6.833	0.135	0	0	0	0	0
	H_8	0	0	0	0	0	0	0.017	99.663	0.181	0.139	0	0	0	0	0
	I_9	0	0	0	0	0	0	3.118	0	96.862	0.021	0	0	0	0	0
	J_10	0	0.011	0	0	0	0	0.032	0.252	0.005	99.7	0	0	0	0	0
	K_11	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0
	L_12	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0
	M_13	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0
	N_14	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0
	O_15	0	0.004	0	0	0	0	0	0	0	0	0	0	0	0	99.996

Fig. 5. Confusion matrix resulting from RF predictions. The predicted fleet segment classification for each observation is compared to the respective reference classification. The confusion matrix diagonal shows the percentages of correctly classified observations among 10-fold cross-validation (green). Non-diagonal tiles show the proportion of misclassified categories.

DTS VL1218 and DTS VL1824 were each assigned one SAR, but the DTS VL2440 received none. This SAR was Western Baltic cod – cod.27.22–24, which is only a relevant target species for the fleet segments operating in the Baltic. Similarly, in the DFN VL2440 segment (SHI: 1,85, no SAR), consisting of high seas passive and North Sea passive gear fisheries, discrepancies in SHI and SAR assignments were evident. While the former had no SAR and the SHI was not only low (0.69) but also technically not applicable (assessed stocks accounted for less than 40 % of the segments total catch), the latter had one of the highest SHIs in the analysis (2.32) and one SAR (North Sea sole – sol.27.4). For the DCF segment DFN VL 1218, two SARs were computed (Western Baltic herring - her.27.20–24; North Sea sole – sol.27.4), yet the herring SAR is only attributable to the fraction of the segment assigned to the Baltic passive gear fishery, while sole is only fished by the fraction assigned to the North Sea passive gear fishery. These cases suggest that DCF segmentation may lead to overestimations or underestimations depending on the stock and the applied metrics.

3.7. Stock exploration analysis

The analysis of how many segments harvest specific stocks showed that Western Baltic herring (her.27.20–24) was harvested by eleven DCF segments but only four alternative segments (see Fig. 6), underscoring potential inefficiencies in the DCF approach. In contrast, North Sea and Northeast Atlantic herring (her.27.1–24a514a) were harvested by more alternative segments than DCF segments, indicating a more refined segmentation in the alternative model.

Graphical analysis of the number of segments necessary to assess

100 % of stocks' total catch, six commercially important stocks revealed that fewer alternative segments than DCF segments were needed to cover a high share (> 90 %) of total catch (see Fig. 7). The mean number of segments required to cover a high share of the analysed stocks was considerably lower in the alternative segmentation (4.07) compared to the DCF segmentation (5.6.).

4. Discussion

4.1. More effective management

The new fleet segmentation method offers a more accurate division of fisheries data into segments that align closely with actual fishing activities compared to the current DCF segmentation. This novel approach not only reduces the total number of fleet segments but also provides a closer link between groups of vessels, their targeted fish stocks, and the fishery performed. The latter became apparent in the analysis of SHIs and SARs, as it exposed the missing connection of fleet segments and targeted fishing stocks in the DCF segmentation as a major downside. Results showed that this method of segmenting fishing fleets can hide concerning imbalances in specific fisheries. Additionally, combining multiple fishing strategies within a single DCF segment can produce inaccurate indicator results, SHIs as well as SARs. If this indicator is inaccurate, it may give a false impression of the actual condition of the fishery. For example, an inaccurate SHI might suggest that a fleet segment might excessively rely on an overfished fish stock, or vice versa might imply an excessive reliance, which is actually not present. Inaccurate SHIs derived from current DCF segmentation can misguide

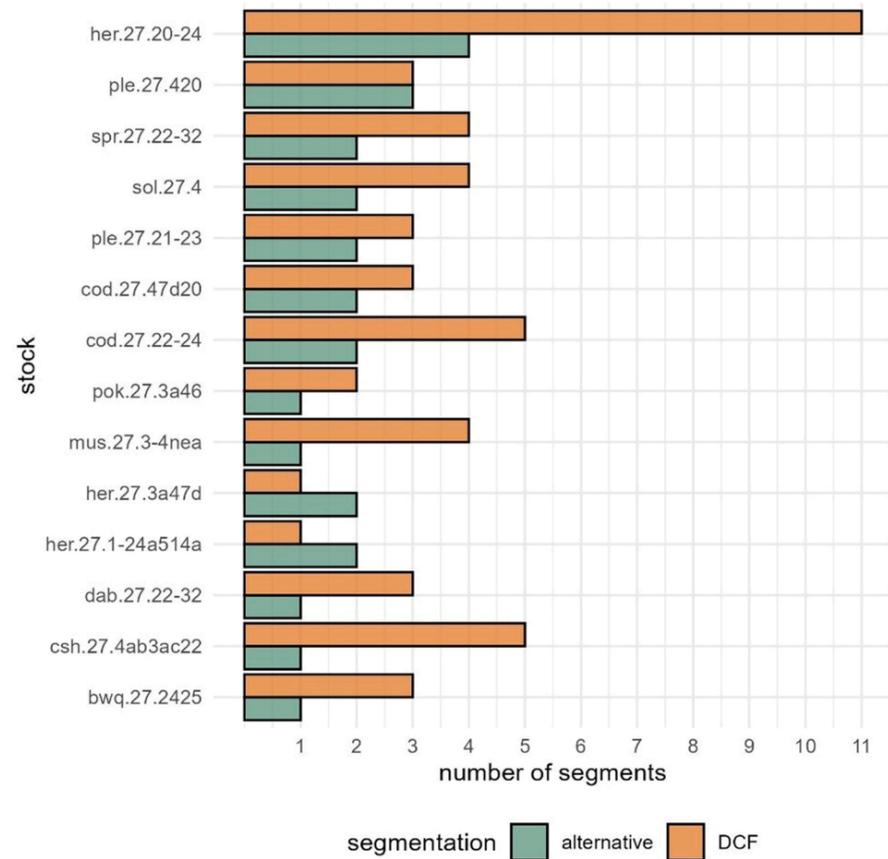


Fig. 6. Bar chart of the number of segments harvesting specific stocks in the German fishing fleet in 2018. The number of segments is displayed on the X-axis; the stocks on the Y-axis. The color signifies the applied segmentation scheme (green = alternative, orange = DCF).

policymakers into implementing measures that do not address the real issues. For instance, a fishery might be subject to unnecessarily strict regulations if SHIs falsely indicate imbalances, or it might be under-regulated if SHIs and SARs falsely suggest that fleets are in balance. A good example of such a case is the situation of German trawl fisheries (DTS) described in the results (see Section 3.6.). The SAR is assigned to the demersal trawl DTS segments referred to Western Baltic cod (cod.27.22–24), which was mainly targeted by the Baltic fraction of German trawl fisheries ('Baltic mixed demersal fishery' in alternative segmentation), yet, it was in a very critical state and has reached a catastrophic stock collapse recently, critically jeopardizing the continued existence of this fishery (Möllmann et al., 2021). This example highlights how such inaccuracies in fleet segmentation and subsequent indicator calculation can contribute to the continued degradation of fish stocks and the marine ecosystem, ultimately making future recovery efforts more difficult and costly.

Moreover, effective fisheries management involves the allocation of resources, such as funding for conservation efforts, monitoring programs, and enforcement. Inaccurate SHIs can lead to the misallocation of these resources, directing them away from areas that need them most and towards areas that do not. Besides biological implications, this can have significant economic and social consequences for fishing communities. Overly restrictive measures can harm livelihoods, while insufficient measures can lead to the collapse of fish stocks, affecting long-term sustainability and economic stability. Applying the novel segmentation approach reduced the number of segments harvesting specific stocks. Consequently, these refined segments can represent fishing strategies more accurately and precisely than DCF segments. With fewer segments

involved, it is easier to analyze the socio-economic impacts of stock-specific management measures, such as TAC reductions, ensuring more targeted and effective fisheries management.

Fisheries management relies on accurate data to make informed decisions. A database derived from a fishery-based segmentation scheme, which categorizes fleets by vessel catch composition and stock reference, is crucial as it acknowledges the variability in fishing activities across different vessels with vessels engaged in multiple fisheries which may be impacted differently by management measures or stock fluctuations.

4.2. Integration with ecosystem-based management approaches

While the shift towards ecosystem-based management approaches is growing (Scotti et al., 2022; Bonsdorff et al., 2015; Möllmann et al., 2014; Gascuel et al., 2012), such methods are still not the norm in fisheries management. For both stock-based and ecosystem-based management, understanding which parts of the fleet are fishing which stocks and to what extent is critical. Only then can well-informed decisions be made and the consequences of management measures for fisheries be accurately assessed. The new approach offers a dynamic and systematic method to link fleet activities directly with current fisheries management practices, which predominantly focus on stock allocations and technical measures. This not only applies to the European fleet segmentation in the DCF, in which the novel approach has been successfully used for national fleet data sets (Grigoraş et al., 2023). The functions of the novel approach also can be and have been applied to a variety of data sets on multiple aggregation levels, e.g., for the

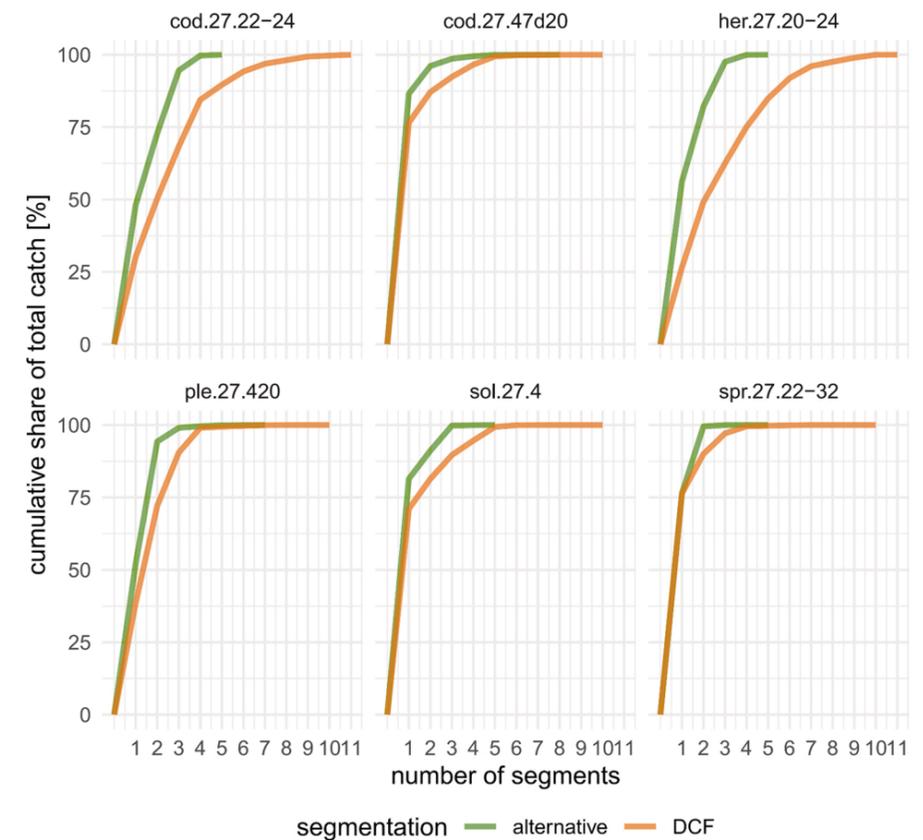


Fig. 7. Ranked cumulative share of total catch of specific fish stocks under DCF and alternative segmentation. The number of segments is displayed on the X-axis; the cumulative share of weight is displayed on the Y-axis. Segments were ranked in descending order according to their share of the total catch of the respective stock. Stocks were selected because of their commercial importance for multiple segments under both segmentation schemes.

classification of haul compositions in the Icelandic demersal trawl fleet (Kasper et al., 2024). Beyond the European scope, it can enable researchers and data globally to not only segment the fishing fleets of their respective interest, but also serve as an explorative toolset in an earlier stage. Participants of the workshops where the approach was tested reported discovering fishing strategies in the researched fleets that they did not know existed before. This highlights the universal applicability of our work in well-established data collection systems as well as in emerging management organizations, where ecosystem-based approaches are yet to be established.

4.3. Compliance with DCF segmentation

'Fishery' is an optional dimension that has been in the DCF data calls for economic fleet data. However, it is not included in the legislative basis, is not clearly defined yet, and is not applied in the DCF environment (STECF, 2023). It is hence recommended to integrate the novel approach with the existing DCF segmentation framework by applying the novel approach to define the 'Fishery'-dimension of segments. To avoid the described disadvantages of the current DCF segmentation, a revision of the length and gear classes within the DCF would additionally be required, for which a possible pathway is described in the following sections. The integration of the novel approach in the DCF framework would enhance the granularity and applicability of the segmentation, allowing for a reduction in the overall number of segments and improving management efficiency.

4.4. Homogeneity in cost structures

Another possible advantage of the new segmentation method is its ability to create fleet segments with a more homogenous cost structure than the DCF segmentation. Cost structure homogeneity is one of the primary goals of the DCF data collection and analysis (STECF, 2023). Cost data of fishing fleets is often sparse and heterogeneous and therefore difficult to analyze, yet, first calculations of cost structures of fleet segments defined using the alternative approach showed promising results (Sulanke, 2020, internal DCF report). Homogeneous cost structures attribute is particularly valuable when evaluating the economic performance of different fisheries or calibrating bio-economic models. However, because cost data is often scarce and collected from a limited sample of vessels, further research using a harmonized analysis procedure, broader data sources from different fishing nations, and thoroughly analyzing the economic indicators applied by the DCF is necessary to validate changes in cost structure homogeneity brought about by the novel approach.

4.5. Spatial component and environmental considerations

By using stock-based catches as the basis of the clustering procedure, the new method includes a spatial component, separating vessels that might use the same gears and target similar species but operate in different areas under varied environmental conditions and management regulations. This feature is essential for accurately assessing the impacts of area-specific management measures such as size restrictions or seasonal closures. Using the fishery-based segmentation procedure, three

fleet segments were identified in a separate workflow not described in detail in this article. Each of these fleet segments included vessels from at least three different DCF segments. Comparing the haul positions reported in the logbooks of vessels revealed spatially distinct mixed fisheries in the Baltic and in the North Sea, targeting substantially different stocks and being affected by different regulations, like, e.g., the Plaice Box, which is only relevant for North Sea fisheries (Beare et al., 2013). This example of demersal fisheries in the German coastal zone illustrates that a stock-based, multivariate analysis allows the identification of spatially distinct fishing fleets, something a purely technical classification alone cannot ensure.

4.6. Future directions and recommendations

The new method is ready to use, as it is implemented in a user-friendly R package. Feedback from scientific partners and workshops (RCG ECON, 2023, 2022 & 2021) has highlighted the need for an automated process within the fleet segmentation package to decide which clusters should be combined into fleet segments without requiring extensive expert knowledge. This improvement would simplify the segmentation process and make it more easily applicable for users with varying levels of expertise. Possible variables to consider in the algorithm are catch composition and catch quantity, technical parameters of the vessels, travel times and extent, and position data, such as VMS data. In the current version of the novel fleet segmentation approach, the decision on which clusters to merge into valid fleet segments is made by the user with the aid of a set of diagnostic methods and comparisons. These methods are not always unambiguous, and in some cases, the decision requires in-depth expert knowledge of the fishing fleet under consideration. While at least basic knowledge of the analyzed fishing fleets substantially aids the application of the approach, the three workshops held on the topic made clear, that only basic knowledge of the R programming language is required to successfully run the package containing the novel approach (RCG ECON, 2023, 2022 & 2021). The machine-learning aspect is yet to be tested in a workshop. Yet, its implementation in the R-package will not reduce the overall applicability of the package and does not require any specific machine-learning skills from the users, but in turn will reduce the overall requirements to the user. Once a sufficient number of years (about 3–4) are segmented using our described protocol, the machine learning approach can automatically assign them to any additional data sets., e.g., older or incoming year classes of fleet data. The presented case study is based on the German fleet, which is, compared to other European fleets, of medium size and complexity (STECF, 2023). The application of the approach to data sets of larger and more diverse fleets during the workshops, e.g., the Spanish, Danish, or French fleets, highlighted the principal applicability to such fleets, yet, possible improvements were also identified. These included the reduction of highly complex catch composition data sets, e.g., by applying principal components, and a novelization of the gear classification, which will be discussed in the following.

Adjustments in the allocation of the main fishing gear and the potential inclusion of special gear classes should be considered to enhance the accuracy and relevance of fleet segmentation. In the novel fleet segmentation approach, vessel gear class is a pivotal yet complex factor. Vessels often use multiple fishing gears, with variations across different seasons. Currently, the main fishing gear is based on its usage over 50 % of the logged fishing time, as documented in the vessel's logbook. However, the gear with the highest usage does not necessarily reflect its significance in terms of catch composition. For example, the Baltic Sea's demersal swamfish fishery segment consists of vessels categorized as DTS, as they predominantly used bottom trawls according to logbook records. Yet, the primary catch of these vessels included herring and sprat, typically caught with pelagic trawls – specifically pair trawls during limited seasonal windows. Despite their shorter time of usage, these pelagic trawls contribute the majority of the total catch, leading to

a potential misclassification in fleet segments.

This discrepancy underscores the need for revising the main fishing gear assignment procedure within the DCF. The current system merges gear types like demersal trawls and seines into a single category (DTS), which does not accurately reflect their distinct operational patterns and cost structures. For instance, demersal seines generally consume less fuel compared to other gear types, affecting operational costs significantly (Cheilari et al., 2013). To address these issues, it's proposed that vessels switching between gears such as pelagic and demersal trawls, or between active and passive gears should be classified into the following categories: mixed active and passive gears (PMP) and polyvalent active gears (MGP).

Though these gear classes exist in the DCF, they are very rarely implemented in current practice. They could be incorporated into the DCF's segmentation scheme as specific fishing techniques (level 1.b, see Annual Economic Report Metadata Protocol, (STECF, 2024)) or as a combination of fishing technique and gear (levels 1.b and 2.b, see Annual Economic Report Metadata Protocol, (STECF, 2024)).

To facilitate the identification of these specialized gear classes, a clustering procedure could be performed before applying a protocol similar to the fleet segmentation approach presented. This preliminary step would help ensure that gear classifications are based on actual operational profiles, enhancing the accuracy of fleet segmentation and ultimately supporting more precise fisheries management practices.

Judging by the experience made in the development and testing stages of the novel fleet segmentation approach, we consider a separation of small-scale fisheries (SSF, under 12 m, following EU definition (Natale et al., 2015)), large-scale fisheries (LSF, over 12 m and less than 500gt) and distant water fisheries (DWF, over 500gt, following the definition used by DCF and widely applied in the fishing sector) instead of the currently applied six length classes. As the analysis of variable contribution to the random forest classification revealed, the gear class is by far the most important variable for the random forest algorithm to assign alternative fleet segments, and the vessel length is among the four most important variables as well. This highlights that these variables, which are the core of the DCF classification scheme, should not be fully abolished. Rather, the classification scheme described above would be beneficial in two ways, as it would ease the application of the novel approach and at the same time make it more closely related to the original DCF segmentation scheme. In addition, revising how gear classifications are determined and applied in fleet segmentation will better align the segmentation process with the real-world complexities of fishing operations. These technical improvements together with the demonstrated overall advances in connectivity of fleet segments and biological fish stock assessment facilitated by the novel approach will lead to considerable improvements in effective and targeted fisheries management at the European level and beyond. As global changes continue to reshape marine environments, an adaptive and well-segmented fleet structure will be indispensable for the future of sustainable fisheries management. Therefore, integrating catch-profile-related aspects into fleet segmentation in a mechanistic, standardized, and easily applicable way has the potential to considerably enhance the effectiveness of fisheries management, as it supports the development of strategies tailored to precisely address today's unique challenges.

CRedit authorship contribution statement

Thorsten Stoeck: Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition. **Sarah Simons:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Jörg Berkenhagen:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Matthias Bernreuther:** Writing – review & editing, Formal analysis. **Erik Sulanke:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Verena Rubel:** Writing – original draft,

Visualization, Methodology, Formal analysis, Data curation, Conceptualization.

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Appendix

Table A1

Geographic indicators to distinguish fleet segments operating in outermost regions or exclusively in non-EU waters, either international waters or in third countries' waters based on fisheries partnership agreements.

code	Name	definitions
NEU	Non EU waters	more the 50 % of activity occurs in non-EU waters
IWE	International waters exclusively	100 % of activity occurs in non-EU waters
NGI	No geographical indicator	National waters, EU waters
P2	Madeira	Portuguese outermost region (autonomous region)
P3	Azores	Portuguese outermost region (autonomous region)
IC	Canaries	Spanish outermost region (autonomous community)
MA	Morocco Coastal	Most of the activity occurs in 34.1.1
GF	French Guiana	French outermost region (overseas department)
GP	Guadeloupe	French outermost region (overseas department)
MQ	Martinique	French outermost region (overseas department)
MF	Saint-Martin	French outermost region (since 2009) (overseas community)
RE	Reunion	French outermost region (overseas department)
YT	Mayotte	French outermost region (overseas department)

Table A2

Fleet segments of the German fishing detected using the alternative segmentation approach. Included are the name and size of the new fleet segment, vessels main fishing gear of the vessels, and length, engine power, and mean trip duration, all described by minimum, maximum, and mean in parentheses. Also depicted are the main target stocks (official ICES stocks are indicated in bold, otherwise species abbreviation and FAO area are indicated), and the DCF segments of the vessels included in the new segment.

Fleet segment	Number of vessels	Main fishing gear	Main target stocks	Vessel length (m)	Engine power (kW)	Mean trip duration (d)	DCF segments included
Blue mussel fishery	4–14 (9)	Dredges (DRB)	– Blue mussel (<i>Mytilus edulis</i> , MUS, 27.4b)	9.2–45.65 (37.33)	58–1200 (594)	1.13	VL2440DRB, VL40XXDRB, VL2440TBB
Brown shrimp fishery	173–253 (214)	Beam trawls (TBB)	– Brown shrimp (<i>Crangon crangon</i> , CSH, 27.4abc)	4.10–35.67 (16.59)	5–1103 (182.39)	1.46	VL0010PG, VL0010TBB, VL1012TBB, VL1218TBB, VL1824TBB, VL2440TBB
Sole fishery	5–20 (9)	Beam trawls (TBB)	– North Sea sole (<i>Solea solea</i> , sol.27.4) – North Sea plaice (<i>Pleuronectes platessa</i> , ple.27.4.20)	15.69–41.82 (32.59)	184–1471 (820)	4.02	VL2440TBB, VL40XXTBB
North Sea passive gear fishery	3–12 (6)	Gillnets and stow nets (DFN)	– North Sea cod (<i>Gadus morhua</i> , cod.27.47d20) – North Sea sole (<i>Solea solea</i> , sol.27.4) – Smelt (<i>Osmerus eperlanus</i> , SME, 27.4b)	5.3–31.78 (16.38)	7–485 (167)	3.28	VL0010_TBB, VL1218DFN, VL1824TBB, VL2440DFN
Baltic passive gear fishery	3–17 (10)	Gillnets (DFN)	– Western Baltic herring (<i>Clupea harengus</i> , her.27.20–24) – Western Baltic flounder (<i>Platichthys</i> spp., bwq.27.2425)	6.6–32.36 (16.43)	18–441 (136)	0.93	VL1218_DFN, VL1218_FPO

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Table A2 (continued)

Fleet segment	Number of vessels	Main fishing gear	Main target stocks	Vessel length (m)	Engine power (kW)	Mean trip duration (d)	DCF segments included
High seas passive gear fishery	3–6 (5)	Gillnets (DFN), Pots and traps (FPO)	– Baltic plaice (<i>Pleuronectes platessa</i> , ple.27.24–32) – Anglerfish, North Sea and British isles (<i>Lophius budegassa</i> , & <i>piscatorius</i> , anf.27.3a46) – Blackbellied anglerfish, Keltische See und Biscaya (<i>Lophius budegassa</i> , anf.27.78abd) – Red deep-sea crab (<i>Chaceon quinque-dens</i> , KEF, 27.6. u. 27.7)	26.72–32.36 (29.67)	404–442 (425)	35.88	VL2440_FPO, VL2440_DFN
Small-scale passive gear fisheries	662–1012 (860)	Mixed passive gears (PG)	– Western Baltic herring (<i>Clupea harengus</i> , her.27.20–24) – Western Baltic cod (<i>Gadus morhua</i> , cod.27.22–24) – Plaice, Kattegat, Belt Seas and the Sound (<i>Pleuronectes platessa</i> , ple.27.21–23) – Eel (<i>Anguilla anguilla</i> , ele.2737.nea) – Pike-Perch (<i>Sander lucioperca</i> , FPE, 27.3)	3.10 – 11.99 (6.66)	0–221 (26)	<1	VL0010_PG, VL1012_PG
Baltic pelagic herring fishery	1–9 (4)	Midwater trawls (TM)	– Western Baltic herring (<i>Clupea harengus</i> , her.27.20–24)	11.30–37.31 (21.56)	100–735 (209)	1.14	VL1824_TM, VL2440_TM
Coastal pelagic forage fish fishery	1–4 (2)	Midwater trawls (TM)	– Baltic sprat (<i>Sprattus sprattus</i> , spr.27.22–32) – Norway spring-spawning herring (<i>Clupea harengus</i> , her.27.1–24a514a) – North Sea sprat (<i>Sprattus sprattus</i> , spr.27.3a4) – Sandeel – Area 4 (<i>Ammodytes</i> spp., san.sa.4)	17.35–53.55 (41.34)	219–2309 (1025)	7.36	VL40XX_TM
High seas pelagic fishery	3–6 (4)	Midwater trawls (TM)	– Northeast Atlantic Blue whiting (<i>Micromesistius poutassou</i> , whb.27.1–91214) – Norway spring-spawning herring (<i>Clupea harengus</i> , her.27.1–24a514a) – Sardine, Mauritania (<i>Sardina pilchardus</i> , PIL, 34.1.3) – Northeast Atlantic Mackerel (<i>Scomber scombrus</i> , mac.27.nea) – North Sea herring (<i>Clupea harengus</i> , her.27.3.a47d)	62.22–140.8 (108.68)	1764–8640 (4756)	31.8	VL40XX_TM
Baltic demersal forage fish fishery	3–54 (30)	Demersal trawls (DTS)	– Baltic sprat (<i>Sprattus sprattus</i> , spr.27.22–32) – Western Baltic herring (<i>Clupea harengus</i> , her.27.20–24) – Eastern Baltic herring (<i>Clupea harengus</i> , her.27.25–2932) – Plaice, Kattegat, Belt Seas and the Sound (<i>Pleuronectes platessa</i> , ple.27.21–23) – Baltic whiting (<i>Merlangius merlangus</i> , WHG, 27.3b,c)	9.23–39.48 (16.99)	50–961 (203)	1.13	VL1012_DTS, VL1218_DTS, VL1824_DTS, VL2440_DTS
Baltic mixed demersal fishery	15–64 (33)	Demersal trawls (DTS)	– Plaice, Kattegat, Belt Seas and the Sound (<i>Pleuronectes platessa</i> , ple.27.21–23) – Western Baltic flounder (<i>Platichthys</i> spp., bwq.27.2425) – Western Baltic cod (<i>Gadus morhua</i> , cod.27.22–24) – Baltic dab (<i>Limanda limanda</i> , dab.27–22–32)	8.38–32.34 (16.43)	37–588 (183)	1.47	VL0010_DTS, VL1012_DTS, VL1218_DTS, VL1824_DTS

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Table A2 (continued)

Fleet segment	Number of vessels	Main fishing gear	Main target stocks	Vessel length (m)	Engine power (kW)	Mean trip duration (d)	DCF segments included
North Sea mixed demersal fishery	7–19 (13)	Demersal trawls (DTS)	– North Sea plaice (<i>Pleuronectes platessa</i> , ple.27.420) – Norway lobster in the areas 5 und 33 (<i>Nephrops norvegicus</i> , nep.fu.5, nep.fu.33)	14.72–40 (24.38)	159–1440 (282)	4.41	VL1218_DTS, VL1824_DTS, VL2440_DTS
Saithe & cod fishery	6–17 (10)	Demersal trawls (DTS)	– Saithe, North Sea and adjacent waters (<i>Pollachius virens</i> , pol.27.3a4a) – Northern hake (<i>Merluccius merluccius</i> , hke.27.3a46–8abd) – North Sea cod (<i>Gadus morhua</i> , cod.27.47d20)	15.11–40.26 (32.65)	130–1720 (641)	5.13	VL2440_DTS, VL40XX_DTS
High seas demersal fishery	4–6 (5)	Demersal trawls (DTS)	– Cod, Northeast Arctic (<i>Gadus morhua</i> , cod.27.1–2) – Western Greenland halibut (<i>Reinhardtius hippoglossoides</i> , ghl.27.561214) – Eastern Greenland cod (<i>Gadus morhua</i> , cod.2127.1f14) – Pelagischer redfish (<i>Sebastes mentella</i> , reb.27.1–2.sp und, reb.27.1–2.dp)	57–92.1 (77.96)	1764–4500 (3242)	51.18	VL40XX_DTS

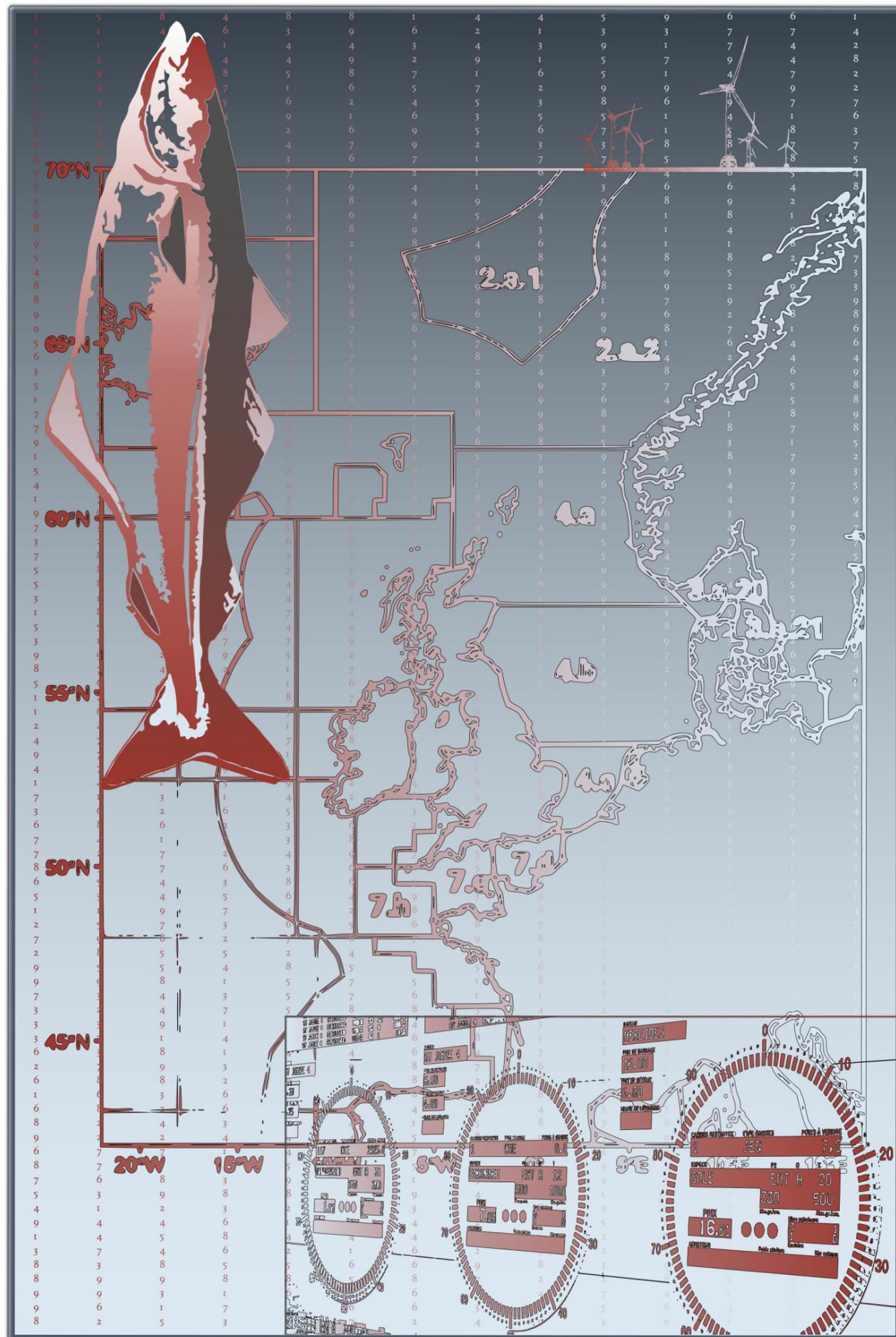
Table A3

SHI and SAR of both the alternative and the DCF segmentation approaches for the reference year 2018.

segment name	segmentation	SHI	number of SAR	comment
Baltic passive gear fishery	alternative	1.85	1	
Baltic pelagic herring fishery	alternative	1.89	1	
Baltic mixed demersal fishery	alternative	1.85	1	
Baltic demersal forage fish fishery	alternative	1.81	1	
Blue mussel fishery	alternative	NA	0	
Small-scale passive gear fishery	alternative	2.35	2	
Sole fishery	alternative	2.04	1	
Saithe & cod fishery	alternative	1.37	0	
North Sea mixed demersal fishery	alternative	1.18	0	
North Sea passive gear fishery	alternative	2.32	1	
Brown shrimp fishery	alternative	NA	0	
High seas passive gear fishery	alternative	0.69	0	SHI not relevant as proportion of fished stocks with F/Fmsy present is below 40 %
High seas demersal fishery	alternative	0.91	0	
Coastal pelagic forage fish fishery	alternative	1.05	0	
High seas pelagic fishery	alternative	0.94	0	
PG VL0010	DCF	2.44	2	SHI not relevant as proportion of fished stocks with F/Fmsy present is below 40 %
PG VL1012	DCF	2.28	2	
DFN VL1218	DCF	2.28	2	
DFN VL2440	DCF	1.85	0	
FPO VL1218	DCF	1.84	1	
FPO VL2440	DCF	NA	0	
TBB VL1012	DCF	NA	0	
TBB VL1218	DCF	1.34	0	SHI not relevant as proportion of fished stocks with F/Fmsy present is below 40 %
TBB VL1824	DCF	0.95	0	SHI not relevant as proportion of fished stocks with F/Fmsy present is below 40 %
TBB VL2440	DCF	2.11	1	
TBB VL40XX	DCF	1.93	1	
DTS VL1012	DCF	1.65	2	
DTS VL1218	DCF	2.10	1	
DTS VL1824	DCF	1.35	1	
DTS VL2440	DCF	1.38	0	
DTS VL40XX	DCF	1.07	1	
TM VL 1218	DCF	1.95	2	
TM VL1824	DCF	1.88	1	
TM VL2440	DCF	1.65	1	
TM VL40XX	DCF	0.95	0	
DRB VL2440	DCF	NA	0	
DRB VL40XX	DCF	NA	0	

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II. A bio-economic modeling approach to simulate the impact of climate change on fisheries



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Insights into the impact of climate change on economic trajectories of North Sea demersal fisheries derived from a spatially explicit bio-economic model

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ABSTRACT

North Sea demersal fisheries are increasingly challenged by a multitude of pressures. Climate change and its socioeconomic consequences as well as the diversification of marine spatial development for offshore energy production, transportation, and conservation are particularly affecting these fisheries, altering the state of target stocks and cutting off access to fishing grounds. To assess the impact of these developments, we applied the spatially explicit bio-economic simulation and optimization model FishRent to simulate the effects of three different climate change scenarios on the profitability of three North Sea demersal fishing fleets from Germany, Norway, and the United Kingdom fishing for cod, saithe, and hake. Our scenarios, which were based on macroeconomic model projections and developed by climate change and fisheries experts, included projections of prices, management strategies, and spatial development. The simulations indicated a continuous increase in profits in a scenario focused on economic development and open markets, while increases in a scenario centered around sustainable development and conservation were less pronounced, albeit steady. A scenario of increased focus on national economies and reduced global trade led to decreasing profits, linked to the overuse of economically crucial North Sea cod stock. Throughout all scenarios, the effects of price developments and management strategies far outweighed effects of marine spatial competition, which were marginal. Spatial dynamics of the fleets showed regional differences, where fuel price increases and insufficient investments in fuel-saving technologies led to the retraction of the UK fleet to less distant fishing grounds, not fully realizing the allocated quota. Our results highlight the intricate socio-economic dynamics in fisheries that are insufficiently covered in most fisheries models and reveal research gaps, particularly the incomplete mechanistic understanding of area closures and stock-recruitment dynamics. Yet, they also illustrate a basic principle of fisheries management, where consistent unsustainable use of a fish stock leads to economic collapse and substantial long-term economic damage for the participating fleets.

1. Introduction

Climate change, in particular the rise in sea temperatures and an increased frequency of extreme weather events, is profoundly impacting marine ecosystems (Hoegh-Guldberg and Bruno, 2010; Halpern et al., 2019). Ocean warming has been proven to alter species' metabolic rates (Arnberg et al., 2013; Carozza et al., 2019), distribution (Wieland, 2005; Engelhard et al., 2011, 2014; Gervais et al., 2021), and reproduction (Dippner, 1997; Pankhurst and Munday, 2011; Capuzzo et al., 2018). In addition to continuous temperature increases, marine heatwaves have increased in both frequency and severity (Oliver et al., 2018; Laufkötter et al., 2020), imposing both immediate and long-term pressures on marine life (Laufkötter et al., 2020). Concurrently, economic demands on marine resources intensify, leading to competition for space (Jentoft and Knol, 2014a; Bastardie et al., 2015; Jouffray et al., 2020; Letscher et al., 2021). The surge of offshore energy production, spanning both

fossil-based and renewable sources, in combination with increasing political and societal aspirations of marine protection such as the European Union's '30 by 30' initiative to protect 30% of EU waters by 2030 (EU, 2020), further complicate spatial management and generate potential conflicts with traditional industries, including fisheries.

The North Sea offers a particularly complex and valuable setting to examine these intersecting pressures. As a shallow, semi-enclosed shelf sea with a long history of human use (Roberts, 2007), it supports some of the world's busiest cargo shipping routes, well-established fisheries, and expanding offshore energy production (Martins et al., 2023). The intensive human use of the area has led to some of the first Marine Spatial Planning (MSP) in the region, and today, most North Sea coastal states are developing or already implementing MSP frameworks in their territorial waters (Ehler, 2021). However, these MSP efforts often underrepresent fisheries or, if so, reserve only small fractions of the National EEZ as fisheries priority areas. Instead, they focus primarily on

E. Sulanke et al.

offshore energy production, shipping, and Marine Protected Areas (MPAs). While these MPAs can improve biodiversity (Erm et al., 2024), serve as nursery habitats (Russ et al., 2003; Halpern et al., 2009), and be strategically placed to buffer against climate impacts (Queirós et al., 2021), the concurrent push for conservation and offshore energy production, which accumulates to a quarter of the North Sea being used for wind farms (Martins et al., 2023), places substantial pressure on traditional fishing practices. Moreover, the ecological impact of these installations remains uncertain; while some studies suggest that they might provide sanctuary benefits for fish and nursery effects for fish and crustacean species (Bergström et al., 2013; Krone et al., 2017; Methratta and Dardick, 2019; Gimpel et al., 2023; Werner et al., 2024), others indicate potential shifts in primary productivity due to increased water column mixing (Carpenter et al., 2016; Schultze et al., 2020).

Due to its shallow character and limited water exchange with the Atlantic Ocean through the English Channel and at its northern edge, the North Sea has become a climate change hot spot (Schrum, 2001). The intense temperature increases have already altered the ecosystem's structure and functionality (Quante and Colijn, 2016). For example, cod (*Gadus morhua*), which is one of the most significant and iconic fisheries target species in the world, has been of particular importance for demersal fisheries of the region for a long time (Kurlansky, 2011). The North Sea cod stock (cod.27.46a7d20, recently updated and separated into three substocks (ICES, 2023)) remarkably shifted its distribution toward the Northwest and is now practically absent from the Southern North Sea (Núñez-Riboni et al., 2019). This is attributable to a combination of excessive fishing pressure and unfavourable environmental conditions (Cecapollit et al., 2025). Such developments translate to direct economic losses for demersal fisheries relying on the species. In the North Sea, all kinds of fishing vessels from artisanal coastal fisheries to high-seas industrial factory vessels operate demersal trawls and these trawlers contribute substantially to overall fishing revenues (STECF et al., 2023). Moreover, these fisheries are vital for fishing-dependent communities (Kerby, 2013; Natale et al., 2013), generating employment and income for the local population and contributing to the touristic attractiveness of the communities (Ropars-Collet et al., 2017; Pascoe et al., 2023; Nielsen et al., 2024).

Changes in species availability and spatial restrictions can substantially alter the operational costs of fishing fleets, leading to increased fuel costs and longer periods spent at sea (Simons et al., 2015). This study employs a spatially explicit simulation model that integrates data on fish prices, management practices, and marine spatial development to project fleet profitability and spatial dynamics under various climate change scenarios. Although existing models provide insights into these dynamics, the socio-economic consequences of climate change and spatial competition remain insufficiently explored. For instance, in fisheries ecological modelling, fisheries revenues are often directly derived from the biomass made available by the TAC set in the model, hence assuming, all available quota is harvested and the target fishing mortality is reached (Dorleta Garcia et al., 2017). In reality, this is seldom the case, and quota is underused regularly if economic pressures prevent fleets from realizing the full total allowable catch (Errend et al., 2018; McQuaw and Hilborn, 2020). Bridging this knowledge gap is essential for developing effective, sustainable management strategies that address the socio-ecological complexities facing North Sea fisheries.

This study investigates the economic impacts of climate change on North Sea fishing fleets and explores adaptive strategies that could mitigate these effects. By utilizing socio-economic projections alongside expert-modified climate scenarios, a forward-looking analysis of the economic landscape confronting North Sea fisheries is provided. The outcome of this study is intended to equip resource managers with a comprehensive understanding of the ecological, economic, and social dimensions crucial for resilient fisheries management in an era of rapid environmental change.

2. Material & methods

2.1. Dataset

We applied the simulation model to three demersal fishing fleets operating in the North Sea: (1) The German saithe and cod fleet with an initial size of 7 vessels (2) the southern Norwegian coastal trawl fleet with an initial size of 5 vessels, and (3) the UK demersal seine and trawl fleet with an initial size of 42 vessels. The German and Norwegian fleets were defined by applying a novel, catch-based approach to the segmentation of fishing fleets, as the normally applied definitions of fishing fleets were based on technical parameters and thus not suitable for use in FishRent, as fleets segmented in this manner may contain multiple fisheries with distinct differences in operational strategies, economic characteristics and target species, especially in demersal fisheries (Sulanke et al., 2025). The existing UK fleets', which are defined by the public seafood advisory and support organization Seafish, were found to have homogeneous catch profiles, and, thus, no re-definition of existing fleet segments had to be applied. To maintain a manageable model complexity, we restricted our analyses to fleets that primarily operate in the North Sea. Subsequently, all catches obtained from outside the study area, which consisted of ICES areas (1) 4.a (2) 4.b (3) 4.c (3) 7.d. and (4) 3.a.20, were considered as 'other income' even if they belonged to one of the three simulated target stocks. For the simulated fleets, we collected spatially explicit catch and effort data on the ICES rectangle level as well as detailed economic data on revenues, variable costs, crew costs, fuel costs, fixed costs, and opportunity costs (see Appendix table A1 for the full dataset). To accurately calculate travel distances and time, we also gathered information on their main operational home ports, which were Hanstholm in Denmark for the German fleet (as this is closest to their fishing grounds and free access is granted by the European Free Trade Association), Stavanger for the Norwegian fleet, and Peterhead for the UK fleet (see Fig. 1 and 2). Specifically, Stavanger is not the operational port of the Norwegian fleet, but was rather chosen as an approximation, as vessels operated from multiple close-by fishing ports such as Haugegesund and Egersund. As the ratio between fishing effort and steaming effort was only available on the total fleet level, yet, to calibrate the model, steaming and fishing effort needed to be calculated for every ICES rectangle, downscaling of the total steaming effort was conducted. As downscaling, which fully relies on fishing effort distribution, would overemphasize heavily fished rectangles and downscaling solely based on steaming distances (both approaches were applied in former versions of FishRent), a mixed approach was applied. Total fishing effort per rectangle was calculated by applying a fleet-specific square-root sum of fishing effort and distance using

$$Eff_{tot,j,k} = Eff_{fish,j,k} + \sqrt{Eff_{fish,j,k}^* \alpha_j} + \sqrt{Dist_{j,k}^* \beta_j} \quad (1)$$

With $Eff_{tot,j,k}$ being the total effort of the j th fleet in the k th area, $Eff_{fish,j,k}$ being the fishing effort of the j th fleet in the k th area, $Dist_{j,k}$ being the distance the j th fleet has to travel to the k th area, and α_j and β_j being fleet specific constants. These constants were obtained in a calibration procedure where the difference between the overall effort obtained from data collection and the overall effort obtained from the formula was minimized, resulting in a difference of 1.1 seadays or less for each fleet segment. This mixed approach allowed for taking travelling distances into account while recognising fleet-specific differences in the ratio between fishing effort and steaming effort, which mirrors operational efficiency of the modelled fleets.

- For calibration of economic and effort data, we used averages of the three reference years 2018, 2019, and 2020.

The target fish stocks simulated in the model were North Sea cod (cod.27.46a7d20), North Sea haddock (had.27.46a7d20), and North Sea

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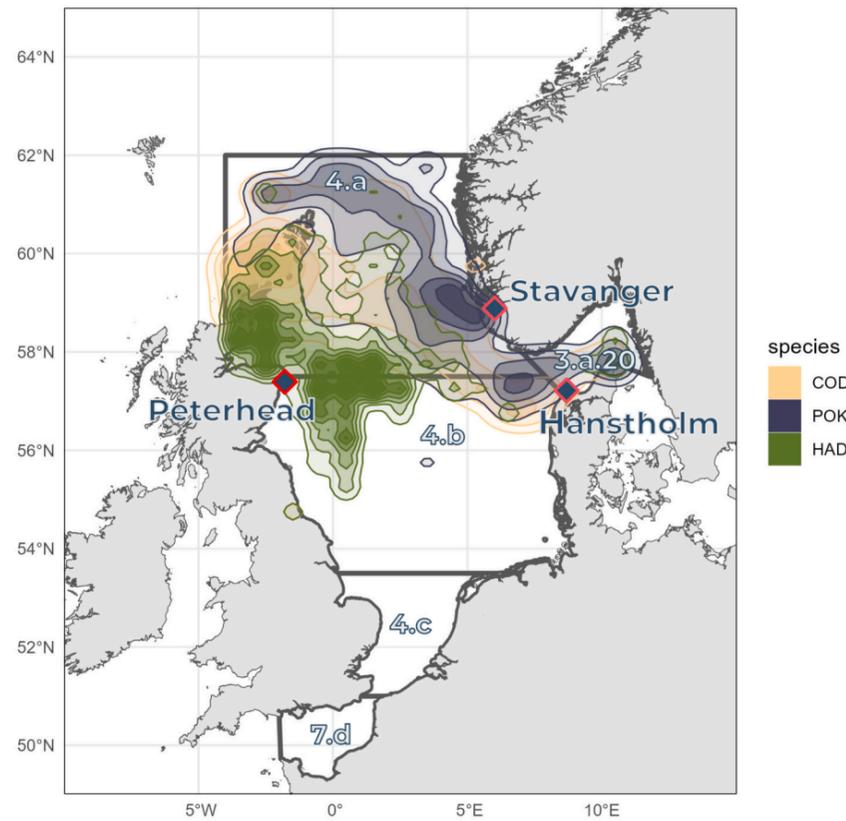


Fig. 1. Map of the study area. The main fishing areas of the three simulated species, as well as the main home ports of the three modelled fleets, as well as the names and borders of the relevant ICES fishing areas, are labelled.

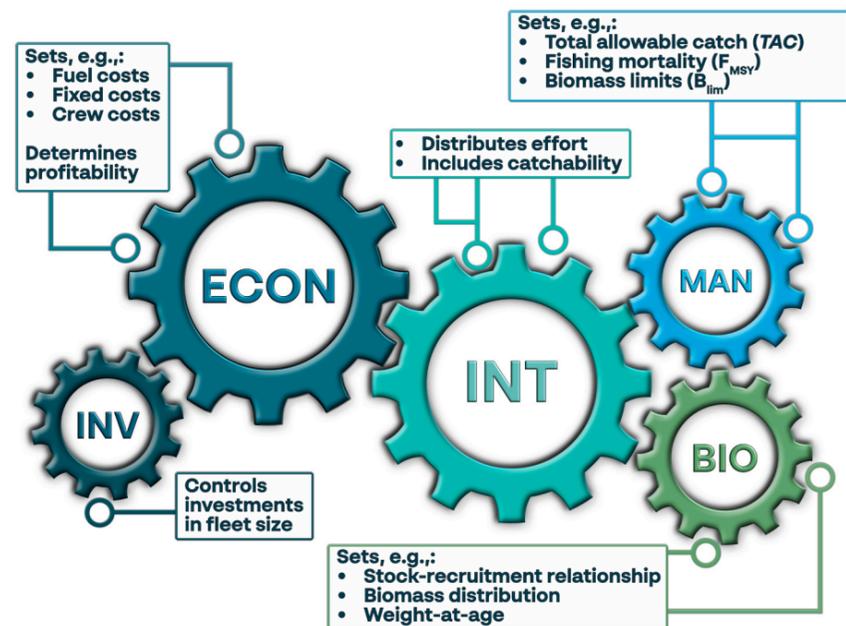


Fig. 2. Schematic overview of the model structure of the FISHRENT model. Depicted are the five modules of the model using the following abbreviations: INV – investment module; ECON – economic module; INT – interface module; MAN – management module; BIO – biological module.

saithe (*pok.27.46a7d20*). All biological variables (spawning stock biomass SSB values and variance, recruitment values and variance,

number of age classes, limit reference point for spawning stock biomass B_{lim} , precautionary reference point B_{pa} , fishing mortality at MSY F_{MSY}) used were taken from the respective ICES advice. As the three reference years for which biological and ecological data was collected were 2018 to 2020, the division of the North Sea cod stock into three substocks, which recently was proposed (ICES, 2024), was not applied. For the stock-recruitment relationship of the three modelled stocks, segmented regressions (“hockey stick models”) were chosen, which align with the current multi-species assessment practices (ICES, 2023). Calibrating SSRs exclusively with recent decade data (2010-2020) ensured a realistic reflection of the lower productivity of these stocks under current conditions, preventing overly optimistic projections of fleet profitability associated with extended datasets.

2.2. Model structure

We applied a spatially explicit version of the bio-economic simulation and optimization model FishRent. This model, originally developed by Salz et al. (2011) has been extensively used in prior studies to assess the consequences of various factors, such as management strategies, spatial plans, price fluctuations or climate change effects on both the temporal (Simons et al., 2014; Rybicki et al., 2020; Rybicki et al., 2021) and spatiotemporal level (Bartelings et al., 2013; Simons et al., 2014; Bartelings et al., 2015; Rybicki et al., 2021). Here the core principles of the model, specific modifications implemented for this analysis, and the functionality of each module within FishRent are described. The spatiotemporal version of the model simulates fishing fleet activity patterns by reallocating fishing effort until overall fleet profit is optimized in the respective simulation loop.

The applied version of FishRent was written in the General Algebraic Modelling System (GAMS) and was run with the CONOPT solver (Drud, 1994) to optimize fishing effort allocation across spatial and temporal dimensions. In the presented version of the model, overall fleet profit is optimized. If overall profit is highest, before allocated quotas are fully fished, unused quota will be forfeited. The model consisted of five interconnected modules: the management module, the biological module, interface module, economic module, and investment module (see Fig. 2). These modules were connected through feedback mechanisms that adjusted parameters and applied constraints throughout each simulation loop, which was structured on an annual basis, i.e., one optimization was performed for every simulated year, to simulate fishing activity from 2020 to 2060.

2.2.1. Management module

The management module contained all management strategy parameters, including the target fishing mortality F_{MSY} , which guided sustainable harvest rates for each fleet segment. These management parameters were established as the initial conditions passed to the biological module, ensuring that the population dynamics could be modelled in alignment with management goals. This approach allowed the appropriate level of fishing pressure to be applied, achieving sustainability targets as defined by the model.

2.2.2. Biological module

In the biological module, population dynamics for the targeted fish stocks were simulated based on parameters set by the management module. Age and size structures, as well as stock-recruitment relationships, were incorporated into the model to estimate stock biomass. The biomass was then distributed across the simulated area based on the distribution of species derived from the sampled catch data, with the assumption of stable relative distribution over time and perfect knowledge of the fleets on the distribution of the stocks. The estimated harvestable fish biomass was used to inform the optimization procedures within the interface module.

2.2.3. Interface module

The core optimization of fishing effort allocation was conducted within the interface module to maximize overall fleet profits. A Cobb-Douglas production function was applied to simulate a non-linear relationship between catch and effort and between catch and stock size (Frost et al., 2013; Rybicki et al., 2020), with iterative adjustments made until an optimal effort distribution was achieved. Non-linear relationships were assumed in the production function to accurately represent the reduction of return increase rates and the spatial competition between fleets as effort increased. The function was calculated as

$$C_{i,j} = q_{i,j} \times E_j^{\alpha} \times B_i^{\beta} \quad (2)$$

Where $C_{i,j}$ is the catch of the i th age class by the j th fleet, $q_{i,j}$ is the respective catchability coefficient, E is the fishing effort, B is the biomass, and α and β are the parameters of nonlinearity, which were set at 0.7 and 0.3, in accordance with Simons et al. (2014a,b), who modelled a comparable fishery applying the same method.

2.2.4. Economic module

Fleet cost structures, including fuel, labour, maintenance, and other operational costs, were assessed within the economic module. Once the profit optimum, i.e., the highest overall profit of all modelled fleets, was reached, fleet-specific profitability was determined, and this information was then passed on to the investment module for capacity adjustments.

2.2.5. Investment module

In the investment module, fleet capacity adjustments were made according to profitability levels calculated at the end of each simulation loop. Fleet size expansion was triggered if fleet profitability exceeded a threshold of 0.5, meaning that at least 50% of the generated fishing revenue surpassed operational costs, and if maximum fishing effort had been utilized for the fleet’s existing capacity. Values for maximal allocatable fishing effort were taken from the reference data, which is described in the following section. Investments were proportional to the obtained profits. Disinvestments in fleet capacities required fleets to be unprofitable, even if the maximal fishing effort was allocated, and were also proportional to the losses in the previous simulation loop. The investment module marked the end of one simulation loop. Investments in fleet capacity were included in the form of increased vessel numbers, i.e. fleet size, but not related to changes in technical vessel parameters.

Based on the results of one loop, new values for the target fishing mortality and the according TAC (total allowable catch) were calculated based on the catches obtained by the fleets in the previous cycle. The Baranov production function (Baranov, 1918) applied for the calculation of TACs and its implementation in the presented model version was described in detail by Simons et al. (Simons, 2014).

2.3. Parametrization

The effects of climate change on both management strategies and economic parameters were projected and incorporated into the model. Projections of fuel and fish prices were obtained from the macroeconomic MAGNET model (Pinnegar et al., 2021) and reviewed by a panel of experts formed within the FutureMARES project. The panel was constituted of six senior-level scientists with backgrounds in climate science, fisheries science and socio-economics. Reviews and adjustments to the projections obtained from the MAGNET model were discussed in two online meetings. Maximum or minimum increase projections instead of average values were chosen to represent scenarios with high likelihoods for extreme developments (e.g., a fuel price surge in National Enterprise due to a decline in oil exports), while average values were chosen to represent developments estimated to be more moderate. Projections for enhanced fuel efficiency and the subsequent reduction in fuel usage were also made for all scenarios, based on the EU strategy for

the reduction of CO2 emissions in fisheries (EPRS, 2023). The expert panel also stipulated scenario-specific exploitation rates of the target stocks, which were implemented by adjusting by modifying F_{MSY} , which is the core stock management projection of the presented modelling approach.

To align marine spatial planning (MSP) with the scenarios, MSP data was collected, supplemented by expert meetings within and beyond the project group (see Table 1). For MPA development, data on the designated MPA areas was collected from the marineregions portal as well as from official marine data registries of Germany, Norway, and the UK. Again, scenario-specific development trajectories were defined: In the Global Sustainability scenario, 30% of these designated MPA areas were fully protected by 2030, increasing to 40% by 2040 and reaching 50% by 2050. In the World Markets and National Enterprise scenarios, 10% of the designated areas were strictly protected by 2030 with no further increase thereafter. The closures and subsequent losses of fishing grounds were simulated by proportionally lowering the total biomass available for fisheries in each rectangle covered by the MPA. If rectangles were partially covered by MPAs, the coverage was also included in proportion. For example, if a rectangle was fully covered by an MPA in the Global Sustainability scenario, the available biomass of all species was lowered by 30% in 2030, by 40% in 2040, and by 50% in 2050. If a rectangle was only partly covered by an MPA, e.g., by 50%, available biomass would be lower by 15% in 2030 (30% protection applied to 50% of the area), 20% in 2040, and 25% in 2050.

Data for offshore wind farm (OWF) development was sourced from Martins et al. (2023). In both the Global Sustainability and the World Markets scenario, OWFs were assumed to be implemented in accordance with the development plans, yet, in the World Markets scenario, 50% of OWF areas were assumed to be opened to fishing with active gears. In Global Sustainability, all OWF areas were entirely closed to fishing. For the National Enterprise scenario, OWF development was assumed to be delayed for 10 years due to limited investment and lack of technological exchange between states. In addition, 50% of the OWF area remained open to fishing. Again, area closures and associated losses of fishing grounds were accounted for by proportionally reducing the biomass available for fishing in relation to the total biomass present in the respective area. Area losses caused by non-overlapping MPAs and OWFs in the same rectangles were cumulative. If OWF and MPA areas overlapped, the higher degree of closure was applied. To reduce computational effort and preserve the state of general model equilibrium, area closures were implemented stepwise in 2030, 2040 and 2050 (see, e.g., Fig. 3), with the first step being in accordance with the EU's "30 by 30" marine conservation and biodiversity strategy (EU, 2020).

2.4. Analytics

Total fleet profit was calculated for each year by subtracting the total costs of fleet segments from their total gross fishing revenue. Gross revenue was calculated by applying the following formula.

$$Rev_j = \sum_i (C_{ij} \times p_{ij}) \times (1 + o_j) \quad (3)$$

Where C_{ij} is the catch of the age i by the fleet j times the price p and o is the share of the landings value coming from the modelled species. The operational costs were calculated by summing fuel costs (FuC), which were a product of the fuel used and the fuel price, the crew costs (CrC), which were calculated as fleet-specific shares of the revenue, and the other variable costs (VaC), which were based on the collected data. To assess the coverage of operational costs by the revenue, the gross cash flow (GCF) of the fleets was calculated using:

$$GCF_j = Rev_j - (FuC_j + CrC_j + VaC_j) \quad (4)$$

Values were then scaled between 0 and 1 for confidentiality reasons. To calculate overall profits, fixed costs and capital costs were subtracted from the GCF and the results then summed.

Two indicators were applied to the analyses of the fleet's spatial dynamics: The Herfindahl-Hirschman index, applied to the respective fleets' fishing effort distribution, and the total number of ICES rectangles containing a relevant fraction of fishing effort.

First, the HHI, which originally is a measure of concentration in a sector of the economy ranging from 1 (very little concentration) to 100 (total concentration) (Hirschman, 1980; Herfindahl, 1997), was adapted to the total fishing effort spent by the fleets to identify trends of effort concentration, i.e., if only few ICES rectangles contained high fractions of fishing effort. The HHI of fleet j was calculated as

$$HHI_j = \sum_{i=1}^n s_{j,k}^2 \quad (5)$$

With s being the share of the fleet j 's total fishing effort allocated to each area k , with s being expressed in percent. The HHI was calculated by summing the squarings of all shares. The HHI was scaled to a range from 0 to 100, with 100 equaling total effort concentration in one rectangle and 0 equaling no effort concentration at all.

The second applied indicator of fleet effort distribution was the number of ICES rectangles where a relevant share ($\geq 0.5\%$) of the total annual effort was allocated, providing additional information on fishing effort concentration.

To further examine the spatial dynamics of the fleets, the annual mean distance travelled to the fishing grounds (D) was calculated for each fleet by applying a weighted mean, which was calculated as

$$D_j = \frac{\sum_{i=1}^n s_{j,k} \times d_{j,k}}{\sum_{i=1}^n s_{j,k}} \quad (6)$$

With d being the travelling distance of each fleet j to each area k and s being the share of effort allocated of fleet j in area k , used as a weight. As in equation (5), s was expressed in percent, j comprised the 3 modelled fleets, and k comprised the areas fished by the respective fleet. A total of 418 areas were included in the model, but no modelled fleet operated in

Table 1
Projection of parameters and management strategies in the respective scenarios. Units are given row-wise in correspondence to the described parameters, the scenarios are given column-wise.

Variable	World Markets - WM	National Enterprise - NE	Global Sustainability - GS	Baseline
Fuel prices [% increase p.a.]	2.69	4.47	2.59	2.69
Fish prices [% increase p.a.]	1.57	2.41	0.6	1.52
Fuel efficiency [% decrease in fuel use until 2050]	75	37.5	75	37.5
Exploitation rate	Maximum economic yield (0.8 MSY)	Maximum social yield (1.1 MSY)	Maximum ecological yield (0.6 MSY)	Current level
MPA protection	10% of designated areas strictly protected by 2030, no increase thereafter	10% of designated areas strictly protected by 2030, no increase thereafter	30% of designated areas fully protected by 2030, 40% by 2040, 50% by 2050	-
OWF development	OWF development in accordance with plans; 50% of OWF areas opened to fishing	OWF development delayed by 10 years; 50% of OWF areas opened to fishing	OWF development in accordance with plans; all OWF areas closed to fishing	-
IPCC climate scenario	RCP8.5, SSP5	RCP8.5, SSP3	RCP2.6, SSP1	-

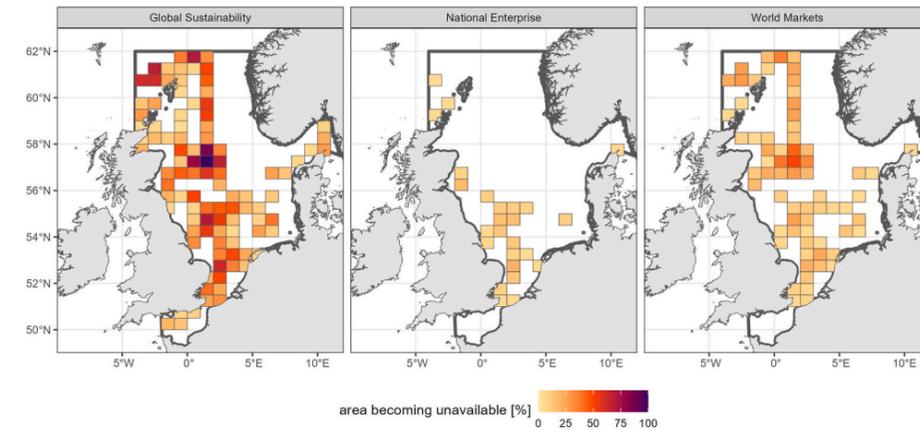


Fig. 3. Map of the study area with fishing ground losses displayed. The color scale depicts the severity of fishing ground losses in % of ICES rectangle area due to MPA and OWF development in the year 2050. The grid labels show the depicted scenario. Only areas with fishing ground losses equal to or higher than 5% are depicted. The black line marks the border of the study area.

all of these areas.

3. Results

The results section presents the key findings from simulations under three main areas: *economic trends*, *spatial dynamics*, and *ecological shifts* across the three scenarios *World Markets (WM)*, *Global Sustainability (GS)*, and *National Enterprise (NE)*. All sub-sections focus on the results gathered from the scenarios combining effects of economic and management projections (abbreviated EMP in the following) and marine spatial planning (MSP) projections. The singular effect strength of both projections is illustrated at the beginning of the spatial dynamics section, emphasizing, that the economic effect of spatial development was negligible.

3.1. Economic trends: differential profit growth across scenarios

Total fleet profits were the optimization variable of the simulation and were therefore considered the most important economic variable. In all scenarios, they exhibited a consistent increase, starting at approximately €15.8 million in 2020 (see Fig. 4). The most pronounced growth occurred in WM, where total fleet profits more than tripled, reaching

€61.7 million in 2060. The second-largest, albeit less pronounced, increase in profit increase was observed in the GS, totaling €28 million profit in 2060. By contrast, NE displayed moderate fluctuations after reaching €20 million in 2026, varying between €17.2 million and €25.2 million without substantial growth. NE was therefore the only scenario without a continuous upward trend in total profits.

While overall fleet profits grew, individual fleet profitability trends varied considerably (see Fig. 5). In the Norwegian fleet, profits increased slowly at first, prompting disinvestment and capacity reductions to enhance profitability (see Fig. 6).

After 2025, profitability grew steadily. During the 2030s in GS and the 2050s in NE, the fleets' profit margins were sufficient to allow the Norwegian fleet to invest and substantially grow in size, reaching a doubled fleet size in both scenarios by the end of the simulation period. In WM, however, the fleet size of the Norwegian fleet showed minimal fluctuation. Following initial disinvestment, the Norwegian fleet grew slightly beyond its original size in the late 2020s and then stabilized.

The other fleets exhibited unique patterns as well. The UK fleet remained consistent in size across all scenarios, yet its profit trajectory varied strongly. In WM, GCF of the UK fleet showed a steady upward trend after achieving a state of equilibrium in the late 2020s. In contrast, NE showed moderate variations until 2040, when profits temporarily

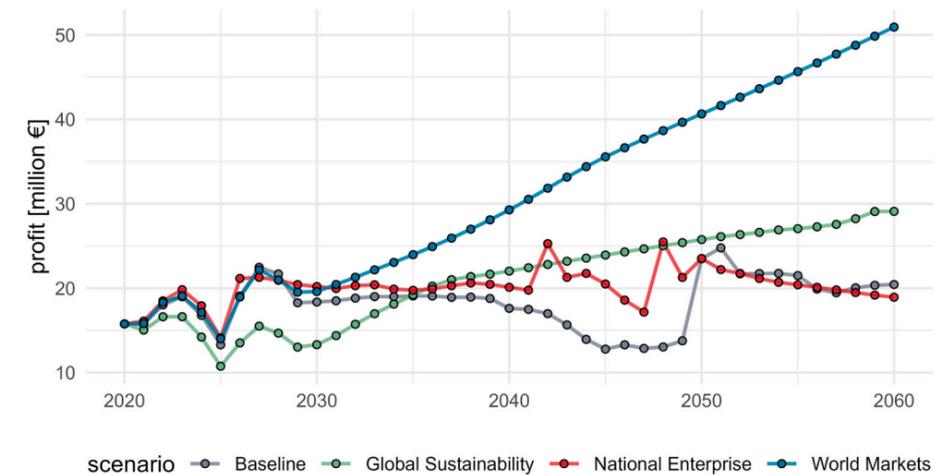


Fig. 4. Profitability timeline of all fleets combined under the three scenarios, with combined EMP and MSP effects, and in the baseline scenario. Net profits are depicted in €; the colors of the dots and lines indicate the applied scenario.

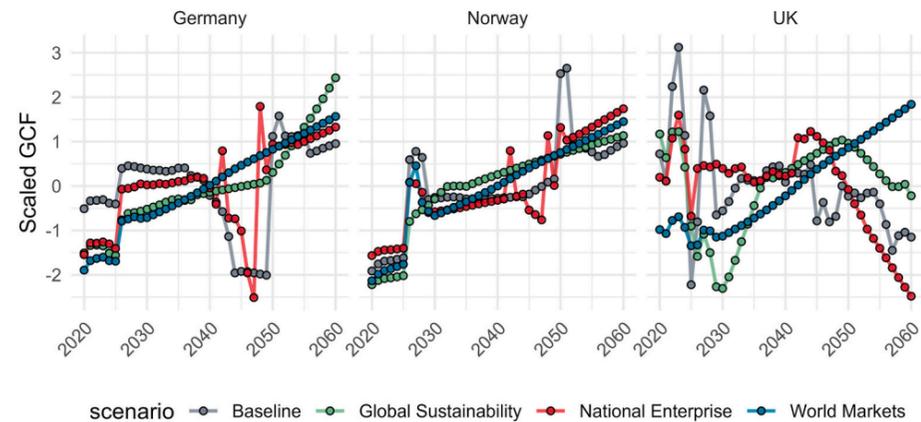


Fig. 5. Scaled gross cash flow (GCF) timeline of the respective fleet under the three scenarios, with combined EMP and MSP effects. GCF values are scaled and therefore without a unit; the colors of the dots and lines indicate the applied scenario. The plot titles indicate the modelled fleets.

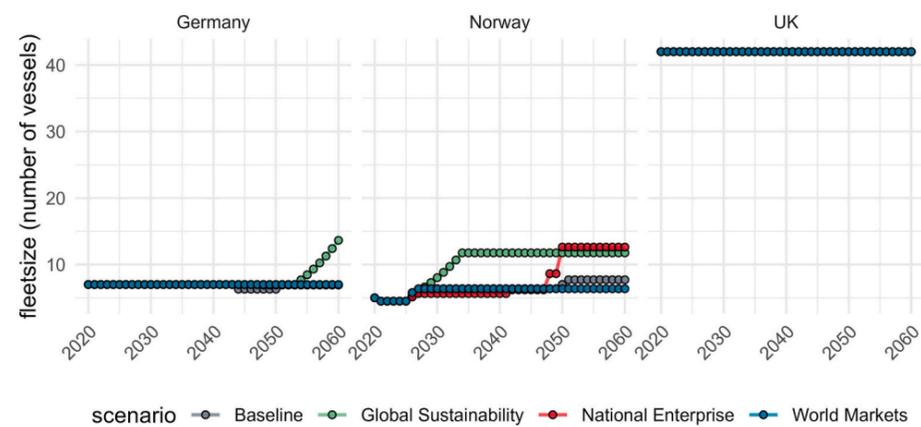


Fig. 6. Fleet size timeline of the respective fleet under the three scenarios, with combined EMP and MSP effects. Fleet size is depicted on the y-axis; the simulated year is depicted on the x-axis; the colors of the dots and lines indicate the applied scenario. The plot titles indicate the modelled fleets.

spiked before declining sharply until the end of the simulation period. In GS, GCF decreased until 2030, then increased until 2050, followed by a moderate trajectory before decreasing again in the final decade.

The German fleet, particularly in GS, saw the most pronounced increase, more than doubling in size by 2060. In other scenarios, the German fleet generally maintained positive GCF trends, except during the 2040s in NE, where profits showed strong year-to-year fluctuations, indicating a temporary loss of the models' state of equilibrium. The observed patterns of fleet profitability and size are mainly driven by the state of profitable target stocks, the operational costs for harvesting them, predominantly driven by fuel costs, and, to a lesser extent, by spatial constraints. A detailed explanation and critical discussion of the model results' transferability to real-world fisheries can be found in section 4.

3.2. Spatial dynamics

The spatial distribution of fishing efforts was examined to understand how fleets adapt their operational areas under spatial and economic pressures. Due to the diversity and complexity of the modelled parameters, the cause and effect of the described profitability changes are difficult to identify. An in-depth analysis revealed that MPAs and OWF development had only a minor effect on fleet profitability. This finding was supported by analyzing the annual percentage change in profits across scenarios where either MSP or EMP was excluded and

comparing them with scenarios where both projections were combined, as well as with the baseline scenario (see Fig. 7). Significance testing revealed that projections excluding EMP effects were significantly different from the full projections (p-value), while projections excluding MSP showed no significant difference from projections with full compositions.

Even though MSP did not significantly affect the profitability of the modelled fleets, they all exhibited notable effort concentration of fishing effort. This effect is illustrated, which is exemplified by mapping of total fishing effort in the Global sustainability scenario (see Fig. 8.). By the end of the simulation, the number of ICES rectangles with equal or more than 0.5% of total fleet effort had decreased across all scenarios (see Table 2) and the HHI at least doubled in each scenario. GS showed the highest concentration, with an HHI of 11.18 at the end of the simulation (compared to 2.27 at the start) and only 26 heavily fished rectangles (compared to 49 at the start) in 2060. The WM showed a consistent medium concentration of 27 heavily fished rectangles and an HHI of 8.81, and NE showed the least degree of concentration with a terminal HHI of 5.31 and 37 heavily fished rectangles.

As fuel prices increased steadily throughout the simulation, and these price increases could not always be counterbalanced by increases in profits or technological advances, the distance travelled by the fleets to their most productive fishing ground changed accordingly. This depended also on the closing of fishing grounds and the productivity of target stocks. The weighted mean of the distance travelled by the fleets

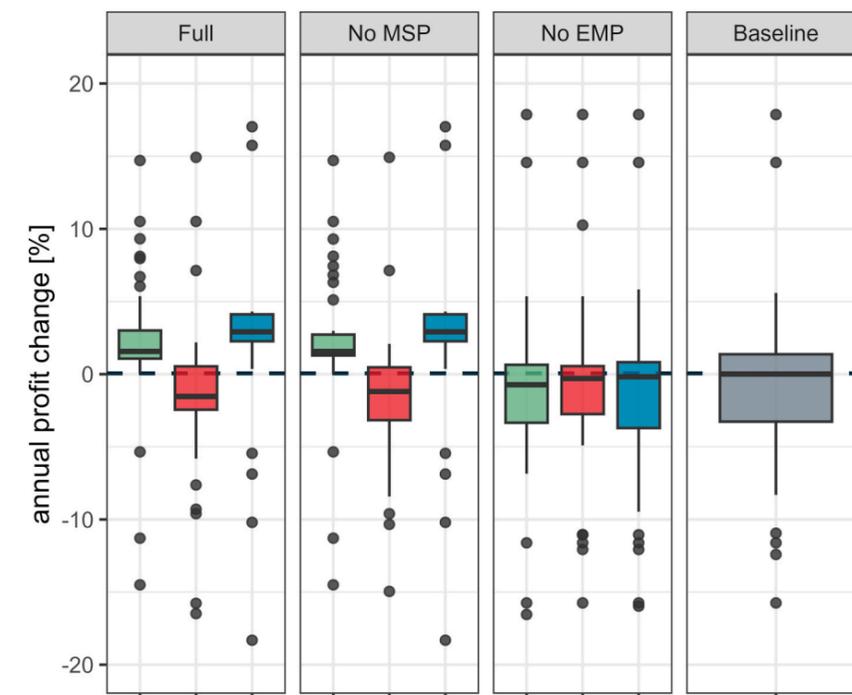


Fig. 7. Boxplot of the annual change in profitability displayed separately in % for all modelled in the fleet in all scenario runs. The color of the box plots indicates the scenario, and the plot titles indicate the modelled fleets.

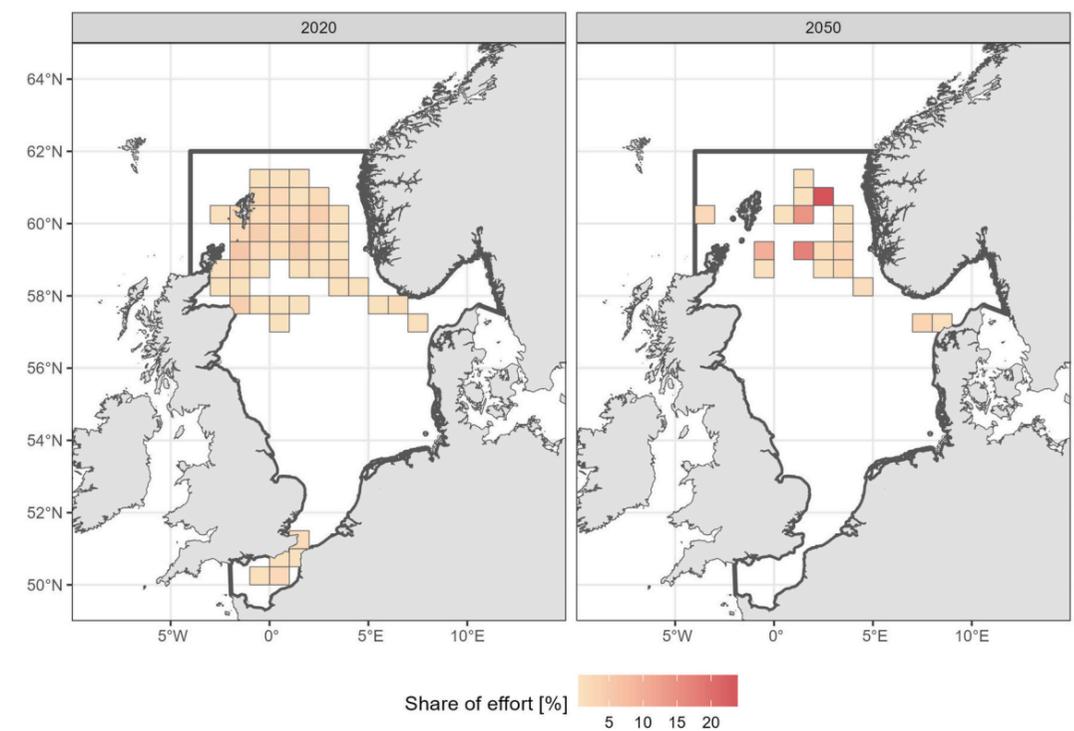


Fig. 8. Map of the total effort of all modelled fleet segments under the Global Sustainability scenario in the years 2020 and 2050. Effort is displayed in % of total effort per ICES rectangle. Only ICES rectangles in which equal or more than 0.5% of total effort was allocated are displayed. The black line marks the border of the study area.

to their respective fishing grounds (with the effort spent in the respective area used as a weight) revealed considerable differences between the

Table 2
Number of ICES rectangles with considerable fishing effort spent (>0.5% of total) and HHI of fishing effort for every scenario at every decade's first year.

Year	Scenario	Number of core fishing rectangles	HHI
2020	Global Sustainability	49	2.27
2030	Global Sustainability	22	11.24
2040	Global Sustainability	18	16.94
2050	Global Sustainability	18	12.20
2060	Global Sustainability	26	11.18
2020	National Enterprise	49	2.27
2030	National Enterprise	32	5.78
2040	National Enterprise	26	5.08
2050	National Enterprise	37	4.18
2060	National Enterprise	37	5.31
2020	World Markets	49	2.27
2030	World Markets	27	8.81
2040	World Markets	27	8.81
2050	World Markets	27	8.81
2060	World Markets	27	8.81

effort dynamics of the three scenarios (see Fig. 9).

In WM, travel distance remained stable, with the German fleet averaging 200 km, the Norwegian fleet 240 km, and the UK fleet 325 km. In GS, the Norwegian fleet showed similar distances to WM, while the German fleet averaged 260 km. NE displayed the highest variability, with marked fluctuations during the period of disrupted equilibrium (2040 – 2050). Prior to this disruption, the German fleet's travel distance declined sharply from 310 km to 190 km, while the Norwegian and the UK fleets showed more gradual reductions from 280 km to 250 km and from 350 km to 320 km, respectively. Before the end of this phase, the German fleet's travel distance increased to 370 km, while the Norwegian stabilized at 219 km and the UK fleet continued to decline steadily, reaching 210 km, an overall reduction of more than 40%.

3.3. Ecological trends: species-specific catch patterns and stock stability

To understand the ecological impacts of fleet operations across scenarios species-specific catches and SSB were analyzed. These metrics provided insights into how each scenario influenced species distribution, stock stability, and fleet catch composition.

The initial catch composition of all modelled fleets was determined by the reference data. The UK fleet primarily targeted haddock, which comprised 53% of its catch, followed by cod at 30% and saithe at 17% (see also appendix Fig. 1). In contrast, the German and Norwegian fleets relied mostly on saithe, accounting for 72% and 85% of their total catch, respectively. Yet, due to its higher fleet capacity, the UK fleet initially achieved the largest total catch of saithe at around 3.000t (see Fig. 10).

Under WM, catch compositions for the UK fleet remained relatively stable, with catches of saithe and haddock of around 5000t and 7000t, respectively. Cod catches for the UK fleet stabilized at around 4000t by 2050, after declining from 5.400t to 3.000t in 2030. The German and Norwegian fleets showed stable saithe catches in WM, at 3000t and 1500t, respectively, while haddock played only a marginal role. Cod catches of the German fleet increased slightly from 550t to 660t, and even though the catches of the Norwegian fleet doubled, they made up the smallest fraction, totaling 140t by the end of the simulation.

In WM, SSB for all three species remained stable toward the end of the simulation, with varying trajectories (see Fig. 11). Cod SSB followed a sigmoidal shape separated into a steep increase in the first half of the simulated period and stabilizing at around 86000t. Haddock and saithe SSB peaked around 2026/2027, then stabilized at around 177000t for both species. GS displayed similar patterns but with lower SSB levels: cod stabilized at 69000t, haddock at 20000t, and saithe showed a continuous upward trend, stabilizing at 250000t.

In GS, cod and saithe catches of the UK fleet declined significantly in the last decade, from 4500t to 3600t and 2900t to 1100t, respectively. These decreases were offset by increases in German fleet catches of the same species, with cod reaching 1670t and the saithe 5200t by 2060. UK haddock catches remained stable at 6000t after reaching equilibrium by 2030. The Norwegian fleet, which expanded considerably in GS, increased its saithe catches to 2400t by 2032, while haddock and cod catches remained low.

The NE scenario showed the most complex and diverse catch patterns. Cod catches remained consistently low for the Norwegian fleet, under 75t, while both German and UK fleets showed continuous declines. For the UK fleet, cod catches dropped sharply from an initial 5400t to just 345t by the end of the simulation. In NE, cod SSB declined steadily, approaching a near-collapse state by 2060 (see Fig. 11), as recruitment levels failed to reach the maximum potential due to severe

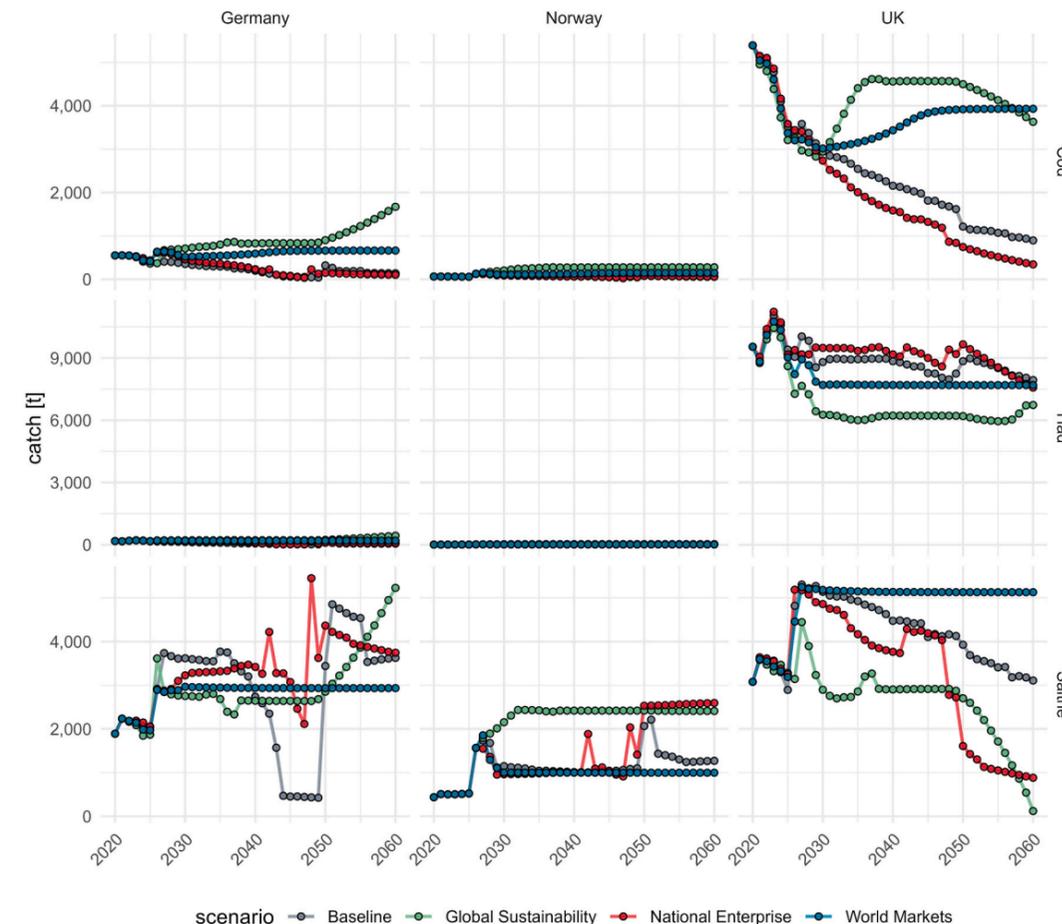


Fig. 10. Species- and fleet-specific catches in all three scenarios and the baseline scenario. The simulated year is depicted on the x-axis; the catch in tons is displayed on the y-axis. The colors of the dots and lines indicate the applied scenario. The grid columns indicate the fleets; the grid rows indicate the species.

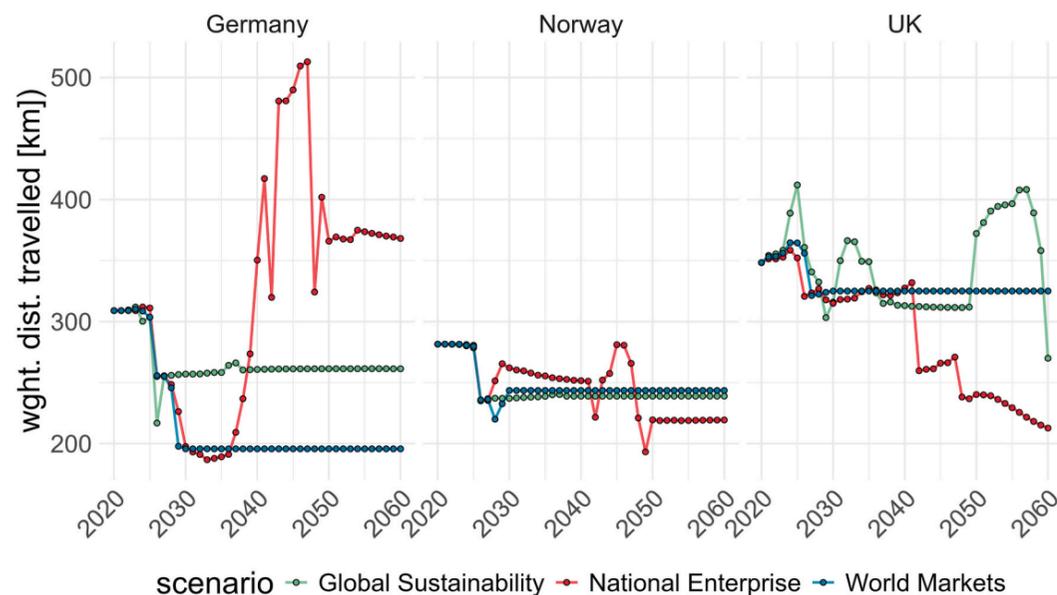


Fig. 9. Travel distance of the fleets in all three scenarios and the baseline scenario. The simulated year is depicted on the x-axis; the effort-corrected travelled distance is displayed on the y-axis. The colors of the dots and lines indicate the applied scenario; the plot titles indicate the fleet.

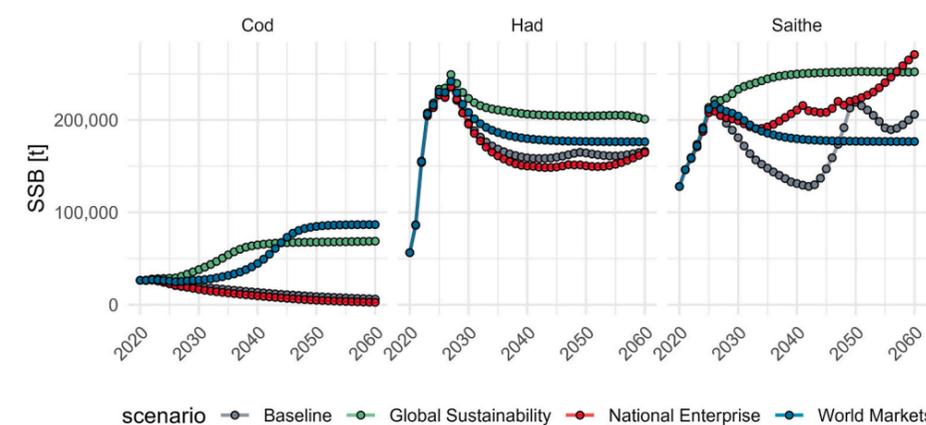


Fig. 11. Timeline of the spawning stock biomass of the three modelled species, given in tons. The colors of the dots and lines indicate the scenarios. Only the baseline and full scenarios (MSP and EMP effects combined) are depicted.

overfishing (see Appendix Fig. A2).

Haddock catches in the UK declined from 9500t to 7600t, while SSB for haddock remained stable at around 150000t for most of the simulation, following an initial increase to over 220000t in 2025 and a subsequent decade of decline. In the final simulated decade, haddock

SSB increased again to nearly 165000t in 2060.

Saithe's catches diverged remarkably across fleets in the NE. In the UK fleet, catches increased rapidly from 3100t to 5200t within the first six years, then declined sharply, particularly between 2045 and 2050, dropping from 4200t to 1600t. Simultaneously, Norwegian saithe

catches increased from 1000t to 2500t during this period, after remaining stable earlier in the simulation. The German fleet's saithe catches in NE gradually increased from around 2000t to 3800t by the end, showing fluctuations in the 2040s. SSB for saithe in NE increased gradually from 130000t to 270000t, the highest observed value for this species across all scenarios (see Fig. 12).

The decline of cod and saithe catches in the UK fleet led to a drastic shift in catch composition. By the end of the NE scenario, cod and saithe shares in the UK fleet's total catch had fallen from 30% to 17% to 4% and 10%, respectively (see Fig. 12).

4. Discussion

This study aimed to address the knowledge gap regarding the economic and ecological resilience of fishing fleets under diverse future scenarios, highlighting how fleet profitability, spatial dynamics, and species-specific stock trajectories interact under varying market and regulatory conditions. The results revealed several key principles and relationships among these factors, illuminating how different management approaches and market conditions shape the economic and ecological outcomes in fisheries.

The diversity in fleet profit trajectories across scenarios is a vivid example of the susceptibility of fisheries economics and activity to diverse future economic and regulatory contexts. As total fleet profits increased threefold in the World Markets Scenario, which enabled open market access and incorporated technological subsidies, this led to a threefold increase in total fleet profits in 2060. This substantial surge in profitability aligns with the anticipated benefits of open market access, increased demand, and political subvention of technology, indicating the potential economic viability of such scenarios. In addition, the technological advances counteracting the increasing fuel prices do not transfer to higher operational costs in the model, i.e., governmental subsidies for technological transformation are implicit in the model. Subsidies for fishing operations are globally prevalent and commonly criticized for creating socio-economic imbalances and putting stocks at risk of overfishing (Sakai et al., 2019; Schuhbauer et al., 2020; Skerritt et al., 2020, 2021). Yet, they might pose a necessity in a transformational process toward sustainable harvesting strategies, given that they are tailored towards technology transition and sustainable practices. Such subsidies fostering the transition towards low-emission

fishing technology were also included in the Global Sustainability scenario. This scenario, with emphasis on sustainable management practices such as MPAs, offshore wind farms (OWF) exclusions, and conservative catch limits, yielded a more gradual but steady increase in fleet profits. This finding supports the long-term economic benefits of sustainable fishing practices, as shown in prior studies (Pauly et al., 2002). Especially by 2036, GS profits overtook those in the National Enterprise scenario, demonstrating that sustainable management can yield stable and competitive returns without compromising ecological goals. Nevertheless, the profitability trajectories simulated in the model are highly sensitive to firstly balance and secondly model assumptions. As the simulated fleets considerably differ in size, model results are disproportionately driven by larger fleets, i.e., the UK fleet in the presented model version. As FishRent is designed to maximize overall fleet profit, this constraint needs to be taken into account when interpreting results. Adjusting fleet sizes would not reflect real-world circumstances, where oftentimes specific fisheries are numerically dominated by single nations and subsequently, fleet sizes are imbalanced. In addition, multiple economic parameters included in the model have the potential to shape fleet size and profitability trajectories. For example, the constraint of TAC-changes being 15% or the investment threshold applied directly influence fleet growth and profitability potentials. Yet, rapid changes always inherent the risk of breaking the general equilibrium repeatedly and, therefore, impede the computation of robust model results. Additional research should be undertaken to examine the sensitivity of the model to variations in these parameters.

Spatial dynamics, specifically the concentration of fishing effort, illustrated how fleets adapt to regulatory and economic constraints. Contrary to concerns that MPAs and OWFs might reduce fleet profitability by restricting access to fishing grounds, results indicated that the economic impact of these spatial closures was marginal. Instead, fleets adjusted by concentrating effort in high-yield areas, particularly near home ports, which minimized travel costs. The significant increase in HHI across scenarios underscores the tendency toward effort concentration, a pattern consistent with results of other spatially explicit bio-economic models that demonstrate similar adaptive behaviour in response to spatial restrictions (Bartelings et al., 2013, 2015). This effort concentration, while economically adaptive, raises ecological concerns. Increased fishing intensity in certain areas can lead to habitat degradation (Turner et al., 1999) and localized stock depletion (Prince and

Hilborn, 1998; Hanselman et al., 2007). Although such effects could not be explicitly quantified with this model due to a lack of empirical data on the ecological impacts of concentrated fishing efforts, these findings suggest that spatially focused management efforts, including habitat monitoring, are essential to mitigate potential adverse impacts in heavily fished zones.

The results emphasize the potential synergies between conservation efforts and sustainable harvesting strategies, particularly in GS, where fleet profitability, stock health, and conservation targets were simultaneously achieved. The economic impact of area closures due to Marine Protected Area (MPA) and Offshore Wind Farm (OWF) development on fleet profits appears marginal in the presented model. This result challenges prior claims of the impact of MSP (Jentoft and Knol, 2014b; Bastardie et al., 2015; Janßen et al., 2018), yet, similar results have been observed in similar models, where fleets maintained profitability by concentrating their fishing effort in the remaining areas open for fishing (Bartelings et al., 2013). In Bartelings et al. (2015), who applied a very similar spatially explicit bio-economic simulation model, closures on the contrary did negatively affect fleet profitability. The significant difference lies in the kind of areas which were assumed to be closed, as the closures in our version of the model mainly comprised low-productivity areas, while in Bartelings et al. (2015), valuable fishing grounds for target species were closed, negatively affecting fleet profitability. This difference in mechanistically very similar models signifies the need for tailored, case-study-specific evaluation processes in MSP.

Effort concentration, rather than profit or fleet size reduction, emerged as a pervasive trend in our results, prevalent across all scenarios and intensifying over the simulation. The overall reduction of ICES rectangles where high fishing effort was located and the simultaneous increase in the Herfindahl–Hirschman index of effort concentration illustrates the fleets' strategic concentration in specific areas, preferably in productive zones close to their home ports. As described above, research indicates that fishing effort concentration might be linked to habitat degradation and local stock depletion, yet, the lack of empirical quantifications of such effects made it impossible to implement them in the FishRent model. The same is true for potential sanctuary and spillover effects of MPAs and OWFs, which are commonly hypothesized (Roberts et al., 2005) and have been documented in selected cases (Holland and Brazee, 1996; Roberts et al., 2001; Russ et al., 2004), yet should not be generalized (Tupper, 2002; Hilborn et al., 2004; Babcock et al., 2010; Miller and Russ, 2014). Spillover and nursery effects are among the biological variables, that could significantly alter the outcomes of bio-economic models, but either can't be implemented at all or only with large uncertainties. Future research should focus on the quantification of such mechanisms and their mechanistic implementation into bio-economic models, as fishing effort concentration is likely to be highly prevalent in a future of intensifying spatial competition at sea. This would improve the quality of predictions derived from these models immensely, as the closing of vast marine areas undoubtedly will have significant ecological effects holding the potential to drastically alter spawning stock biomass trajectories, which were among to most important variables affecting fisheries profitability in the presented version of our model.

The scenario-specific analysis of these spawning stock biomass trends provided insights into the ecological consequences of different management approaches. The drastic decline in cod SSB in the National Enterprise scenario, falling to a mere tenth of its initial size by the end of the simulation, signifies the risks of lenient harvest regulations and the associated risk for the economic collapse of stocks. Unfortunately, examples of such stock collapse due to unsustainable harvest regulations are manifold in the history of fisheries (Mullon et al., 2005), and cod itself provides a rather famous one, as the collapse of the Newfoundland cod stock, once one of the most productive fish stocks in the world, left an entire region deprived of its foundation of livelihood (Kurlansky, 2011). Our results, in line with other studies (Pauly et al., 2002; Ulrich et al., 2017; Nilsson et al., 2019; Andersen et al., 2024), advocating

sustainable harvest limits, illustrate the necessity of strict quota settings to prevent stock collapse. Conversely, saithe showed a steady increase in SSB in the NE scenario, deviating from cod and haddock trends. This exception highlights the complex interplay of economic constraints and ecological outcomes. The underutilization of the saithe quote in NE, due to high fuel costs making saithe less economically viable, mirrors real-world cases such as the North Sea plaice, where quotas remain unmet due to low market prices (Fischmagazin, 2013). Therefore, this model successfully captured this economic-ecological dynamic, often challenging for coupled models to replicate due to forced effort or catch constraints.

On the other hand, such ecosystem models feature sophisticated population dynamics and ecological interactions. Even though state-of-the-art stock-recruitment relationships (SRRs) in the form of segmented regressions were used in the presented version of FishRent, natural variability in stock size, especially for species like haddock, remains challenging to capture (Wright et al., 2011). Segmented regressions, even though they realistically reflect the limited capacity of stocks to regrow depleted biomass, lack the ability to account for the natural variability of recruitment. Especially the haddock stock, which is one of the major demersal fish stocks in the region (Hislop, 1996) and a key stock in our model is characterized by massive fluctuations and lone but extremely large year classes (Fogarty, 2001). Such fluctuations are difficult to implement in empirical models, yet, additional climate forcing in the form of bottom temperature and prey availability has been successfully included in SRRs for North Sea cod (Olsen et al., 2011). A promising approach delivering significantly improved results, it should be considered for inclusion in further bio-economic-modeling aspirations, as it has the potential to significantly improve the prediction accuracy by accounting for the effect of climate change on recruitment, a factor that has been proven to particularly sensitive to global warming and ocean acidification (Dippner, 1997; Pankhurst and Munday, 2011; Capuzzo et al., 2018).

In addition to its influence on SRRs, climate change has been proven to alter the distribution of fish species (Cheung et al., 2010; van Hal et al., 2010), including those modelled in the study (Engelhard et al., 2014), and this alteration is projected to continue in concurrence with the oceans' warming (Gordó-Vilaseca et al., 2024). Therefore, our model assumption of stable relative stock distribution over time is unlikely to reflect realistic conditions, especially in the distant future. Previous studies applying fishrent have included temperature as well as density-dependent distribution of target stocks (Rybicki et al., 2021) or seasonal movements (Simons et al., 2014) with the intent to simulate their effects on fisheries profitability. As highlighted before, differentiating cause and effect in a complex, spatially explicit simulation model like FishRent becomes increasingly difficult with the introduction of additional variation, therefore, each version of the model inherently includes trade-offs. The fleets simulated in the presented version are mainly fishing cod, saithe and haddock in the northern North Sea, for all of which Townhill et al. (2023) projected reduced habitat suitability and a northward shift of latitudinal centroids applying an ensemble of ecological niche models. Given the potential severity of such distribution shifts for associated fisheries, especially considering the demonstrated impact of increasing operational costs, future versions of FishRent should focus on including the impacts of such distribution shifts. To reduce model complexity and enable sensitivity analysis, we suggest reducing the emphasis and degree of detail attributed to spatial closures, since our results suggest their effects on fleet profitability to be marginal.

5. Conclusion

By integrating economic, ecological, and regulatory aspects of North Sea demersal fisheries, we revealed complex interactions that influence fleet profitability, spatial dynamics, and stock stability. Our projections are based on model results predicting societies' and economies'

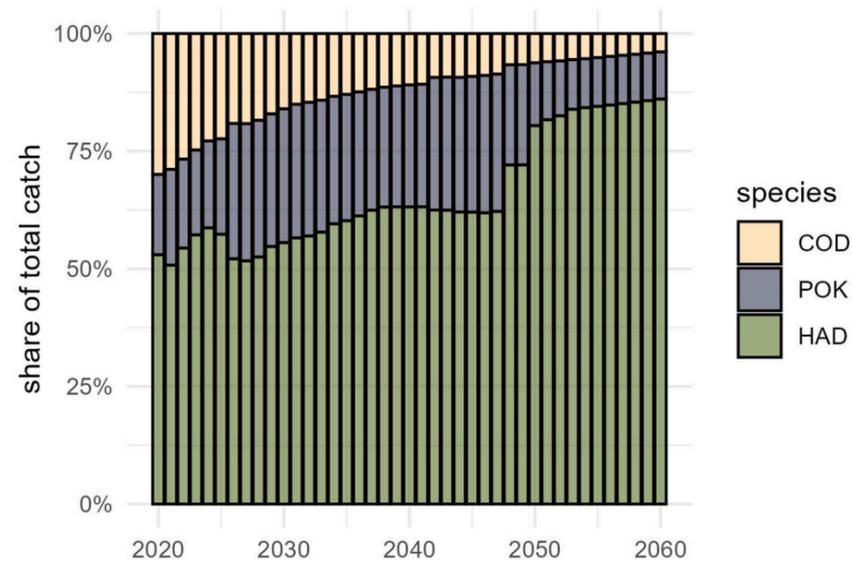


Fig. 12. Timeline of species shares in the catch composition of the UK fleet in the National Enterprise scenario. The catch composition is given in % of the total on the y-axis, the color indicates the species.

responses to climate change, a dimension which is seldom considered in depth in fisheries models. A comprehensive examination of the simulation results gave valuable insights into the intricate interplay of economic, ecological, and regulatory factors. The results underscore the critical role of climate-induced price developments and management trajectories in shaping fleet profitability while highlighting the relatively marginal impact of spatial competition. Although spatial constraints primarily led to effort concentration without significantly affecting profitability, this finding aligns with comparable work but may partially reflect model mechanics. Consequently, these results should not be utilized to downplay the significance of spatial competition in the North Sea. Rather, they emphasize the need for a deeper mechanistic understanding of spatial dynamics and effort concentration.

The findings advocate for ongoing efforts to refine bio-economic models by incorporating these spatial nuances. Furthermore, the results underscore the importance of adaptive management strategies that balance economic sustainability with ecological resilience. Such adaptive approaches suggest a promising future in which sustainable, profitable fisheries can coexist with a strictly protected and spatially managed North Sea, especially with adequate public support to facilitate the transition toward sustainable practices.

The dynamics revealed contribute valuable guidance for policy-makers and fisheries managers facing the challenge of managing a constantly changing marine environment. Further research can build upon these findings by incorporating additional factors, such as temperature-influenced and prey-dependent recruitment, which are among the biological traits most affected by climate change, as well as spillover and sanctuary effects of protected areas. In addition, future bio-economic modeling efforts need to account for distribution changes attributable to climate change, as they might have significant effects on the modelled fleets. These adjustments will enhance the accuracy and robustness of projections. With such advancements, bio-economic modelling can contribute to guiding sustainable fisheries management, advancing a balanced approach to marine resource use and conservation in times of climate change.

Appendix

CRediT authorship contribution statement

Erik Sulanke: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Øystein Hermansen:** Writing – review & editing, Validation, Data curation. **Matt Elliott:** Writing – review & editing, Validation, Data curation. **Arina Motova:** Writing – review & editing, Validation, Data curation. **Marta Moran-Quintana:** Writing – review & editing, Validation, Data curation. **Sarah Simons:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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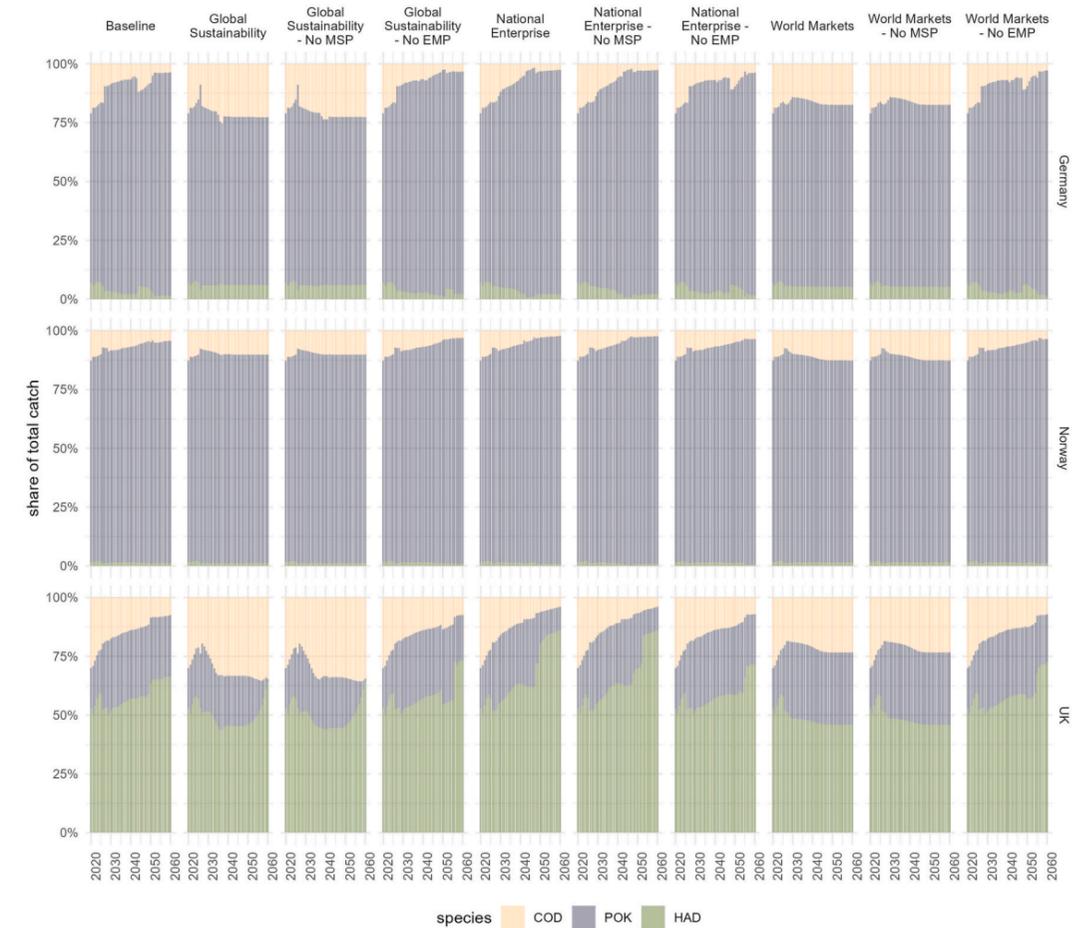


Fig. A1. Timeline of species shares in the catch composition of all fleets (grid rows) in all scenarios (grid columns). The catch composition is given in % of total on the y-axis, the color indicates the species.

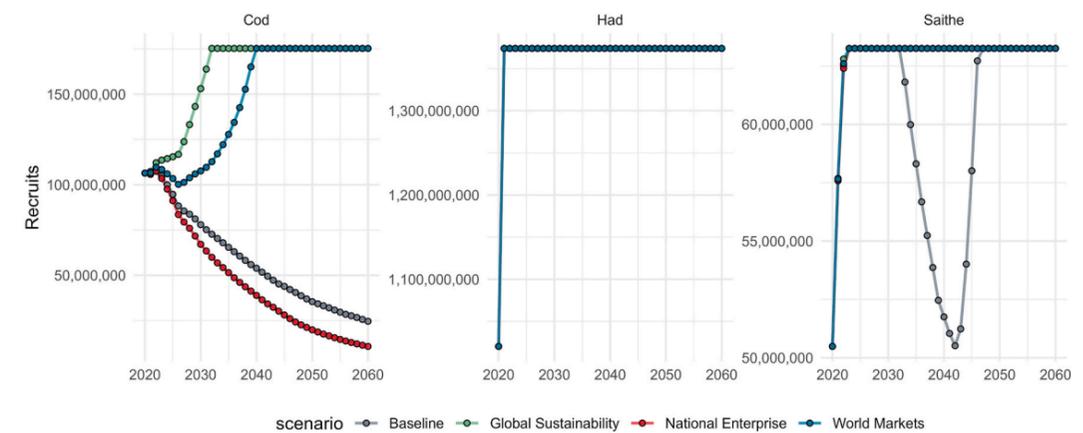


Fig. A2. Timeline of the recruitment of the three modelled species. The number of recruits per year and species is displayed on the y-axis. The colors of the dots and lines indicate the scenarios. Only the baseline and full scenarios (MSP and EMP effects combined) are depicted.

Table A1
Economic parameters of modelled fleets. Variables are given row-wise, the three modelled fleets are given column-wise.

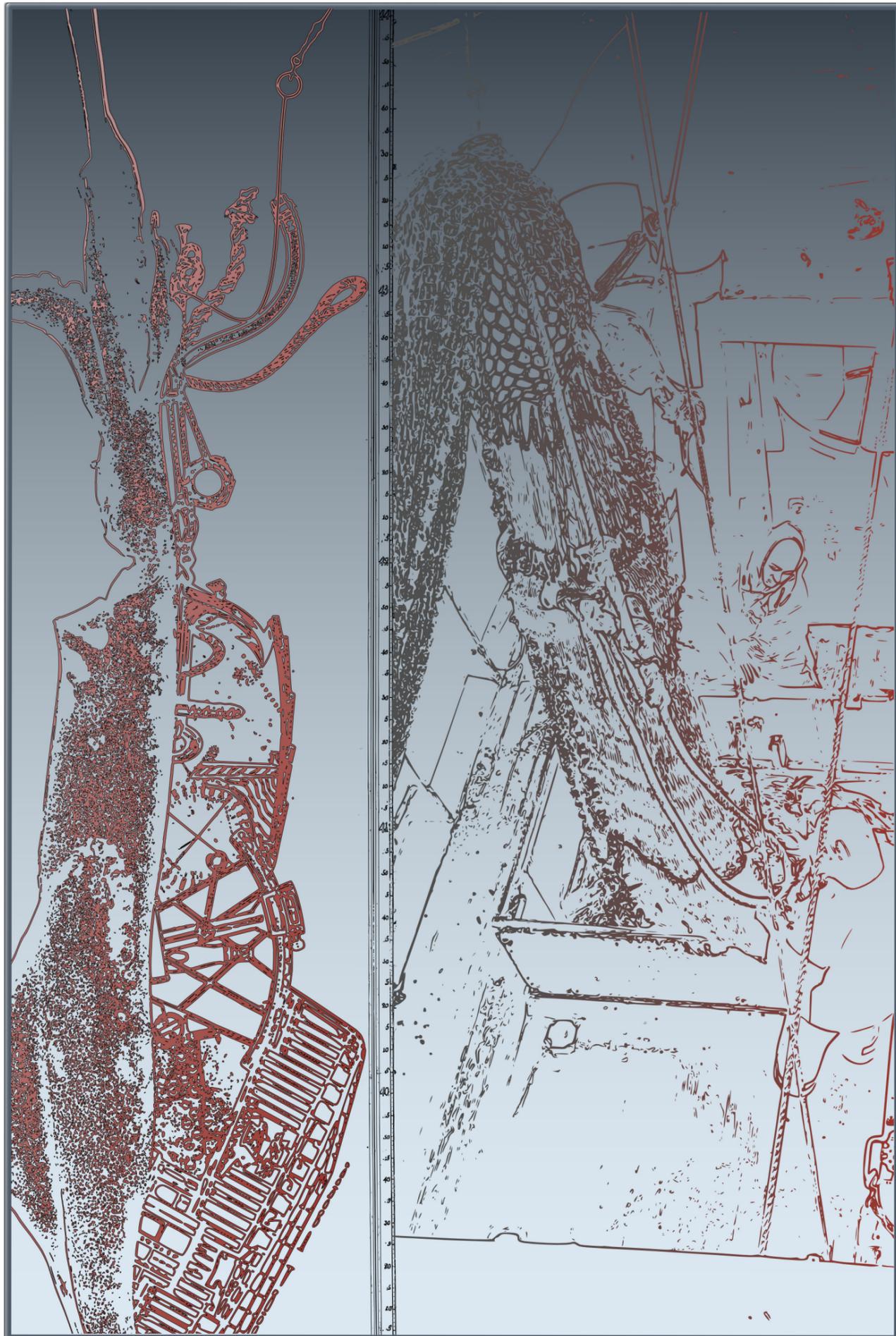
Variable	Germany	Norway	UK
Number of vessels	7	5	42
Initial fuelprice (€/l)	0.478935	0.477476	0.509576
Fuel use (l/seaday)	4622.532	5628.526	1539.718
Revenue coming from modelled species (fraction of revenue)	0.777867	0.325058	0.56874
Crew costs (fraction of revenue)	0.268956	0.213178	0.290096
Variable costs (fraction of revenue)	0.083547	0.029197	0.208432
Fixed costs (€)	218673.4	134879	262981.5
Maximum seadays/vessel	187.9048	107.8	200.881
Initial revenue (€)	15085055	4440430	77944093
Initial fuel costs (€)	2912005	89016.15	6619704
Initial crew costs (€)	4057220	228619.7	22611299
Initial variable costs (€)	1260318	30895.89	16246052
Initial fixed costs (€)	1530714	137206.6	11045222
Initial profit (€)	5322035	3954620	21416836
Investment threshold parameter – effort (fraction of seadays)	0.9	0.9	0.9
Maximum disinvestment (fraction of fleet size)	0.1	0.1	0.1
Maximum investment (fraction of fleet size)	0.1	0.1	0.1

Data availability

The data that has been used is confidential.

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III. Species redistribution and its economic implications: Squid in the southern North Sea as a case study

III.-I. Value and volatility of squid as a fisheries resource in the North Sea and adjacent waters – starting point for a sustainable management

NOTE 

Value and Volatility of Squid as a Fisheries Resource in the North Sea and Adjacent Waters—Starting Point for a Sustainable Management

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In the Greater North Sea, climate change has led to the redistribution of commercially important fish species (Perry et al. 2005; Engelhard et al. 2014; Gordó-Vilaseca et al. 2024) and management decisions, like the ban of pulse trawls by the EU parliament, or the reduction in quota due to Brexit, left many demersal fisheries searching for alternatives. Fishers had to switch back to heavy beam trawls to catch flatfish species, and increasing fuel costs are making that fishery more and more unviable (Kraan et al. 2020). The quota cuts from Brexit and less favourable conditions for quota exchange (Letschert et al. 2021; Döring 2023) intensified the economic hardship and were a further incentive to tap into alternative resources (Döring et al. 2017).

Species that benefit locally from climate change or have newly entered accessible fishing grounds present such an alternative fishing resource, given that they are marketable. They are often not subject to quota management, and only basic fishing restrictions exist; thus, they can be utilised with very few limitations. In the North Sea, squid is increasingly targeted by demersal fisheries. Within the last decades, new stocks have established themselves (Oesterwind et al. 2020), and landings increased substantially (ICES 2024). Among the 24 described cephalopod species in the North Sea (Oesterwind et al. 2022), 5 squid species are of particular interest for fisheries. These include three loliginids: *Loligo forbesii*, *Loligo vulgaris* and *Alloteuthis media* (formerly classified as *Alloteuthis subulata*) (Sheerin et al. 2022); and two ommastrephids: *Illex coindetii*, *Todaropsis eblanae*. Considerable knowledge on the biology, life cycle and fisheries impacts of these North Sea squids was gathered in numerous research projects, and several studies have been published within the last years (e.g., Boyle and Pierce 1994; de Heij and Baayen 1999; Boyle et al. 2002; Pierce and Boyle 2003; de Heij

and Baayen 2005; Oesterwind et al. 2010; Oesterwind et al. 2015; Barrett et al. 2021; Laptikhovskiy et al. 2022). However, there is no fishing regulation for cephalopods under the Common Fisheries Policy in EU waters, and in practice, squid fishing is only regulated via technical measures, e.g., with minimum mesh sizes, and the bycatch regulations of TAC-regulated species, such as *Merlangius merlangus*. Therefore, further increases in fishing effort due to the economic attractiveness of squid fishing hold the risk of overexploitation.

In the past decade, squid have passed cuttlefish and bobtail squids in terms of landing revenues in the North Sea (STECF 2024). A detailed spatial disaggregation of these squid catches reveals the volatility of these fisheries (Figure 1). In the northern North Sea, yields from the targeted spawning ground fishery on *Loligo forbesii* in the Moray Firth have declined since 2019, while landings from the southern North Sea squid and the eastern English Channel (most likely *Loligo vulgaris*, Sulanke, personal observation and communication) have been constantly increasing. 2020 and 2021 present a remarkable exception, attributable to the COVID-related closure of gastronomy in southern Europe, a major sales channel of cephalopods in Europe (Visserijnieuws 2025). After the reopening of restaurants and markets, the fishery has resumed, and especially in the Southern North Sea, the surge of landings from 470 t in 2022 to 2260 t in 2023 is striking.

In light of these developments, we aim to stimulate the discussion about sustainable squid fisheries in Europe and suitable management plans, which are still treated as a ‘Cinderella subject’. The rapid increase in the economic value of squid fisheries in the North Sea and the English Channel underpins the need

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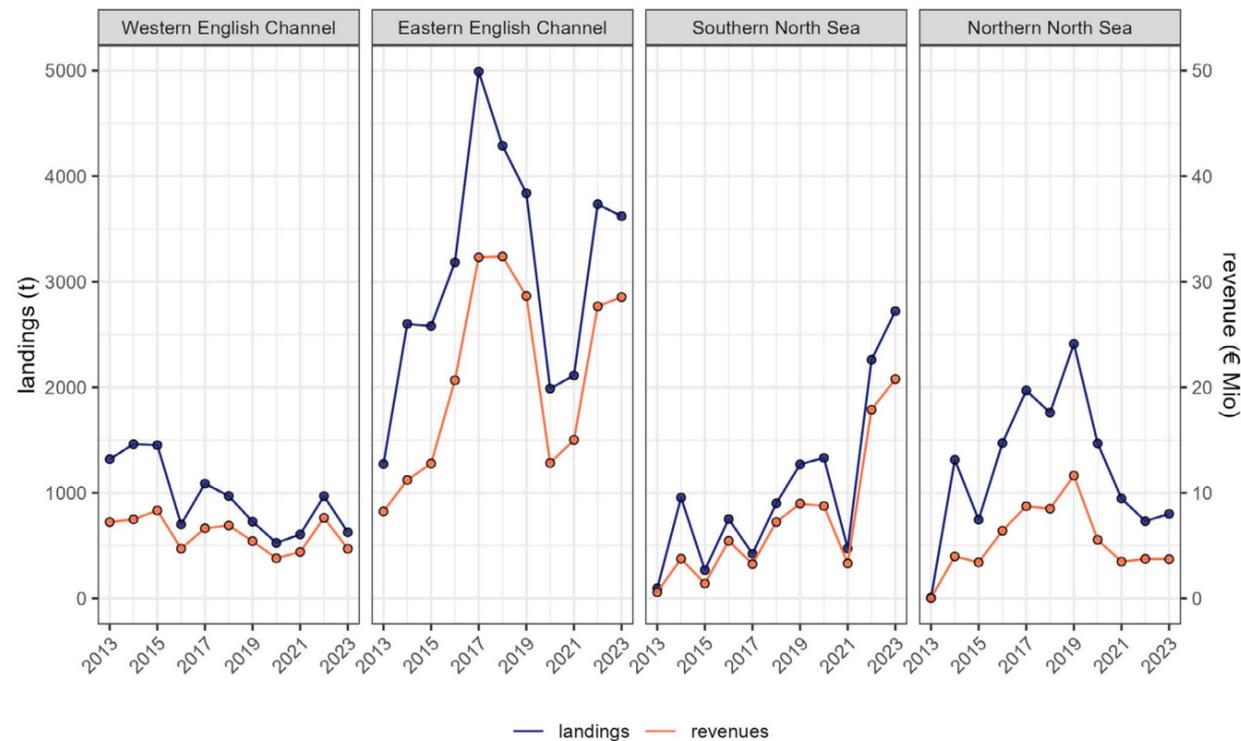


FIGURE 1 | Summarised squid landings in the Greater North Sea area from 2013 to 2023. The colours of lines and dots indicate the metric depicted (blue—landings in thousand tonnes; orange—revenues in million €). All landings' data were derived from the fisheries-dependent information (FDI) database of the European Union (STECF 2024). Landings were analysed for the following areas: 27.7e (Western English Channel); 27.7d (Eastern English Channel); 27.4.c (Southern North Sea); and 27.4.a (Northern North Sea).

for sustainable management. Besides the brief analysis shown, the latest news from the fishing sector hints at a steadily growing squid fishery in the southern North Sea, eyeing new record profits in the future (Visserijnieuws 2025). The combination of increasing fishing pressure and the short semelparous life-style of cephalopods, which means that they are fished before they spawn and thus before they reproduce, can lead to unforeseen collapses of stocks and very sudden onsets of overfishing (Rosenberg et al. 1990; Pierce et al. 2025). One of the world's major squid fisheries in the Falkland Islands area, providing more than half of the European demand, was closed entirely due to alarmingly low pre-season biomass levels (Science 2024). To prevent stock collapses of the European squid stocks, sustainable management needs to be implemented. Collapsing stocks will have major impacts not only on the fisheries relying on them but also on the environment, as cephalopods play an important role in marine food webs. They exert top-down pressure on lower trophic levels but also have a bottom-up function as major prey for various marine mammals and predatory fish species (Bello 1991; Clarke 1996; Caddy and Rodhouse 1998; Piatkowski et al. 2001; Oesterwind and Piatkowski 2023; Schäfer et al. 2024).

Although there are many approaches to assess squid "stocks", Caddy (1983) has already shown that many assessment methods are not applicable to cephalopods, as typical model assumptions do not reflect their ecology. More recent publications build on his findings and recommend real-time assessments and

the use of depletion models (e.g., Arkhipkin et al. 2021; Roa-Ureta et al. 2021). In addition, the International Council for the Exploration of the Sea Working Group on cephalopod fisheries and life history (ICES WGCEPH) has applied several variants of production models with moderate success due to various reasons (ICES 2016, 2017, 2019, 2020). Furthermore, abundance indices (catch rates and monitoring data from standard research surveys) have been widely used in other areas (e.g., Hendrickson and Showell 2016) and, in some cases, recruitment indices are applied (Sobrino et al. 2020), but so far have never been implemented to inform managers for squid fisheries in Europe (see also Pierce et al. 2025).

In addition to the difficulties of squid population analyses stemming from their ecological traits, there are imprecise stock definitions that make it difficult to assess the stocks (ICES 2024; Bobowski et al. 2024). This is not only the case for the North Sea and European waters; thus, numerous examples of unregulated cephalopod fisheries also exist worldwide (Seto et al. 2023). However, there are few cephalopod fisheries in which assessments and sustainable management plans are implemented (Arkhipkin et al. 2021; Seto et al. 2023; Peng et al. 2024). A detailed overview of the challenges and needs for cephalopod management and the general status of squid fishing is given by Arkhipkin et al. (2015) and Pierce et al. (2025). Despite these challenges, even if they are already being tackled, such as the definition of European stocks (Göpel et al. 2022; Sheerin et al. 2022; Bobowski et al. 2023, 2024) and the development

of assessment models in European waters (Keller et al. 2015; Alemany et al. 2017), sufficient data is already available to assess some cephalopod species like cuttlefish or squid and calculate simple biomass indices, illustrating biomass trends over time (Bobowski et al. 2023). First trend assessments were performed by the ICES WGCEPH. Annual updates of landing trends and biomass indices allow a relative trend-based indication of the stock status (e.g., ICES 2024), but are yet to be used as advisory tools. In addition, Bobowski et al. (2023) illustrate the possible evaluation of the cephalopod stock status in European waters within the European Marine Strategy Framework Directive based on the available public data. However, besides these efforts to evaluate the cephalopod stocks, it becomes clear that considerable data is missing, as, e.g., landing data is only available on higher taxonomic groups and not on the species level. There is no dedicated scientific monitoring for the species, no onboard observer programme for squid or other cephalopod fisheries, and current knowledge is based on non-dedicated surveys.

In addition to the technical implementation of management, there might also be a political problem, as a substantial amount of fishing activity of Dutch, German, French, British and Belgian vessels on squid takes place in the Eastern English Channel, where the EEZs of Belgium, the Netherlands, France and the UK are in proximity. So far, the same rules apply to all vessels, but this may not last, as the UK may alter its fishing policies further as it is no longer a part of the European Common Fisheries Policy (CFP). If governments decide to limit squid fisheries via fishing quotas, substantial time might be spent on negotiations of the quota distribution between the EU and the UK, and fishing pressure might push the stocks outside of safe biological limits in the meantime. In addition, there has been campaigning on banning fly shooting (or Scottish seining) (Fishing News 2023), which is mainly used to catch squid species, further complicating the playing field. Unified rules and coordinated management and enforcement would not only benefit the fisheries operating in the area, but they would also enable researchers to develop plans for sustainable harvesting strategies. Squid fishing in the North Sea is still a young and ever-changing business, yet it can serve as a trial case for the development of modern ecosystem-based fisheries management in the face of climate change.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in Data dissemination on EU Fisheries Dependent Information at https://stecf.ec.europa.eu/data-dissemination/fdi_en.

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III.-II. First description of the emergence of targeted squid fisheries in the German North Sea demersal trawl fleet



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First description of the emergence of targeted squid fisheries in the German North Sea demersal trawl fleet

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ABSTRACT

As demersal fisheries in the southern North Sea are struggling for profitability, alternative high-value resources are in dire need. In the past few years, squid fishing has emerged as a profitable seasonal fishery. Due to the novelty of this fishery, detailed knowledge remains scarce, as no observer program has been facilitated yet, and catches are not reliably reported on the species level. Conclusions on the ecological and socio-economic implications of this novel strategy, therefore, remained speculative. We combined spatiotemporal hotspot data analysis and clustering techniques with onboard sampling to provide the first scientific description of this novel fishery. We identified a targeted fishery on the common squid *Loligo vulgaris*, taking place on highly localised fishing grounds, particularly four hotspots in the Southern North Sea and the Eastern English Channel, identified using Getis-Ord *G* statistics. Fishing activity followed a distinct seasonal trajectory shifting northwestwards from the beginning (October) towards the end (March) of the season. The economic relevance for the North Sea demersal fishing fleet is significant, as the share of overall revenues generated by squid rose from under 1 % in 2018–21 % in 2024. Targeted squid fishing requires considerable investments, but is, in terms of regulations, relatively open, as no quotas and only very few technical regulations apply under EU and UK law. Acknowledging the rapid increase of this fishery's economic importance, we highlight the need for commencing a strategic management process for emerging squid fisheries in the North Sea, ensuring long-term sustainability and avoiding ecological damage.

1. Introduction

North Sea demersal fisheries are currently in a serious crisis. These fishing fleets, which contribute significantly to the overall productivity of fisheries in the North Sea (STECF, 2023), are under a multitude of pressures, as both their target species and fishing operations are affected by larger-scale developments. A surge in fuel prices has led to a sharp increase in operational costs (Guillen et al., 2023), and this fishery is already particularly fuel-intensive (Tyedmers, 2001; Bastardie et al., 2022). At the same time, quotas for traditionally targeted high-value species such as cod (*Gadus morhua*) in the southern North Sea or sole (*Solea solea*) have steadily decreased, as complex combinations of climate-induced ontogenetic (Fincham et al., 2013; van de Wolfshaar et al., 2022) and distribution (Engelhard et al., 2011; Teal et al., 2012) shifts and decade-long fishing pressure (Mollet et al., 2016) led to local reductions of available biomass. With stocks shifting northwestwards to deeper, colder waters (Dutz et al., 2016; Støttrup et al., 2017),

commercial-sized plaice (*Pleuronectes platessa*), which is another key target species of demersal fisheries, is increasingly hard to catch in a marketable size in the southern North Sea (ICES, 2024a) and has been at least partially substituted by Southern (*Lepidopsetta bilineata*) and Northern Rock Sole (*Lepidopsetta polyxystra*) from the Pacific on the European market (Neerlandia-Urk, 2022). This development has led to a continuous decline in quota utilization of plaice, and in 2024, the German fleet landed only 16 % of the plaice quota it was allocated in the North Sea, Skagerrak, and Kattegat (ICES, 2024a). The reliability of Norway lobster (*Nephrops norvegicus*), another high-value target species of demersal fisheries in the North Sea (Sulanke et al., 2025), has also abated, as quota to fish it is primarily obtained by trading it with the United Kingdom for cod quota, and this system is jeopardised by the turmoil Brexit has caused in the European fisheries landscape (Letschert et al., 2021). In addition, fisheries are facing increasing competition for space, as not only offshore industries are rapidly growing in the North Sea (Jentoft and Knol, 2014; Martins et al., 2023), but also ambitious

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conservation programs are put into place, and calls for the exclusion of mobile bottom-contacting gears from these protected areas have been repeatedly made (Seas At Risk, 2022; OceanCare, 2023; Bearzi et al., 2024). Identifying alternative fishing resources has become an urgent priority in light of these challenges.

Among the potential alternatives, squid fisheries have emerged as a valuable and accessible strategy. Recent shifts in the distribution of several commercially interesting squid species, which were induced by climate change, have led to increasing abundances of squid in the North Sea (Schickele et al., 2021; Laptikhovsky et al., 2022; Oesterwind et al., 2022), reaching levels that facilitate directed fisheries. While targeted squid fisheries in the eastern English Channel and the southern North Sea are a novelty, other cephalopod fisheries are well-established in the Greater North Sea area. Squid and cuttlefish fishing has been established in the western English Channel for over a decade, where catches have fluctuated immensely (Alemany et al., 2017), which is primarily attributable to the shifts in cuttlefish reproductive strategies. Climate change has most likely altered their life cycle, leading to the emergence of annual reproduction instead of the former biannual cycle (Laptikhovsky et al., 2024). Another well-established cephalopod fishery in the North Sea is the seasonal fishery in the Moray Firth, where *Loligo forbesii* are fished when they aggregate in autumn and winter for spawning (Young et al., 2006). A long-time economic pillar of local coastal trawl fisheries, its management is constrained by a lack of reliable data, and the targeted squid show signs of shifting northward (McBride, 2025c). On the contrary, demersal trawling and seining vessels have reported a steep increase in squid catches in the southern North Sea (27.4.c) and the western English Channel (27.7.d) over recent years, and a novel fishery has emerged, predominantly carried out by Dutch, Belgian, French, and UK fishing vessels (Sulanke, pers. communication). The German demersal trawl fleet of the North Sea (Sulanke et al., 2025), though comparably small in size (STECF et al., 2023), is also participating in this new fishery, yet the extent, commercial significance, and even the targeted squid species were unknown. Therefore, our research closes an important knowledge gap, addressing the socio-economic importance as well as ecological implications of this first documented fishery of the German fleet that is directly enabled by the consequences of climate change and management decisions.

Squid species are of high commercial interest and targeted by many directed fisheries around the world (Seto et al., 2023), yet the semelparous lifestyle and short lifespan make them difficult to manage using traditional stock assessment frameworks (Bobowski et al., 2023). Therefore, often ad-hoc or real-time assessments are applied (Arkhipkin et al., 2021; Moustahfid et al., 2021; ICES, 2024b; Peng et al., 2024), setting critical biomass thresholds or CPUE boundaries. Nonetheless, excessive fishing pressure has led to multiple examples of squid stocks being overfished, leading to economic hardship for associated fisheries (Seto et al., 2023; Science, 2024; Pierce et al., 2025). Cephalopods, especially squids, have high reproductive potential and are flexible, highly mobile, and very efficient predators, and most likely benefit from climate change on a global scale (Doubleday et al., 2016). Regionally, multiple squid species such as *Illex coindetii*, *Loligo vulgaris*, and *L. forbesii* have altered their distribution (Göpel et al., 2022; Oesterwind et al., 2022), abundance (Göpel et al., 2022) and phenology (Oesterwind and Schaber, 2020; Laptikhovsky et al., 2024) with most of these changes being attributed to climate change. Due to their high reproductive potential and adaptability, they are principally well-suited as a fisheries target species, yet their volatility and high degree of fluctuation require tailored management approaches and a degree of economic robustness in the fisheries targeting them (Arkhipkin et al., 2021). A detailed analysis such as the one presented is therefore crucial for profoundly assessing the socio-economic characteristics of this fishery and deriving conclusions about its potential long-term sustainability.

2. Material and methods

Data on landings, revenues, and vessel positions were retrieved from the German federal fishery data registry provided by the German Federal Office of Agriculture and Food (BLE), which are routinely collected annually. An alternative fleet segmentation approach described in detail in Sulanke et al. (2025) was used to identify the mixed demersal trawl fleet operating in the North Sea. Of this fleet, vessel-based catch, revenue, and position data were analyzed. To analyze the spatiotemporal dynamics of the squid fishery in the two seasons present in the data, 2023 and 2024, reported catches were aggregated to a $0.1^\circ \times 0.1^\circ$ grid covering all ICES-areas of the ICES Greater North Sea Ecoregion (27.4.a, 27.4.b, 27.4.c, 27.7.d, and 27.3.a.20). From the catches aggregated in this manner, a contiguity-based spatial weights matrix was computed to calculate the Getis-Ord Global G statistic (Getis and Ord, 1992) to test overall spatial heterogeneity. Local spatial autocorrelation statistics (Ord and Getis, 1995) were applied to identify local hotspots and cold spots. Centroids of grid cells belonging to hotspots were clustered using hierarchical agglomerative clustering with the unweighted pair-group method with arithmetic mean (UPGMA) as the fusion algorithm (Sokal, 1958). The optimal number of clusters was determined by computing average silhouette widths for solutions between 0 and 30 clusters and choosing the number of clusters with the highest average silhouette width (Rousseeuw, 1987). To analyze relative temporal distribution of fishing activity in hotspots, Kernel density estimates of fishing activity distribution were computed using a Gaussian smoothing Kernel (Parzen, 1962), which is fully implemented in the *geom_density()* function of the *ggplot2* package (Wickham, 2016). For all data analysis and visualization, the R statistical software was applied (R Core Team, 2024), making extensive use of the packages and functions included in the *tidyverse* package (Wickham et al., 2019) family. Maps were created with the help of the *sf* package (Pebesma and Bivand, 2023), spatial statistics were computed applying the *sfdp* package (Josiah Parry, Locke, 2024), and oceanographic bathymetry data were retrieved and mapped using the *marmap* package (Pante et al., 2023).

To gather information on the socio-economic conditions and operational characteristics, a commercial squid fishing trawler was observed and sampled during a peak-season fishing trip from January 2nd to January 5th, 2025, in the southern North Sea (see Fig. 1). For confidentiality reasons, the vessel's technical data are not given, as they would allow identification. All nine hauls conducted during the fishing campaign were sampled, the catch was identified to species level, and squid dorsal mantle lengths (DML) were measured in cm. ANOVA (Fisher, 1954) and Tukey's-HSD-test (Tukey et al., 1985) were used to test the significance of length differences between all size classes. All sorting of squid into four size classes (SQU1: >1000 g, SQU2: >500 g – 1000 g, SQU3: 300 – 500 g, SQU4: <300 g) was done by the crew members by hand, as auctions, which are the only feasible selling channel for freshly caught squid in the North Sea, demand pre-sorted catches. All additional catches were identified to species level. Additional interviews with stakeholders were held at fish auctions and in fishing ports to integrate the socio-economic characteristics of the fishery.

3. Results

3.1. Data analysis

Analysing the German North Sea mixed demersal trawl fleets' catch and logbook data revealed the remarkable emergence of the squid fishery. Before 2019, squid and other cephalopods accounted for minimal fractions of less than 1 % of the overall fleet revenues (see Fig. 1) and were bycatch. After 2019, squid catches surged, accounting for 10 % of the fleet revenues in 2023 and nearly 21 % in 2024, making them the second most valuable species caught. Other significantly important species are Norway lobster, sole, turbot, and plaice. Plaice was the

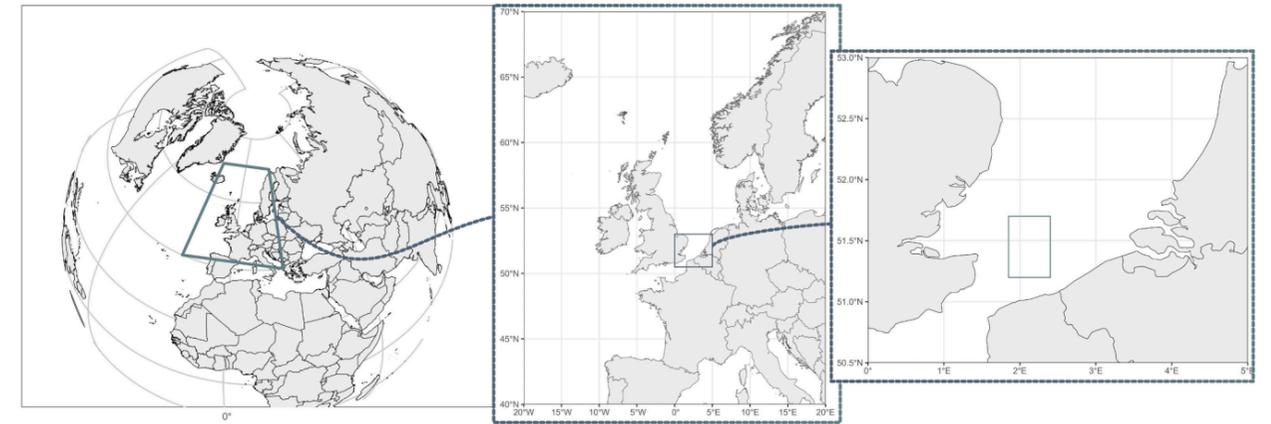


Fig. 1. Study area mapped on a global (left), regional (center), and local (right) scale.

commercially most important species of the fleet in 2013, accounting for nearly 45 % of its revenue. This value continuously decreased over the analysed period, falling to 16 % in 2024. Norway lobster, the overall most valuable target species of the fishery, showed remarkable fluctuations in the share in overall revenues, with 9 % in 2020 and 57.5 % in 2017 being the lowest and highest, respectively. With 26 %, the share of Norway lobster is within the range of the timeline average share of the species of 32.7 %. Sole, another high-value target species, showed strong fluctuations as well, as it fell from a very high share of 34.5 % in 2020 to just 1.2 % in 2024. The share of turbot, on the other hand, remained relatively stable at around 10–14 %.

Both species are high-value species, fetching high ex-vessel prices of over 12€/kg in recent years (see Fig. 2). Yet, these high prices are the result of a steady recovery, as prices for multiple high-value species notably fell in 2020. Sole prices dropped from 14.28 €/kg to 9.63 €/kg, and turbot prices from 9.10 €/kg to 7.15 €/kg. Norway lobster showed a similar price trajectory, as prices fell from 5.75 €/kg to 3.78 €/kg and

recovered steadily afterwards, reaching their highest mark of 7.47 €/kg in 2024. Squid prices steadily increased after 2019 from 3.83 €/kg to 8.61 €/kg. Ex-vessel prices for plaice and cod remained relatively stable at approximately 2.50 €/kg and 3.50 €/kg, respectively. Cuttlefish only became relevant as a target species in 2020 and only account for roughly 1 % of the revenues (see Fig. 1) as they have comparably low prices in the range of plaice and cod of about 4€/kg (see Figs. 2 and 3).

Logbook analysis of 2023 and 2024, which were the first two years in which a considerable part of the trawl fleet participated in the fishery, revealed a distinct fishing season from October to May (see Fig. 4). Commercial squid and cuttlefish fishing of the German fleet started in 2019, yet catches during that time were obtained by a single vessel using Scottish seines, a fishing technique also called 'fly-shooting'. It was not until 2023 that more vessels entered the fishery, using specifically made trawl nets. Following the establishment of this new fishing technique, peak-season monthly catches more than doubled, exceeding 50 tons in January 2024, which is the highest monthly catch ever recorded for squid in German fisheries.

While in most of the North Sea and the Skagerrak, catches of squid

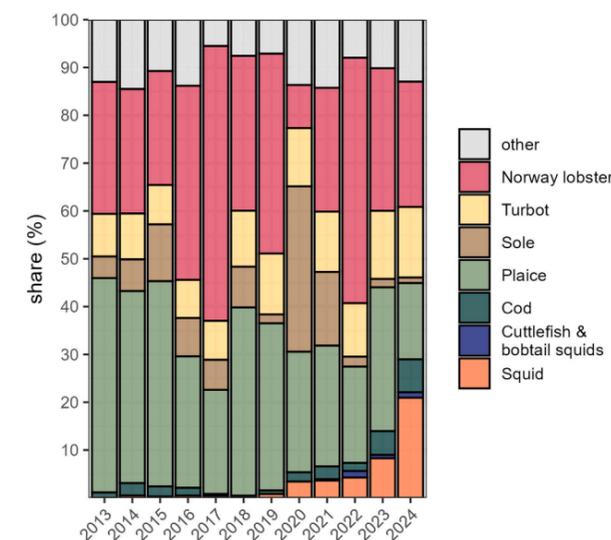


Fig. 2. Timeline of the share of the most important target species in the overall annual revenue of the German North Sea demersal fishing fleet from 2013 to 2024. The year is depicted on the X-axis, the share is depicted on the Y-axis. Target species or species groups are colour-coded. Revenue data was obtained from fisheries landing reports provided by the German Federal Office for Agriculture and Food (BLE).

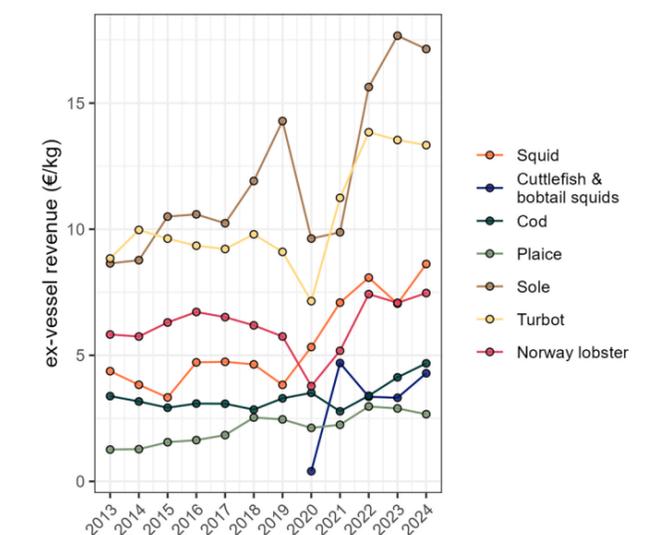


Fig. 3. Timeline of average ex-vessel revenues of selected target species of German North Sea mixed demersal fisheries. Average revenues are given in €/kg, the colour indicates the species or group of species. Revenue data was obtained from fisheries landing reports provided by the German Federal Office for Agriculture and Food (BLE).

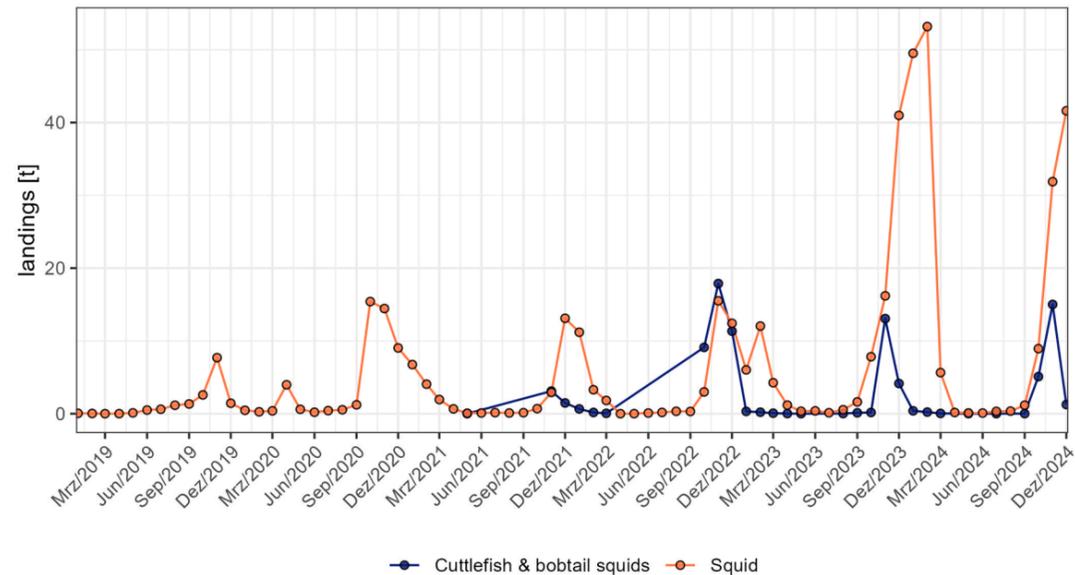


Fig. 4. Seasonal timeline of squid, cuttlefish, and bobtail squid catches of the German North Sea mixed demersal trawl fleet. Monthly catches between January 2019 and December 2024 in tons are displayed; the colour of the points and lines indicates the species group. Catch data was obtained from fisheries landing reports provided by the German Federal Office for Agriculture and Food (BLE).

were rather small at less than 100 kg/haul, although widespread and common, with only a few hauls of 100–500 kg per squid, big catches of more than 500 kg or more than 1000 kg of squid per haul were concentrated in the southern North Sea (see Fig. 5 - (A)). The Getis-Ord Global G statistic applied to the 0.1° -grid-aggregated dataset revealed significant difference from random spatial distribution (Global G 5.48×10^{-3} , Expected G under random distribution 7.45×10^{-5} , p -value $< 2.2 \times 10^{-16}$), indicating significant spatial clustering of hot spots in the data ($Z = 86.61$). Local Getis-Ord G statistic revealed hotspots (G greater than 0) of moderate (p -value ≤ 0.05 and ≥ 0.01) and high (p -value ≤ 0.01) significance, cold spots (G smaller than 0) of high (p -value ≤ 0.01) significance and insignificant spots. All cold spots showed high significance values. Mapping of local G test results (see Fig. 5 - (B)) indicated spatial clustering of highly significant hotspots in the southern North Sea and the Eastern English Channel, while in the central and northern North Sea, only hotspots of moderate significance were present. Hierarchical clustering of the Euclidean Distance matrix computed from hotspot grid cell centroids was performed, in which the optimal number of clusters was determined at 4, with the highest average silhouette width at 0.731. Plotting the four hotspot clusters revealed their spatial distribution: Cluster I was located the furthest west of all clusters, in the Eastern English Channel near the coast of France in the Baie de Seine, with a single outlier grid cell further towards the center of the Channel. Cluster II was also located in the Eastern English Channel, but further to the east and closer to the coast than Cluster I. Cluster III was located slightly north of the Strait of Dover, and Cluster IV in the southernmost part of the North Sea, the Southern Bight (see Fig. 5 - (C)). To assess temporal dynamics, the Kernel density estimate of monthly haul distributions in the four hotspot clusters was plotted. Cluster I had the highest relative density of hauls in December and March, Cluster II in November and December, Cluster III in November and December, with December being the most pronounced relative peak of the dataset, indicating a high spatiotemporal concentration of fishing activity, and Cluster IV in January and February (see Fig. 5 - (D)). Overall, the combined application of spatial and temporal clustering and distribution analysis revealed a significant spatiotemporal concentration of the squid fishery and a pronounced northwestward trajectory of fishing activity concentration in the progression of the fishing season.

3.2. Commercial fishery sampling

The fishing trip of an anonymous commercial fishing vessel targeting squid at DS was sampled at the height of the squid season from January 2nd to January 5th, 2025. Squid were caught with a specifically manufactured squid trawl with an approximate opening width of 40 m between trawl doors and an approximate opening height of 8 m. Acquisition costs of the net were approximated at 35,000€ by the fishers, as the net was acquired by the fishing company owning the vessel and several others. Trawls were undertaken only during daylight hours, as squid aggregate close to the seabed during the day and disperse in the water column at night, presumably for feeding. All hauls were towed in a narrow seabed area approximately 25 NM long and 5 NM wide at depths between 37 m and 42 m, bounded by a rocky area with shallow (10 m to 15 m depth) dune ridges to the southeast and a basin of over 60 m depth to the northwest (see Fig. 5). A total of 9 hauls was conducted in two days of fishing. Trawls were towed for 1–3 h and distances between 4.8 NM and 13.4 NM, with an average duration of 1.9 h (SD: 0.82 h) and an average distance of 8.16 NM (SD: 3.73 NM). The fished area was located at the intersection of the EEZ borders of Belgium, France, and the UK, and multiple hauls were towed across multiple states' EEZs (see Fig. 5). As it was peak squid season, the fishing ground was densely populated by approximately 20 trawlers of different nationalities, towing northeast to southwest and vice versa.

A total of 1020 kg of squid specimens were caught in the two-day fishing campaign, which were all *Loligo vulgaris*. The largest size class accounted for the smallest share of the catch with only 1.28 % of the catch weight (see Fig. 6). All other size classes had comparable shares of the catch weight with 36.39 %, 35.24 %, and 27.1 % for SQU2, SQU3, and SQU4, respectively. As sorting was done by hand and therefore had a degree of subjectiveness, the mantle lengths of the four size classes showed considerable overlap, yet median mantle lengths reflected the size differences, nevertheless. SQU4 had a median mantle length of 16 cm (MW: 15.68 cm; SD: 2.71 cm), SQU3 had 21 cm (MW: 21.45 cm; SD: 1.89 cm), SQU2 had 30 cm (MW: 30.45 cm; SD: 4.00 cm), and SQU1 had the biggest median mantle length of 48 cm (MW: 48.36 cm, SD: 2.31 cm). The largest individual caught (54 cm DML) was in SQU1, which is the maximum reported DML of North East Atlantic *L. vulgaris*

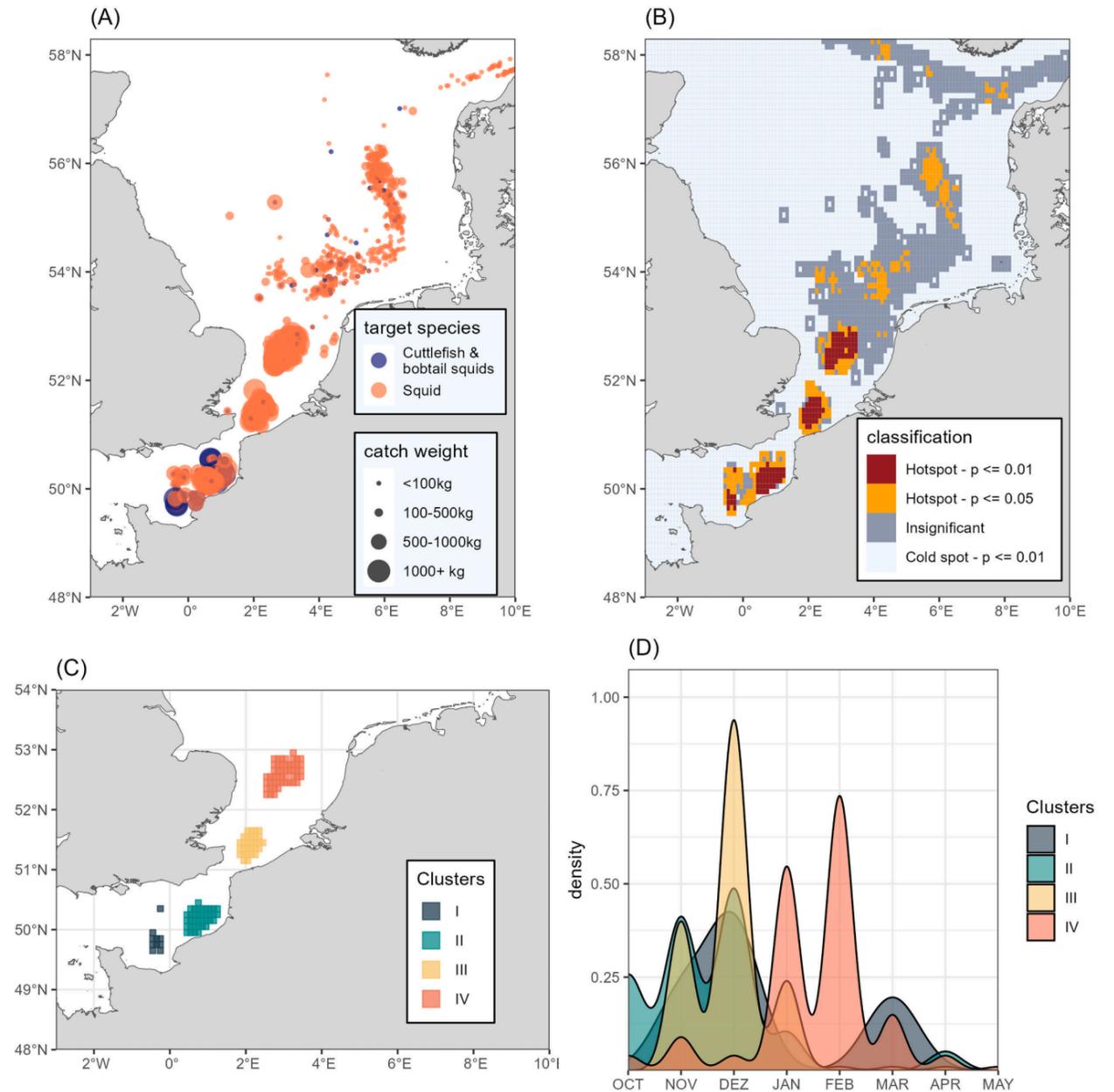


Fig. 5. Grid of figures displaying spatiotemporal dynamics of German squid fisheries for the years 2023 and 2024. A) Map of fishing positions of German North Sea demersal trawl fisheries catching cephalopods in the Greater North Sea Ecoregion. Positions were taken from the logbooks of 2023 and 2024. Point sizes correspond to the catch weight, the colour of the points indicates the species group caught. Haul sizes were categorized into minor (< 100 kg), small (100–500 kg), medium (500–1000 kg), and big (1000 + kg). Fishing locations were obtained from logbook reports provided by the German Federal Office for Agriculture and Food (BLE). B) Map of spatial hotspot analysis result. Hotspots with high ($p < 0.01$) and medium ($p < 0.05$) significance, insignificant spots, and high significance cold spots ($p < 0.01$) are displayed. C) Map of hierarchically clustered hot spots of squid fishing. The four clusters are color-coded. D) Kernel density estimate of empirical haul distribution during the squid fishing season within the four identified squid fishing hot spots. The month is displayed on the x-axis, following the continuity of the winter fishing season from October to May, the Kernel density estimate is displayed on the y-axis.

(Moreno et al., 2007) and is only 10 cm below the maximum published mantle length of this species (Perales-Raya, 2013). Median mantle lengths of all size classes were significantly different from each other (ANOVA p -value: $2e^{-16}$, Tukey-HSD-test p -values of all pairings approximating 0). All squid were kept chilled on ice and sold fresh at an auction, limiting the duration of the fishing trip to no longer than three days after obtaining the first catches. Whiting (*Merluccius merlangus*) was

the most common bycatch, and the part of the catch exceeding the minimum conservation reference size (27 cm, EU 1998) was kept, which was approximately 200 kg in total. Undersized whiting was discarded, which is a legal exemption from the existing landing obligation for the species (EU, 2023). Many whiting individuals showed bitemarks from squid beaks, which most likely were sustained in the cod-end of the net during hauling. Other bycatch species, of which only a few individuals

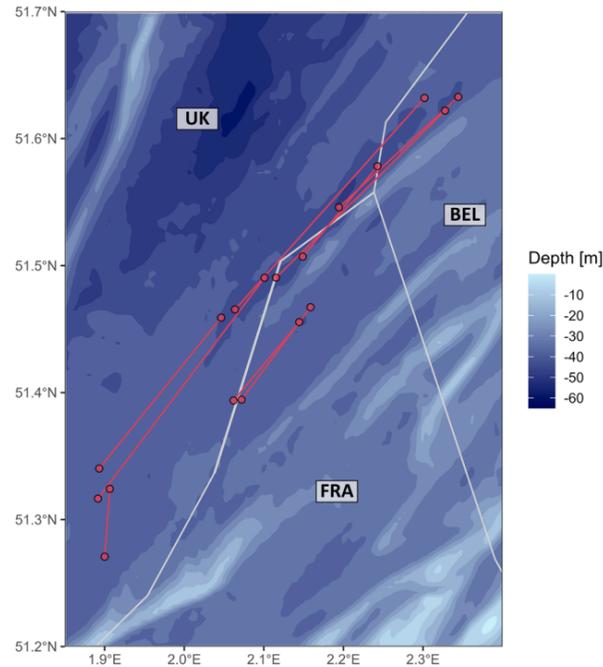


Fig. 6. Map of trawl tracks covered by the exemplary squid trawler during the sampled trip. Points mark deployment and retrieval positions; the colour scale depicts the depth. White lines mark EEZ borders, the governing nations are marked with the corresponding abbreviations (UK = United Kingdom; BEL = Belgium; FRA = France).

were caught and kept for their high market value, were: European seabass (*Dicentrarchus labrax*), Greater weever (*Trachinus draco*), John Dory (*Zeus faber*), Lemon sole (*Microstomus kitt*), Cuttlefish (*Sepia officinalis*), and tub gurnard (*Chelidonichthys lucerna*). Other very common, yet mostly discarded, bycatch species were dab (*Limanda limanda*) and striped red mullet (*Mullus surmuletus*) (Fig. 7).

3.3. Auctions & sales channels

Interviews on sales channels were held both on board and at the IJmuiden fish auction, which is one of the most important auction sites for squid, together with Vlissingen and Den Helder in Belgium, depending on the season and the fishing activity at the previously described fishing grounds. Fishermen and auction visitors unanimously reported that all squid size classes reach similar ex-vessel prices of around 10 €/kg, with fluctuations being driven by supply and demand in the main buying regions, which are Spain, Portugal, and France. The majority of the squid sold at auctions is processed in the Netherlands, primarily in Urk, and wholesalers buy large quantities to supply the processing sites. Yet, wholesalers and restaurants also buy smaller quantities for high prices, contributing to the overall revenue of the fishery.

4. Discussion

Our results revealed a unique and completely novel fishery that the German fleet had never undertaken before. News from the fishing sector and scientific reports (ICES, 2024b) suggested increased fishing activity on squid by Dutch, Belgian, British, French, and German vessels in the southern North Sea and the eastern English Channel, but a full scientific description was, to our best knowledge, missing. Identifying the fishery as a targeted fishery on *L. vulgaris*, which is only one of several squid species in the North Sea showing increasing abundances and widened distribution ranges, increases the ecological understanding of squid population dynamics in the area (van der Kooij et al., 2016; Schickele et al., 2021; Oesterwind et al., 2022), as squid species are usually not or not reliably reported to the species level in commercial catch statistics (ICES, 2024b) and are only insufficiently assessed in scientific surveys, because no delegated survey for squids exists. The very specific fishing areas identified, which are also used in seasonal succession, support the notion of the underrepresentation of squid in scientific surveys. The fished area sampled in the study was approximated at 25NM long and 5NM wide, equalling 125 square miles. For comparison, a rectangle of the International Bottom Trawl Survey in the area is around 37NM times 30NM, which is 1110 square miles. Given this size difference, the pronounced seasonality we described, and the low sampling frequency of scientific surveys, sampling this fishery without a specifically designed program is highly unlikely. We, therefore, urge not only including this

fishery in the respective on-board sampling and observer programs of the EU and UK, but also for a multilateral initiative to create a specifically designed, coordinated research survey.

Squid are highly efficient predators that play a significant role in marine ecosystems both as predators and prey (Bello, 1991; Clarke, 1996; Caddy and Rodhouse, 1998; Piatkowski et al., 2001; Oesterwind et al., 2022; Oesterwind and Piatkowski, 2023; Schäfer et al., 2024). The fishery we described makes use of aggregations of individuals that are highly specific in time and space, which most likely form because individuals are either spawning or feeding, or a combination of both. Many whiting individuals had visibly full stomachs, and sampling revealed that most of them were feeding on sandeel (*Ammodytes* sp.). The sandeel individuals found in whiting stomachs constitute a potentially suitable prey organism for squid (Pierce et al., 1994; Oesterwind and Piatkowski, 2023), and the fishing area is a suitable habitat for sandeel (ICES, 2025a). In addition, area and timing match the reproductive cycle of the Downs herring stock, and fishers interviewed linked the appearance of the squid to the spawning herring. Squid are capable, opportunistic predators and capable of preying on herring (Pierce et al., 1994; Oesterwind and Piatkowski, 2023), as herring spawning aggregations have been proven to attract predators, e.g., haddock and whiting (Toreisen, 1991). Yet, the season also matches the reproductive cycle found for *L. vulgaris* in previous work (Oesterwind et al., 2010; Laptikhovskiy et al., 2022) and the pronounced fishing season and strong seasonality align closely with the findings of Marcout et al. (2025). Their promising approach of a standardised index for spatiotemporal variability assessment should be followed up harnessing international fleet data sets and, preferably, catch data identified to the species level. The area documented in our study has been documented as a spawning site by the mentioned as well as earlier studies (Jereb et al., 2015), yet the abundances in which the squid were aggregating in the area are, according to the fishers participating in this novel fishery, unprecedented. The stock component spawning in the southern North Sea (*L. vulgaris typica*) might benefit from regional warming and milder winters, creating more favorable temperature conditions for egg development. Alternatively, the aggregation could be a feeding aggregation, potentially on sandeel, which has been documented as a prey item for *L. vulgaris* before (Jereb et al., 2015), in preparation for spawning in more western areas of the English Channel. The rapid end of the squid season in the southern North Sea in early to mid-March could be interpreted as an indication of the semelparous squid dying after spawning, yet only fecundity sampling of individuals caught in the southern North Sea can provide a definitive answer.

Regardless of the specific reason for *L. vulgaris* aggregating in the sampled area, climate change and the warming of the North Sea are likely to be at least an influencing factor in this distribution change. Especially in the shallow, semi-enclosed North Sea and the adjacent Baltic Sea, where climate change effects are comparably pronounced (Colijn and Quante, 2016; Meier et al., 2022), traditional key fisheries target species such as cod and herring are impaired by the effects of ocean warming. The subsequent economic damage to the German demersal fishing fleet has been immense, and vessel numbers are continuously declining (STECF, 2024). The *L. vulgaris* fishery is the first documented example of targeted cephalopod fishing by the German fishing fleet. It is a much-needed economic relief for the North Sea demersal trawl fleet, which suffers from the pressures described in the introduction of this article, and the unparalleled rapid growth of the economic importance of the fishery reflects that. *L. vulgaris* is not only a high-value target species fetching excellent auction prices, but it is also subject to very few regulations. As previously described, fishers need to follow only the minimum mesh size and bycatch regulations when engaging in the squid fishery. Yet, the bycatch regulations have become somewhat problematic, as patrol boats have found bycatch of undersized whiting exceeding allowed limits during controls, resulting in closures of the fishing area for up to three weeks (McBride, 2025b). Given the described short season and spatial limits of squid fishing in the

southern North Sea, these closures have severe economic consequences for the vessels. Whiting in the North Sea is well within safe biological limits, and the quota is not fully utilized (ICES, 2025b). A feasible solution for the problem might be a temporary increase of the allowed percentage of undersized whiting bycatch and a simultaneous development program for specialized squid trawls, avoiding whiting bycatch. At the same time, and more importantly, the ecological and economic sustainability of this new resource needs to be safeguarded. The semelparous lifestyle of squid in combination with their short life span, makes it particularly hard to perform traditional stock assessments, which are the pillar of EU fisheries science and the subsequent management. Determining a total allowable catch of *L. vulgaris* before the season starts is extremely challenging and, if performed, most likely to come with a lot of uncertainties. Therefore, established management measures from other squid fisheries around the globe, such as pre-season biomass indices or live assessments during the fishing season, might have potential for managing the southern North Sea *L. vulgaris* fishery as well (Agnew et al., 2005).

Our analysis revealed that the southern North Sea *L. vulgaris* fishery takes, at least in part, place on the intersection of EEZ borders of EU member states and the UK, highlighting the urgent need for standardised management procedures for a fishery in which both EU and UK vessels participate. Technical and catch-related management measures can only be effective if they are multilaterally agreed upon and implemented by all relevant nations. This is especially challenging as the UK has left the EU and, therefore, also the European Common Fisheries Policy (CFP). The agreement on unchanged conditions for EU Fishing vessels following 2027 (including no change in the 2026 quota distribution key between the UK and the EU) could be a sign that both sides are interested in a common management of resources. Fisheries agreements between the two parties are currently set for fixed periods, which is not an ideal situation for fostering long-term sustainability and should be changed to longer-term objectives and measures.

Since leaving the CFP, the UK has implemented novel regulations such as mandatory VMS tracking for small coastal vessels (Marine Management Organisation, 2025) or a ban on sandeel reduction fisheries in protected areas, the latter being successfully contested by Danish sandeel fishers using the dispute settlement mechanism included in the BREXIT agreement (McBride, 2025a). To keep the southern North Sea squid fishery from becoming the next subject of contention in EU-UK fisheries relations, commonly agreed management strategies should be preferred to unilateral advances. This also applies to gear regulations, as the demersal trawls and seines currently used in squid fishing are opposed both in the UK and the EU (Seas At Risk, 2022; OceanCare, 2023), and campaigns for banning them have gained momentum in recent years. In other regions of the world, squid are commonly caught using jigs on a commercial scale (Chen et al., 2008), which have no contact with the seabed, use less fuel than trawls (Davie et al., 2015), and usually have very little bycatch as they are using specialised squid hooks without barbs. Yet, scientific trials of commercial-scale squid jigging in the North Sea have not been successful, and it is currently only applied on a recreational level (Marine Management Organisation, 2023). If a ban on mobile bottom-contacting gear should be implemented in the southern North Sea, it cannot be expected that fishers can make a rapid transition to jigging, as it requires considerable technical and operational adjustments. Therefore, a transitional phase would need to be facilitated, ideally including funding and support.

5. Conclusion

Combining data analysis and field sampling, we conducted the first scientific description of a novel regional squid fishery in the southern North Sea. As we highlighted, the economic importance of the fishery is significant, as the targeted high-value *L. vulgaris* constituted a fifth of the analysed fleet's annual revenues. A high level of specialisation in terms of gear and operational strategy is required by the participating vessels,

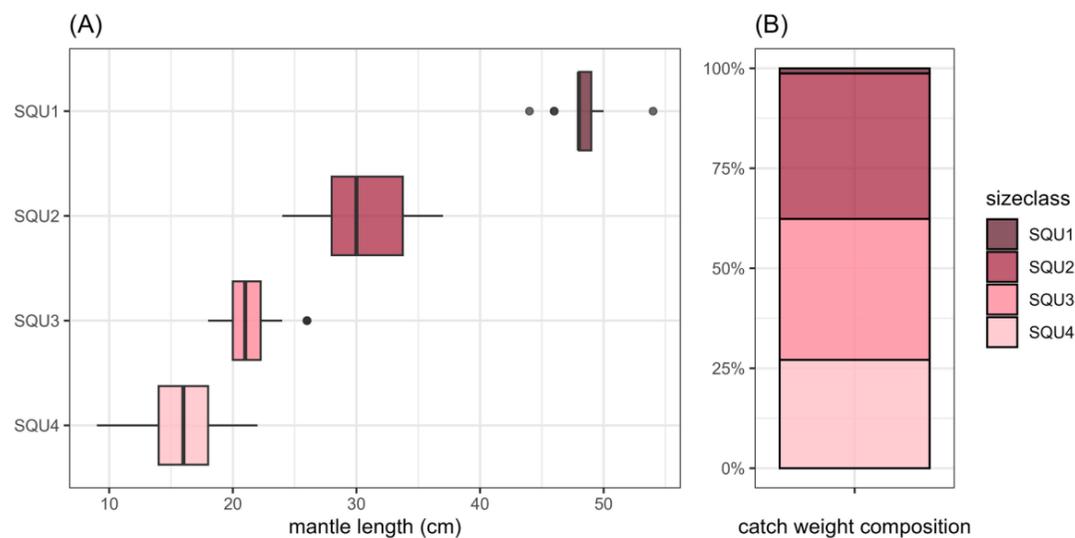


Fig. 7. Grid of catch characteristics measured during the sampled trip on *Loligo vulgaris* specimen. Boxplot (A) depicts the range of mantle lengths in cm of the four squid size classes. Plot (B) depicts the share of the four size classes in the total catch obtained during the sampled trip. The colour depicts the size class.

yet a high market demand and ex-vessel price, fueled by the struggles of other global squid fisheries, states a compelling incentive to join the fishery. Our analysis is largely restricted to the German fleets, and further research and onboard observer programs should be facilitated as soon as possible in the Netherlands, France, the UK, and Belgium to cover the other, often considerably larger, fleets participating in this fishery. Furthermore, a strategic, multilateral management process should be commenced, utilising existing research and creating a road-map to safeguard the long-term sustainability of the resource. Southern North Sea squid fisheries are indubitably at least partly caused by the effects of climate change and can serve as a stress test for the European fisheries management landscape. Traditional target species can no longer sufficiently guarantee the long-term economic viability of North Sea fisheries, and fishers are in dire search for alternatives. As continuous warming of the ocean will cause accelerating changes in species distribution and ecology, the squid fishery will not be the last 'new' target fishery in the Northeast Atlantic. The rapid speed of the ongoing ecological change will continuously force fishers, managers, and researchers to adapt and develop feasible solutions, avoiding previous mistakes of unsustainable harvesting and overfishing of valuable resources.

CRedit authorship contribution statement

Daniel Oosterwind: Writing – review & editing, Writing – original draft, Visualization, Validation. **Ralf Döring:** Writing – review & editing, Conceptualization. **Erik Sulanke:** Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no competing interests or personal relations influencing the objectivity of the presented work.

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Data availability

The authors do not have permission to share data.

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IV. Fisheries in the Blue Economy and the potential of alternative management measures



Community Development Quotas and Support of Small-Scale Fisheries as Two Key Concepts for Blue Growth in Fisheries

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Blue Growth has become one of the key topics of ocean management. It is defined as a holistic framework for an environmentally friendly and socio-economically sustainable development of ocean-related activities with a special emphasis on technological innovation. Capture fisheries are widely considered to have no substantial growth potential and consequently are not subject to the European Union's Blue Growth strategy. In our review, we, however, argue that capture fisheries should play an essential role in national Blue Growth strategies. We identified two interconnected management strategies to foster Blue Growth in fisheries, a) the implementation of Community Development Quota (CDQ) systems and b) the support of small-scale fisheries (SSF). They hold the potential to benefit fishery-dependent coastal communities and therefore counteract consolidations in the fishing sector. Additionally, they provide the possibility to improve quota access for small-scale fishermen. Besides having better access to quota, the future of SSF depends on sources of public funding for technical improvement and innovation as well as increased representation in the management. In this perspective, we present different cases that successfully implemented CDQs (the Alaska pollock fishery) or have considerable potential to implement CDQ programs or improve their current approaches (United Kingdom, Ireland, and Iceland). We further discuss examples for successful management strategies to support SSF directly. If these aspects are considered in a Blue Growth strategy, the survival of fishery-dependent communities could be assured, and SSF could develop from predominantly part-time or subsistence fisheries to a full-time occupation. By those means, they would be part of a fostering Blue Economy and strengthen environmentally friendly and socio-economically sustainable fishing practices in Europe.

Keywords: Blue Economy, community quota, small-scale fisheries, sustainability, management strategies, common fisheries policy

INTRODUCTION

Blue Growth has become the key framework of the European Union's (EU) ocean governance (European Commission, 2019). Conceived in analogy to the terrestrial Green growth strategy of the EU adopted in 2010 (European Commission, 2010), it is based on a holistic management approach accelerating economic growth of ocean-related activities by supporting innovation and knowledge development. At the same time, ecological damage, climate impact, and social injustice are expected to be minimized (Boonstra et al., 2018; Burgess et al., 2018; Pauly, 2018). While Blue Economy comprises all forms of commercial activities of the marine realm, be it cargo shipping, harbor activities, or fisheries, the European Blue Growth Strategy focusses on the five sectors deemed to have the highest potential for sustainable growth: Aquaculture, coastal and maritime tourism, biotechnology, renewable energy and ocean mining (European Commission, 2012). The terms are widely used among countries inside and outside the EU as well as institutions (e.g., Burgess et al., 2018; Howard, 2018; Pauly, 2018; FAO, 2020; Sari and Muslimah, 2020), yet, the practical implementation of a balance between economic interests and ecological sustainability remains unclear (Soma et al., 2018).

In the past three decades, global fisheries catch has stagnated at a level of around 90 Mil. tons (t), and relevant increases in seafood production were observed due to the rapid growth of the aquaculture sector. During the same period of time, it grew by 527% and has produced more fish for human consumption than capture fisheries since 2014 (FAO, 2020). Due to the limitations in production (Pauly, 1996; Watson and Pauly, 2001) and the rising ecological (Pauly and Palomares, 2005; Worm et al., 2006; Hiddink et al., 2017) as well as socio-economic (Coulthard et al., 2011; Olson, 2011; Bavinck et al., 2018) concerns, capture fisheries are often assessed to have no potential for Blue Growth (Ehlers, 2016) and are therefore not in the focus of the EU's Blue Growth strategy (see **Figure 1**). However, some authors argue that capture fisheries should play an important role in all Blue Growth strategies, as it secures the livelihood and protein supply of millions of people (Hilborn and Costello, 2018). It is not only a significant economic activity in the marine realm but has a tremendous, if not the largest, anthropogenic influence on marine ecosystems and has caused numerous stock collapses (Pauly et al., 2002). Therefore, it is important to consider fisheries in every Blue Growth plan for monetary reasons but also to ensure ecological sustainability of ocean-related activities. If neglected in Blue Growth management strategies, fisheries will most certainly face increased competition for space, which will result in increasing fish pressure on the remaining areas still available for fishing activities. The accumulated fishing effort in these areas could be a serious hazard to the environment and fish stock health.

In most fishing industries, small-scale fisheries (SSF), which have also been called the "coastal employment system" (Sønvisen et al., 2011), represent the vast majority of vessels. In fact, 90% of the global employment in capture fisheries is counted among the SSF sector (FAO, 2020) and is thought to support approximately 10–12% of the global population (FAO, 2012). Historically, all generations within a fishing community have worked together

and contributed to its viability as well as livelihood of the families. Generally, men were onboard the vessels, and women, as well as children, took care of the fish processing, gear mending, food gathering, and organization of the enterprises (Frangoudes, 2013). Until the nineteenth century, the fishing sector was mostly dominated by SSF with limited technologies, but especially after the Second World War, technological developments increased rapidly (Sala et al., 2018). On a global scale, subsidies were mainly issued to large-scale vessels, as the SSF only received 7% of the total subsidies (Schuhbauer et al., 2017), which immensely increased the gap between the large- and SSF. Together with massive resource declines and markets that are mostly focused on industrial catches, the small-scale sector is facing a loss of catch opportunities and increasing bureaucratic pressure (Davies et al., 2018; Symes et al., 2020). This is an alarming development since SSF are often still essential for supporting family households in rural, fishery-dependent areas (Symes et al., 2020). Due to the historical development of these communities, they usually lack suitable economic alternatives to fisheries and face economic declines as well as a continuous labor outflow (New Economics Foundation, 2016). Additionally, both the political and scientific attention still primarily focuses on the large-scale fleets, although the reformed Common Fisheries Policy (CFP), a European framework, intended to create a better framework for SSF. Yet, most Producer Organizations (POs) do not involve SSF, and although the impact of SSF on stocks is largely unknown, under the CFP, they had to follow the same scrapping regulations applicable to larger vessels (Pascual-Fernández et al., 2020). Even though the importance of SSF for the livelihood of coastal communities is often emphasized for the global south, the global north and the Northeast Atlantic region are home to long-established, traditional SSF as well. Albeit frameworks, such as the CFP, aim to strengthen the position and representation of SSF in networks like the low-impact fishermen of Europe (LIFE), they are pressured by the aforementioned stressors, and their survival is endangered. This is an alarming development since they not only do represent a traditional form of food production with specific knowledge of their fishing grounds, but they are an important part of life in coastal communities (Pascual-Fernández et al., 2020). Our review focusses on the possibility to both strengthen the economy of such fishery-dependent coastal communities and to foster Blue Growth in SSF with the establishment of Community Development Quota (CDQ) schemes, where a public board or council holds and manages part of the quota shares on a stock on behalf of the community. We will present four case studies to illustrate and substantiate our claim, the first being the case of the Alaska Pollock fishery, where a CDQ scheme has successfully strengthened the economy of fishery-dependent communities. In the other three case studies, we describe situations in the northern European island nations; the United Kingdom, Ireland, and Iceland. All three nations not only have a rich tradition in fisheries and large coastal fishing fleets but also tried to establish management schemes comparable to CDQs, yet did not or only partially succeed. We aim to emphasize the potential of establishing CDQs and of the political empowerment and targeted funding of SSF as integral concepts of Blue Growth Strategies in fisheries management. These two

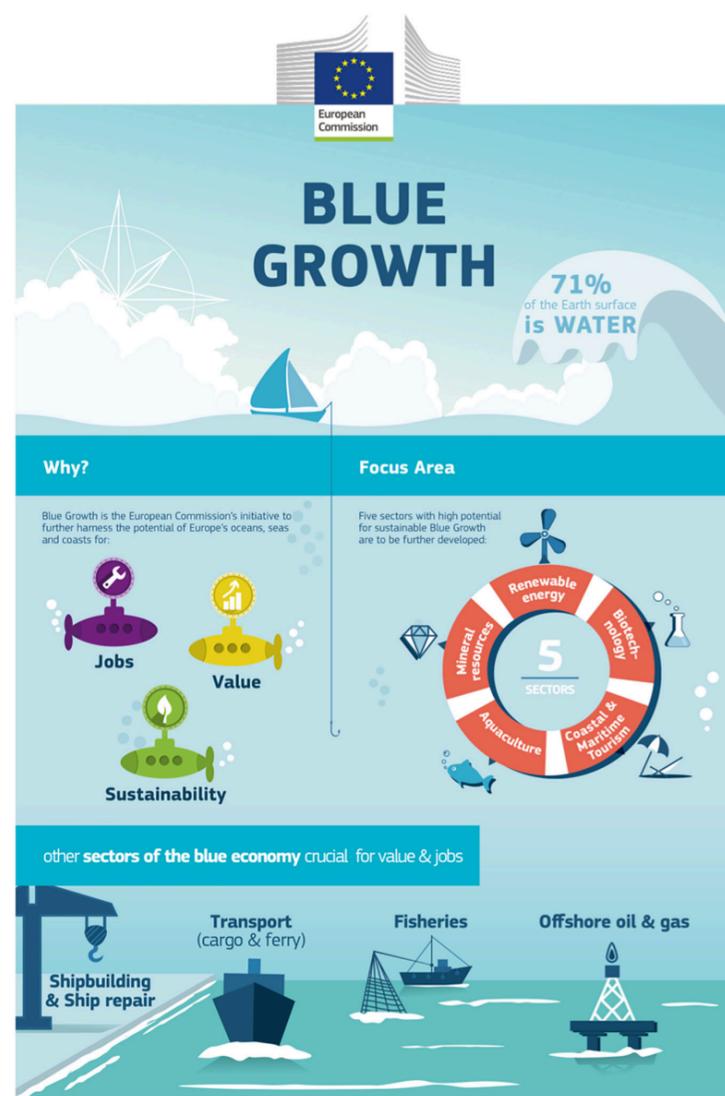


FIGURE 1 | Schematic depiction of the EU Blue Growth Strategy's focus area, reasoning, and other crucial sectors for the Blue Economy Adapted from European Commission (2012).

strategic trajectories are not discussed separately, but rather their potential for reciprocal reinforcement is emphasized.

CASE STUDIES

Establishment of a Successful Community Development Quota-System—The Alaska Pollock Fishery

Alaska or walleye pollock (*Gadus chalcogrammus*) belongs to the family Gadidae and can be found in the northern Pacific

Ocean from Washington State up to Russia and the waters of northern Japan and Korea (Strong and Criddle, 2013). This whitefish forms schools close to the seafloor and is especially plentiful in the Bering Sea and the Gulf of Alaska. The main products are filets for fast-food restaurants and grocery retail, roe, and surimi (primarily in Japan), fish oil, and fishmeal (Strong and Criddle, 2013). The Alaska pollock fishery started in the early 1960s and was Japanese and Russian. With the Magnuson Fishery Conservation and Management Act in 1976, however, an “Americanization” of the fishery started, and a battle between the United States of America (U.S.) and foreign fishermen commenced. The dispute occurred mainly between the inshore-based processors with corresponding catcher boats and

the factory trawlers (motherships) with their associated catcher boats operating further offshore (Strong and Criddle, 2013). For the inshore-based U.S. firms, it was a premiere to catch and process groundfish in this region (Strong and Criddle, 2013). During the 1980s, the demand for seafood within the U.S., especially Atlantic cod, grew substantially until the imports and domestic production could not keep the level anymore. Hence, Alaska pollock was increasingly used as a product and became more and more popular (Strong and Criddle, 2013). Besides, fishing and processing methods became much more efficient with improving technologies. In the late 1980s, it became obvious that the number of fishing vessels and capacity of processing facilities would exceed the stock biomass. The offshore sector with their factory trawlers was expanding, while the inshore sector realized they would lose the competition for Alaska pollock. Therefore, they lobbied to receive a fixed portion of the Total Allowable Catch (TAC) and exclusive rights to specific fishing zones around their processing facilities (Strong and Criddle, 2013). The inshore sector started to receive substantial political support to increase livelihoods and job possibilities in Alaska. In 1989, new factory trawlers legally entered the Alaska pollock fishery catching more than 37,000 t during 6 weeks. Consequently, the fishery had to be shut down early, thus preventing the smaller, inshore-based vessels from fishing their portion of pollock (Criddle and Strong, 2013; Strong and Criddle, 2013; Kotlarov, 2019). The war between the inshore and offshore sectors built up even further.

In 1992, a CDQ program was established as a sector allocation under the North Pacific Fishery Management Council's Inshore-Offshore sector, providing a fixed Alaska pollock quota allocation of 7.5% to 65 Alaska communities, including 27,000 people, which are now organized in six non-profit corporations (Ginter, 1995; Kotlarov, 2019). In the Alaskan region, people have lived off the sea for thousands of years and established the oldest continuous maritime culture in the world (National Research Council, 1999). However, as the Alaskan region is among the most impoverished in the U.S. in terms of per capita income and no other relevant industry is present to provide employment (Ginter, 1995; National Research Council, 1999; Szymkowiak and Himes-Cornell, 2018), the introduction of a CDQ scheme was an effective tool for increasingly stable incomes and infrastructure developments in those communities. Many of these entities, however, leased their quotas in the first years of the CDQ-program by bids since they did not possess the processing capacities needed to process catches (Strong and Criddle, 2013; Kotlarov, 2019). The flexibility to choose the place, time, and technique to fish increased substantially, encouraging fishermen to aim for maximum profitability per pound of catch rather than maximizing the amount of fish caught per day.

The race-for-fish did not come to an end until 1998, with the implementation of the American Fisheries Act (AFA). The CDQ program was also amended to a permanent Alaska pollock quota allocation of 10% in 1998 (AFA, 1998), and today, 10% of the TAC and bycatch caps for all managed groundfish stocks and shellfish within the U.S. Exclusive Economic Zone (EEZ) as well as portions of the Eastern Bering Sea are under CDQ-management (Haynie, 2014; NOAA, 2018a; Szymkowiak and Himes-Cornell, 2018; Lyons et al., 2019). As a reference, in 1992, the TAC for

Eastern Bering Sea walleye pollock averages about 1,300,000 t, of which 7.5% are about 97,500 t or approximately 3.5 t per capita (NOAA, 2018b). Additionally, the TAC for 2020 was 1,425,000 t, of which 10%, i.e., 142,500 t or 5.3 t per capita, were allocated to the CDQ communities (NOAA, 2020). The increased efficiency of the fisheries also increased overall fleet profitability and reduced the overcapacity through firm consolidations (Kotlarov, 2019).

From 2001 on, 100% of the CDQ quota of Alaska pollock was harvested by highly efficient catcher-processor factory vessels (Haynie, 2014). Other groundfish and shellfish species are, however, fished by a mixture of harvest gears, and some species, such as Pacific Halibut, are entirely fished by rather than small-scale, coastal vessels that are either owned by the CDQ organizations or by residents of the CDQ communities (Strong and Criddle, 2013; Haynie, 2014; NOAA, 2018a). In 2004, the Alaska pollock fishery even received a certification from the Marine Stewardship Council (MSC), as the fishery was able to respond to stellar sea lion population and salmon bycatch (Strong and Criddle, 2013). The MSC certificate is the largest certification system for seafood products in the world, and by 2019, 17.4% of all wild-caught fisheries were MSC-certified (MSC, 2020b). Although it received criticism in the past (Ponte, 2012; Bush et al., 2013; Kalfagianni and Pattberg, 2013), the label has proven to be a robust indicator for sustainable fisheries. In a comprehensive analysis of 224 fish stocks, Gutiérrez et al. (2012) found only 9% of the MSC-certified stocks to be overfished, while 27% of the non-certified stocks were overfished according to the Biomass threshold for maximum sustainable yield (BMSY). After 2009, more than 50% of the catcher and processor ownership positions were filled by CDQ community members (Kotlarov, 2019).

Where the CDQ communities lack the capacity to directly harvest the CDQ species, CDQs are leased to companies in which the communities hold partial ownership if possible (Strong and Criddle, 2013). Additionally, certain rules do not apply to the CDQ communities. For instance, their quotas can be harvested in areas or at times closed for the conventional fishery (Haynie, 2014). This provides the possibility to supply the market with Alaska pollock products when the supply is low, and the value is high (Ginter, 1995). The consistent increase of Alaska pollock prices as well as the corresponding CDQ royalty leasing rates, which increased threefold from around 100 US\$/t in 1992 to more than 300 US\$/t in 2004 (Figure 2), further promoted the economic performance of the CDQ entities. Between 1992 and 2008, more than 522 million US\$ were earned from CDQ royalties (Criddle and Strong, 2013).

The CDQ entities re-invested those earnings from the quota leases to participate in other regional businesses (Ginter, 1995). Since 2004, they earned more money from non-royalty sources, such as processing and other fishing activities, than from quota leases. In consequence of those business successes, the net assets of the CDQ entities rose from 132.2 million US\$ in 2000 to 737.6 million US\$ in 2010 and have never decreased in the time of their existence (Strong and Criddle, 2013). With the investments from the CDQ program, harbor infrastructure was built, which allows local residents to pursue a variety of fishing activities. Additionally, residents can receive training and employment in the CDQ entities; between 1993 and 2005, more than 13,000

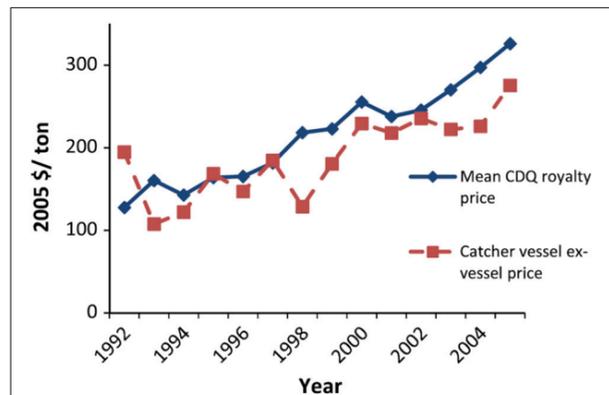


FIGURE 2 | Annual CDQ royalty rates and inshore catcher vessel ex-vessel prices of the Alaska pollock fishery expressed in inflation-corrected (to the year 2005) US\$/t of pollock (Haynie, 2014).

people were trained within the CDQ program. The number of employees engaged in the CDQ program started with only 317 in 1993, but it reached 5,600 in 2010 (Strong and Criddle, 2013). These numbers illustrate an overall successful history of the Alaska CDQ program. Fisheries-dependent communities are often set in rural and remote areas and heavily rely on an active fishing sector. Therefore, it seems logical to manage at least a part of fishing quotas by a community-based entity, and several examples of attempted CDQ programs or similar systems exist. In the United Kingdom (UK), past attempts of establishing CDQ schemes, however, collided with EU law. We will illustrate the reasons and the closely linked, tense relationship between the UK fishing sector and the EU's fisheries management in the next section.

Consolidation in United Kingdom Fisheries and Attempts to Establish Community Development Quota-Systems in the United Kingdom

With the decision to leave the EU, the United Kingdom has the chance to develop and adapt its own national Blue Growth strategy. It is a major player in the exploitation of the European oceans, having the largest EEZ of all European countries (Carpenter et al., 2016), one of the biggest Blue Economy sectors of the EU, and a high-capacity fishing fleet, ranking third in total catch in 2017 among the EU fishing nations (European Commission, 2019, 2020b). Ever since the referendum in 2016, the British fishing sector was a strong proponent of Brexit. British fishermen felt disadvantaged by the regulations of the CFP for years and opposed it since the early 90s (Le Gallic et al., 2018; Phillipson and Symes, 2018). With Brexit, they expected re-negotiations of fisheries management of the Northeast Atlantic and the North Sea, substantially improving their fishing opportunities. They endorsed a system of 'zonal attachment', i.e., reallocating quota shares according to the distribution of fish stocks in the UK EEZ to the UK fishing

industry, instead of the continuation of the EU's system of relative stability, in which a fixed share of TAC is granted to each member state (Phillipson and Symes, 2018). The size of this share has been fixed since the implementation of the system of relative stability in 1983 and was determined using a reference period of fishing activity from 1973 to 1978 (Hoefnagel et al., 2015). Brexit negotiations eventually resulted in a 5-year transition period in which the TAC of the British fleet is gradually increased by 25% and annual multilateral negotiations afterward (European Commission, 2020a). The strong pro-Brexit position of the UK fishermen was primarily explained by their dissatisfaction with the CFP and the system of relative stability. The vast majority of them felt disadvantaged by the EU legislation. From their point of view, they did not only receive an unjustified small share of stocks in their territorial waters, e.g., cod in the English Channel or mackerel in the North Sea, but quota concentration and consolidation within the UK fishing sector was also supported by the CFP (Phillipson and Symes, 2018). It was widely overlooked that the fisheries management system of the UK, which was gradually implemented from 1980 to 2000 and therefore coincided with the introduction of the relative stability system, served as the legal framework of the sector's consolidation (Cardwell, 2014). The pelagic fishery for mackerel and herring provides a good example for this consolidation.

Mackerel (*Scomber scombrus*) and herring (*Clupea harengus*) are among the most extensively used wild fish species in the Northeast Atlantic. With nearly 460 Mio. Euro (€) landed by all EU vessels, mackerel was the most valuable fish species of the EU fisheries in 2017, ranking second in total catchweight (460,000 t). A large fraction of those mackerel catches is obtained in the UK EEZ, mainly in northwestern Scotland around the Shetlands (Figure 3, right). Only herring was caught in larger quantities in Atlantic waters with a total catch of about 780,000 t, which were worth nearly 300 Mio. €, making it the fifth-most valuable species in 2017 (STECF, 2019). TAC, management, and conservation of these species are subject of multilateral negotiations as the EU, the Faroe Islands (which act as an autonomous fishing nation), Norway, Iceland, and most recently, the UK harvest them as independent fishing nations. The high value, widespread distribution, and migration behavior of the species have led to multiple disputes among the fishing nations, including an ongoing "mackerel war." Due to mackerel distribution changes in the North Atlantic, a political dispute regarding access rights to fishing grounds emerged. The mackerel stock shifts and/or expanded toward Iceland and even Greenland since 2007, whose fleets increased their catch significantly (Astthorsson et al., 2012; Bruge et al., 2016; ICES, 2018). In reaction to this, a joint agreement between Norway, the Faroe Islands, and the EU was reached in 2015, but Greenland and Iceland did not join this agreement until today, making this dispute unsolved (ICES, 2018).

Considering the commercial value of those stocks, conflict does not appear to be too surprising. In the UK alone, mackerel and herring account for more than 40% of the landed weight (STECF, 2019). 99% of those landings are obtained by a small group consisting of only around 30 highly efficient large freezer-trawlers (Cardwell, 2014). The agreement reached by the EU

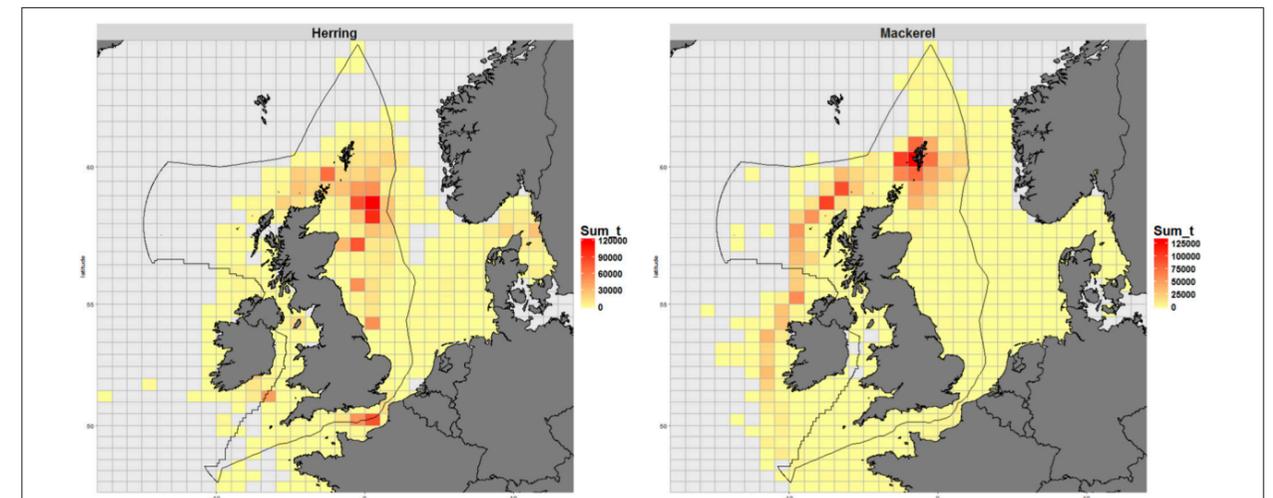


FIGURE 3 | Summed catch (t) from 2011 to 2015 for herring (left) and mackerel (right) from the EU fleet (Doering et al., 2017).

and the UK during the Brexit negotiations includes a significant increase of catch opportunities for the UK, yet there are stock-specific differences in increases. For western mackerel, a 5% increase of the UK's quota shares over the next 5 years has been agreed on, while the quota for North Sea mackerel will only increase by around 0.5% (European Commission, 2020a). The agreement benefits this small, highly efficient pelagic fleet and solidifies a situation comparable to the Alaska pollock fishery prior to the establishment of the CDQ program, in which only very few vessels and companies profit from a very profitable, industrial fishery and most of the remote coastal communities and SSF are excluded from value generated by those natural resources.

Even though UK fishermen were largely disappointed with the outcome of the Brexit trade deal, the additional quota now accessible is worth millions of pounds (£). A lot of remote areas in the UK, for example, in western and northern Scotland, are heavily dependent on fisheries to support their households. Reallocating catch shares to fishery-dependent communities by means of community quotas could generate significant income, provide jobs and stimulate growth. This might provide a more promising Blue Growth trajectory than allocating the newly available quota to the few companies that hold on to the largest part of the quota already. In this case, a Community Development Quota scheme (CDQ) would be a reasonable measure for a fishery-dependent community. A comparable initiative has been established three times in traditional fishing communities in the UK: Orkney Islands, Cornwall, and the Shetland Islands, the latter being the most commonly known example. The Shetland Fish Producers' Organization (SFPO) is the second-largest producer organization (PO) in the UK and, in 2005, had an annual turnover of 34 Mio. £ (Andersen, 2008). In 1993, the SFPO was the first PO to obtain a quota and hold it in its own right by buying two vessels, stripping the quota from them, and reselling them afterward. Later on, their quota access was further enlarged by the

quota of another five ships. This additional quota was managed in a ("ring-fenced") pool system, i.e., it is equally distributed between all members by a linear regression system, which mirrors their catch capacity (Andersen, 2008). Other members of the sector deemed the acquisition of quota by a PO controversial; however, it still successfully operates until this day. In another novel endeavor, the SFPO invested in additional whitefish quota in 1998, acquiring it from trust funds held by the Shetland Development Trust (SDT), which is partially funded by the Shetland Islands Council (SIC). Therefore, this quota purchase was at least to some extent funded by public money. From within the UK fishing industry, complaints of market distortion were filed against this "SDT-quota" to the European Commission (EC), and in 2003, the scheme was found to violate the state aid laws of the EU and therefore to distort the common market (Andersen, 2008). Major modifications had to be made to ensure no preferential access to quota was given to local vessels, and all fishing opportunities would be sold at market rates after the "first-come-first-serve" principle (ABCDS, 2004). This basically removes the core principle of a community quota system. The other CDQs in the UK met similar fates and were also deemed incompatible with EU market laws. In their report on community held fishing quota, the ABCDS stated that an ideal CDQ for their region "would not be in contravention of any UK and EU regulations and in particular would not be in contravention of State Aids rules" and "must not distort or threaten competition by benefiting particular groups. It may, however, be possible to give priority to certain types of people, such as under 35s, new entrants or to under 10-meter vessels" (ABCDS, 2004). Due to the necessary overhauls in the management, Brexit might be an opportunity to successfully implement community quotas in the UK. When implementing CDQs, a quota redistribution within the UK is necessary but could indeed turn out to be problematic since larger companies and POs are likely to oppose a reduction of their quota shares. As already pointed out, especially

the larger POs have a lot of influence and already opposed a community quota scheme in 1999. Yet, the Alaska pollock case study shows how large-scale fishing companies can also benefit from a CDQ system.

Apart from the pelagic species mackerel and herring described in the case study, there are several more species harvested in the UK EEZ, which could be included in a CDQ program. Other species suitable for the CDQ program include pelagic species like blue whiting (*Micromesistius poutassou*), whitefish like cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), and bass (*Dicentrarchus labrax*), flatfish, especially sole (*Solea solea*), and high-value shellfish such as scallops (*Pecten maximus*), brown crab (*Cancer pagurus*), lobster (*Homarus gammarus*), langoustine (*Nephrops norvegicus*), and whelk (*Buccinum* spp.). All these species are of high commercial value for UK fisheries in general and have well-established domestic and foreign markets, and comprise nearly 70% of the landed weight and 66% of the landed value of the UK (Seafish, 2021). Some of the mentioned species are not managed by quota but license systems, but similarly to fishing quotas, these licenses could be managed by community boards in a CDQ-framework.

In the UK, vessels of 10 m or less in length are commonly grouped as small-scale inshore fishery and will be referred to as SSF in this chapter. Such vessels would substantially benefit from such CDQs since current fisheries management disfavors them in multiple ways. Most of them are not organized in POs, their quotas are set centrally per month, and those quotas cannot be transferred (Cardwell, 2012; Carpenter and Kleinjans, 2017). They could be prioritized in quota allocation schemes of the CDQs, as suggested by the ABCDS report (2004). Not all species we discussed as a part of a UK CDQ can be harvested by SSF, for example as blue whiting, which is predominantly found on the slope of the continental shelf far from the coast (Hátún et al., 2009). Yet, equipped with sufficient quota, SSF could increasingly target the herring and mackerel schools migrating into coastal waters and the other species introduced above, of which some are important target species of the UK SSF already (Symes et al., 2020). Of the above-mentioned fish species, bass, sole, cod, and mackerel accounted for around 10% of the average catch value of the SSF between 2013 and 2017 (STECF, 2019). Bass is the only species not managed in a quota system and the species' largest single share of 3.7% (Seafish, 2019a). The aforementioned shellfish species such as lobster, brown crab, langoustine, scallop, and whelk contributed to an average of 70% of the SSFs annual catch value, and only langoustine is managed with quotas (Carpenter and Kleinjans, 2017). In 2000, these species only accounted for 6% of the SSF landings (Mason, 2010). The enormous shift from targeting quota to non-quota species in just one and a half decades indicates the necessity for the SSF to change its exploitation strategies due to restricted quota access (Davies et al., 2018; Symes et al., 2020). Other factors enhancing this shift in fishing strategy include rising shellfish export prices (Bannister, 2006) and increases in shellfish abundance due to climate change (Shephard et al., 2010). SSF are often family-owned vessels with no organizational network and a comparably modest budget, limiting their capacity to compensate years with low TACs and/or get access to quota-regulated stocks

(Symes et al., 2020). This is reflected in the socio-economic data of the fleet. Even though they account for 79% of the fleet and nearly 50% of the jobs (STECF, 2019; Seafish, 2020a), they hold only 1.6% of the quota (Marine Management Organisation, 2019) and generate only 11% of catch value (Seafish, 2020a; Symes et al., 2020). Because of their disadvantageous position, SSF skippers often work as part-time or subsistence fishermen and try to diversify their fishing techniques and target species as much as possible to lower the risk for their businesses (Phillipson and Symes, 2018). This is, however, difficult in the times of modern fisheries management, where access to quota and fishing licenses is regulated more strictly (Davies et al., 2018; Symes et al., 2020).

The Inshore Fisheries of Ireland and the Heritage License Bill

As the UK's neighboring island nation, the Irish fishing fleet's structure shares many features with the fleet of the UK. The fleet, although being particularly smaller with 1,756 vessels compared to 4880 vessels in the UK in 2018, mainly consists of small-scale fishing vessels (STECF, 2020). The definitions of SSF are, however, inconsistent between different nations and the management frameworks, and the UK and Ireland are well-suited examples for that. As described above, in the UK, vessels under 10 m length using active and passive gears are referred to as SSF, while in Ireland, the term "inshore fisheries" is used more commonly than "small-scale fisheries," referring to vessels under 12 meters (m) length using passive and active gears in Irish territorial waters (12 nautical miles (NM) of the coast) (Fitzpatrick et al., 2020). The common definition of small-scale fisheries in the European Scientific, Technical, and Economic Committee for Fisheries (STECF) comprises vessels under 12 m of length using passive gears (STECF, 2019). This inconsistency in definitions can cause problems in management and science communication and will be discussed later. In this chapter, the Irish inshore fishery will be discussed, defined, as it is the nation's common practice, as vessels under 12 m length using passive and active gears in Irish territorial waters (6 NM of the coast). This definition is also used by the National Inshore Fisheries Forum (NIFF), which is the management framework of the Irish inshore fisheries sector, established in 2014. The inshore fleet is of major social, cultural, and economic significance for Irish coastal and island communities, yet it is troubled by multiple factors and a subject of ongoing political dispute (Fitzpatrick et al., 2020). Similar to the previously described case study from the UK, we will focus on two major stressors of the small-scale, or rather inshore fishery: Access to quota and an obstructive management framework.

The Irish inshore fleet is a mixed fleet using active gears such as trawls or dredges as well as passive gears like driftnets and pots. The most important target species are crustaceans like brown crab or edible crab (*Cancer pagurus*), lobster (*Homarus gammarus*), shrimps (*Palaemon serratus*, *Crangon crangon*), and velvet crab (*Necora puber*), and mollusks such as whelk (*Buccinum undatum*), razor clams (*Ensis* spp.), and scallops (*Pecten maximus*) (Fitzpatrick et al., 2020; STECF, 2020). The only TAC-managed finfish species caught in relevant

quantities by inshore fisheries are pollack (*Pollachius pollachius*), hake (*Merluccius merluccius*), mackerel (*Scomber scombrus*), and turbot (*Scophthalmus maximus*), yet they still only accounted for a combined 7.4% of the total catch weight and 5.5% of the catch value of the Irish inshore fisheries in 2018 (Figure 4).

Only around 10% of the Irish inshore fisheries catch value consisted of TAC-managed species in 2018, following a decade of consistent decline from nearly 41% in 2008. Only five of the fifteen species accounting for 95% of the inshore fishery catch value were TAC-managed species (Figure 4; STECF, 2020). However, this data needs to be treated with caution, as Irish fishing vessels under 10 m length are not required to carry logbooks, and therefore, the catch weight and revenue of the Irish inshore fleet is likely to be underestimated by the AER of the STECF, for which data from a number of sentinel vessels is collected (Fitzpatrick et al., 2020). This lack of logbook data directly affects the inshore fishery, as they are not able to present track records of pelagic fish catches and are therefore disfavored in quota allocation. Less than 1% of the quota for mackerel, which is an equally important species as in the UK (BIM, 2020b), is allocated to the inshore hook and line fishery because no track records of mackerel catches could be provided when quotas were allocated (Delaney, 2021). The hook and line fishery for mackerel is a seasonal fishery that would be typically complemented by a pot fishery for crustaceans (Fitzpatrick et al., 2020). Historically, another common Irish SSF fishery was the driftnet fishery targeting Atlantic salmon (*Salmo salar*). After 2006, it was impossible to continue due to the driftnet moratorium for salmon, which was enacted after three decades of stock decline from more than 2,000 t in the mid- 1970s to less than 500 t in the early 2000s and less than 100 t in

2006 (WWF, 2001; Brennan and Rodwell, 2008). The reasons for the decline of salmon stocks were lively debated. In the end, an interplay of environmental factors and human use-pressures is considered to be the most likely explanation for the steep decline of salmon stocks (Collins et al., 2006; Brennan and Rodwell, 2008). An additional issue of the quota allocation for the inshore fishery is the monthly quota allocation, which cannot be transferred to another month. Since inshore vessels are limited in their area of operation and more affected by adverse weather conditions, they are often not able to fish their full allocated quota (Fitzpatrick et al., 2020). The described losses in catch opportunities, together with the unfavorable position of the inshore fisheries in the quota allocation process, forced the majority of the inshore fleet to participate in the year-round fisheries targeting non-quota shellfish species (Fitzpatrick et al., 2020). Nonetheless, these fisheries are managed by the Department of Agriculture, Food, and the Marine, which sets minimum landing sizes, fishing effort controls, and species-specific management measures, such as a landing ban on egg-bearing and breeding lobster females (Browne et al., 2001).

Managing this diverse, polyvalent, and not well-documented fleet is a difficult task, and inshore fisheries management in Ireland has been a subject of ongoing changes in the past two decades. The first approach to establish a self-management and representation body for the inshore fishery was undertaken in 2005, but it was abandoned only 4 years later (Fitzpatrick et al., 2020). The aspired co-management approach failed due to a lack of commitment by the responsible department and capabilities and motivation of the involved fishermen, who rather aimed to maintain personal profit and were not able to constructively participate in co-management

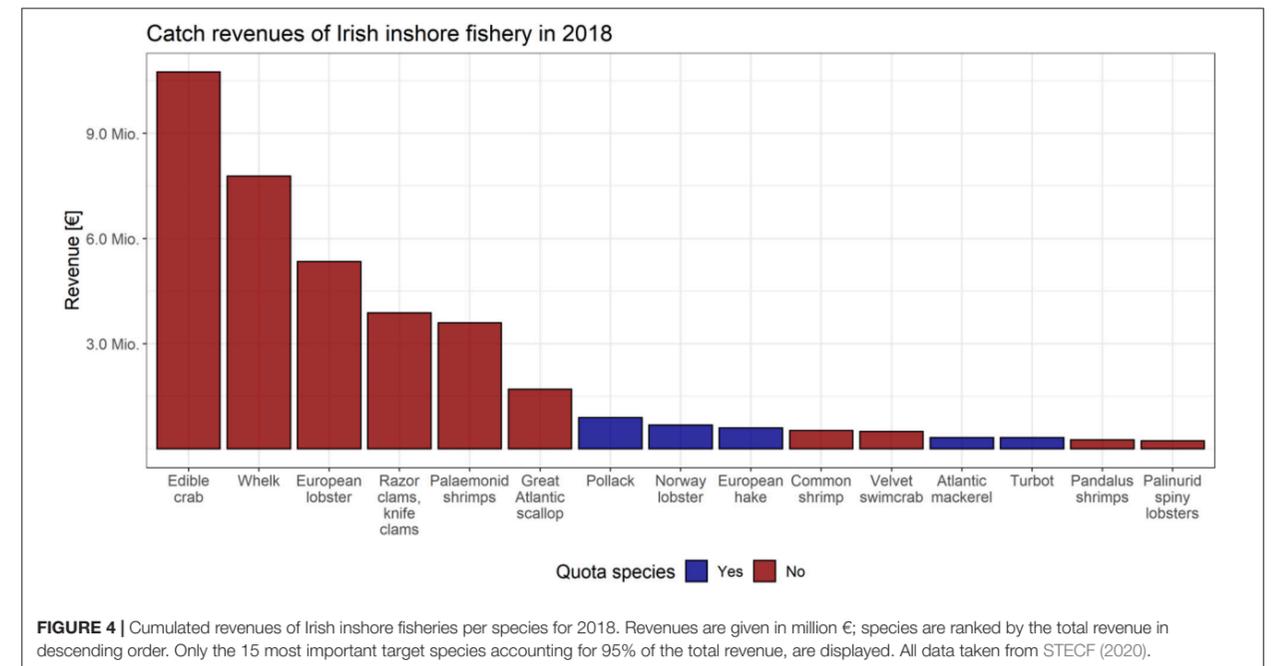


FIGURE 4 | Cumulated revenues of Irish inshore fisheries per species for 2018. Revenues are given in million €; species are ranked by the total revenue in descending order. Only the 15 most important target species accounting for 95% of the total revenue, are displayed. All data taken from STECF (2020).

processes (Fitzpatrick, 2013). After another 5 years, the NIFF was formed in 2014 as a superordinated management body, representing the Irish inshore fisheries as well as participating in quota, EMFF funding, and research cooperation meetings (Fitzpatrick et al., 2020). It consists of the six Regional Inshore Fisheries Forums (RIFFs), North, Northwest, West, South, South East, and South West, from which the respective chairs and vice-chairs are delegates at the NIFF. Despite the regional subgroups, some fishermen felt underrepresented by the NIFF and sidelined in decision-making processes (Fitzpatrick et al., 2020). This is especially true for the fishermen of the smaller offshore Islands, who have been organized in their own representative body, the Irish Islands Marine Resources Organization (IIMRO), since 2014. The IIMRO originally dates back to 2006, when it was founded by Donegal Island fishermen who were struggling because of the aforementioned drift net ban on salmon. It exclusively represents island fishermen from the County's Donegal, Mayo, Galway, and York, operating vessels under 12 m in length and using non-towed gears. For the mainland inshore fishermen, a complementary representative organization, the National Inshore Fishermen's Association (NIFA), was founded in 2017. Yet, IIMRO is more established, associated with the Low-impact Fishermen of Europe (LIFE), and the only inshore fisheries representative organization with a seat in the European Northwestern Waters Regional Advisory Council (NWWRAC). It has campaigned for the Irish island fishermen with multiple efforts. One of their latest initiatives was the support of the Island Fisheries Heritage License Bill.

Based on a report of a designated sub-committee of the Irish parliament (Oireachtas, 2014), the Heritage License Bill aimed to equip island-resident inshore fishermen using non-towed gears with non-transferable or rentable heritage licenses. In particular, an additional Mackerel quota of 106 t was discussed, equaling 0.1% of the total national quota allocation (Oireachtas, 2019). With this additional quota, the survival of small-scale island fisheries was supposed to be ensured. Fisheries are an important economic factor for the smaller Irish islands that widely suffer from an exodus to the urban areas on the mainland due to dwindling economic prospects. Some islands populations have declined by as much as 50% in the past three decades (Oireachtas, 2018). The bill was vehemently disputed and ultimately lapsed due to the dissolution of parliament and senate. Major points of criticism were:

- The bill would discriminate against non-island resident inshore fishermen (Oireachtas, 2018).
- The terms and conditions, such as the stocks managed by the new scheme, were insufficiently specified (Oireachtas, 2018).
- The bill would violate the CFP (Oireachtas, 2018). Consultations of a high-level EU fisheries representative by IIMRO revealed, however, that the bill is actually in accordance with European fisheries law (Fitzpatrick et al., 2020).
- The bill would foster quota privatization. This opinion was opposed by supporters of the bill, who interpreted the

bill's aim as establishing a ring-fenced community quota (Oireachtas, 2017; Brennan, 2019).

As described in the previous case study for the SFPO and their ring-fenced whitefish quota, a truly ring-fenced community quota held by a private body and acquired without state public funding does not violate the CFP. However, it is unlikely that a representative producer organization of the Irish inshore fisheries would be able to acquire additional quota without state aid. The lapse of the Island Fisheries Bill is an unfortunate backlash for small island inshore fisheries and the associated communities. For rural and island communities in Ireland, the seafood sector is an important economic driver and anchor for associated sectors (BIM, 2020b). Additionally, the seafood industry, especially the inshore fisheries, is closely linked to coastal tourism. It not only supplies guests with local, fresh seafood, but it also provides services such as fishing tours and is widely perceived as a part of local culture and heritage (BIM, 2020a). Therefore, well-designed, inclusive management frameworks that improve the situation of inshore fisheries in Ireland need to be a central part of the nation's Blue Economy strategy. Before discussing how such a framework could look like, we introduce our third and final case study, in which we address another island nation with a rich fishing history.

Tied Into Knots: The Complex System(s) of Icelandic Coastal Fisheries Management

The SSF management system in such a fishery-dominated country as Iceland is an interesting case study as SSF has always been politically and culturally important yet has also been subject to many changes (Mariat-Roy, 2014). Historically, coastal villages evolved in order to be close to promising fishing grounds, often structured around one locally owned processing enterprise, which also supported several fishing vessels (Skaptadóttir, 2007). Besides, SSF was only carried out seasonally, which changed with the arrival of larger foreign vessels at the beginning of the twentieth century and induced a year-round fishery as well as the construction of larger Icelandic vessels (Figure 5). Especially during the time when seeking independence from Denmark in the 1940s, the fishery increasingly industrialized and became primarily export-driven. From 1980 onwards, an Individual Transferable Quota (ITQ) system was gradually implemented, and since 1990, all boats larger than 6 Gross Tons (GT) were then included in a national ITQ scheme covering most species (Arnason, 2005; Karlsdóttir, 2008; Gunnlaugsson, 2020).

In this system, quota shares can be bought, leased, or sold (Figures 5, 6; Gunnlaugsson et al., 2021). Nevertheless, SSF is thought to remain essential for coastal communities as well as the Icelandic culture and identity in general. Similar to other nations, the SSF in Iceland only accounts for a small catch proportion (8%) of the whole fisheries sector (Chambers et al., 2020). In terms of economic value, however, they constitute approximately 20% of the total catch value due to primarily targeting high valued species [cod, haddock, ling (*Molva molva*), lumpfish (*Cyclopterus lumpus*), saithe (*Pollachius virens*), and Atlantic catfish (*Anarhichas lupus*); Chambers et al., 2020]. In Iceland, SSF

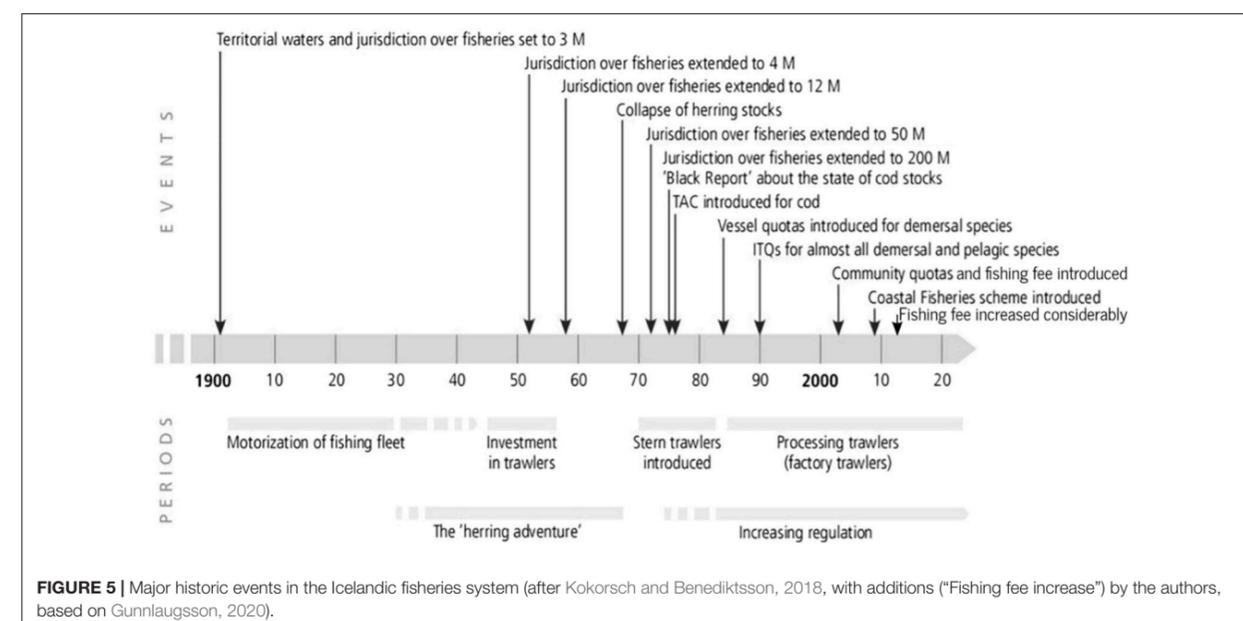


FIGURE 5 | Major historic events in the Icelandic fisheries system (after Kokorsch and Benediktsson, 2018, with additions ("Fishing fee increase") by the authors, based on Gunnlaugsson, 2020).

mainly uses gillnets, long-lines, and hand-lines and since 2013 are defined to be under 30 GT and 15 m in length. In 2014, the SSF accounted for approximately 68% of the total Icelandic fleet (Statistics Iceland, 2016; Chambers et al., 2020). Previously, SSF was defined to be under 10 GT and then under 15 GT. This increase in capacity allowance, although keeping the length regulation intact, led to a quota concentration amongst relatively few high-capacity vessels with engines up to 1,000 horse power (HP), no direct owner on board, and changing crews (Chambers et al., 2020). These vessels did not join the National Association of Small Boat Owners (NASBO), although still belonging to the same category of SSF. Four management measures are currently implemented, (a) a small boat ITQ fishery, (b) a hook and line ITQ fishery, (c) a non-ITQ lumpfish fishery using gillnets, and (d) an open access (non-ITQ) coastal fishery with an overall TAC, called strandveiðar (Chambers et al., 2020). Actually, the non-ITQ fisheries account for 16% of the SSF and 2% of the total catch (Chambers et al., 2020). Discarding, in general, is forbidden, and several area closures, as well as gear restrictions, are implemented to protect sensitive habitats. A quota year always runs from the 1st of September to the 31st of August.

The split of one ITQ fishery to a separate large and small-scale (first for boats under 15 GT, then 30 GT; Þórðarson and Viðarsson, 2014) ITQ fisheries was performed in 2004, in order to prevent further quota concentration processes toward the larger vessels. The SSF ITQ fishery was then further divided into a) small-boats (approximately 75 active vessels in 2014/2015) and b) hook and lines (only longlines and jig gear allowed; approximately 318 active vessels in 2014/2015; Figure 6; Chambers et al., 2020). A hook and lines quota cannot be transferred to small boats, whereas it is possible the other way around. Especially the longliners gained new popularity in the mid-1990 and are now locally and internationally thought to

be of high value and quality as well as of low impact and very sustainable (Mariat-Roy, 2014). They make up the largest amount of the SSF catch (64,632 t in 2014/2015; Chambers et al., 2020).

The lumpfish fishery uses gillnets, primarily targeting female lumpfish for their roe, although they sell them frozen whole to China now, and has always existed outside the ITQ scheme (Figure 6; Chambers, 2016a; Chambers et al., 2020). Approximately 231 active vessels were registered in 2014/2015, also catching the smallest amount (5,952 t; Chambers et al., 2020). The regulation is very specific, as only vessels under 15 GT with a net length of max. 75,000 m and a mesh size of 10.5 and 11.5 inches. Moreover, fishing is only allowed from March to August, and in some areas, closures are additionally employed. Finally, the consecutive days at sea are regulated per license holder, and a flexible entry limit to the fishery is employed, which depends on weather conditions, roe prices, and other economic factors (Icelandic Directorate of Fisheries, 2017). The local fishery for male lumpfish is, however, not regulated.

In 2009, the non-privatized coastal fishery (strandveiðar) consisted of the largest amount of vessels in the SSF sector (630 active vessels in 2014/2015) and was implemented in order to support local communities as a reaction to international political pressures as well as criticisms on the Icelandic ITQ system (Figure 5; Chambers and Carothers, 2017; McCormack, 2017). Similar to the lumpfish fishery, the coastal fisheries are limited seasonally (from May to August), in which they are allowed to fish 12 times per month, as well as weekly, i.e., fishing is only allowed for 14 h a day from Monday to Thursday (Chambers et al., 2020; Fiskistofa, 2021). Additionally, demersal fish are only allowed to be fished with a maximum of four jig machines (mostly electronic and automatic) and up to 650 kg a day (Fiskistofa, 2021). Initially, four areas existed (by importance: Westfjords, northern Iceland, northeast Iceland and

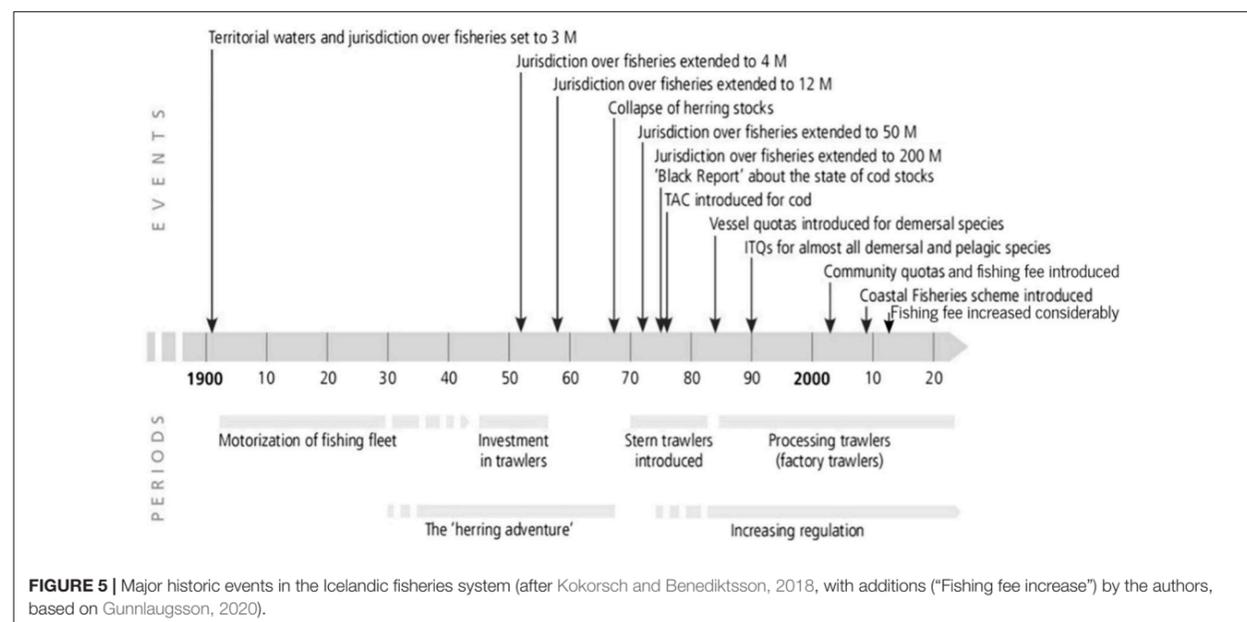


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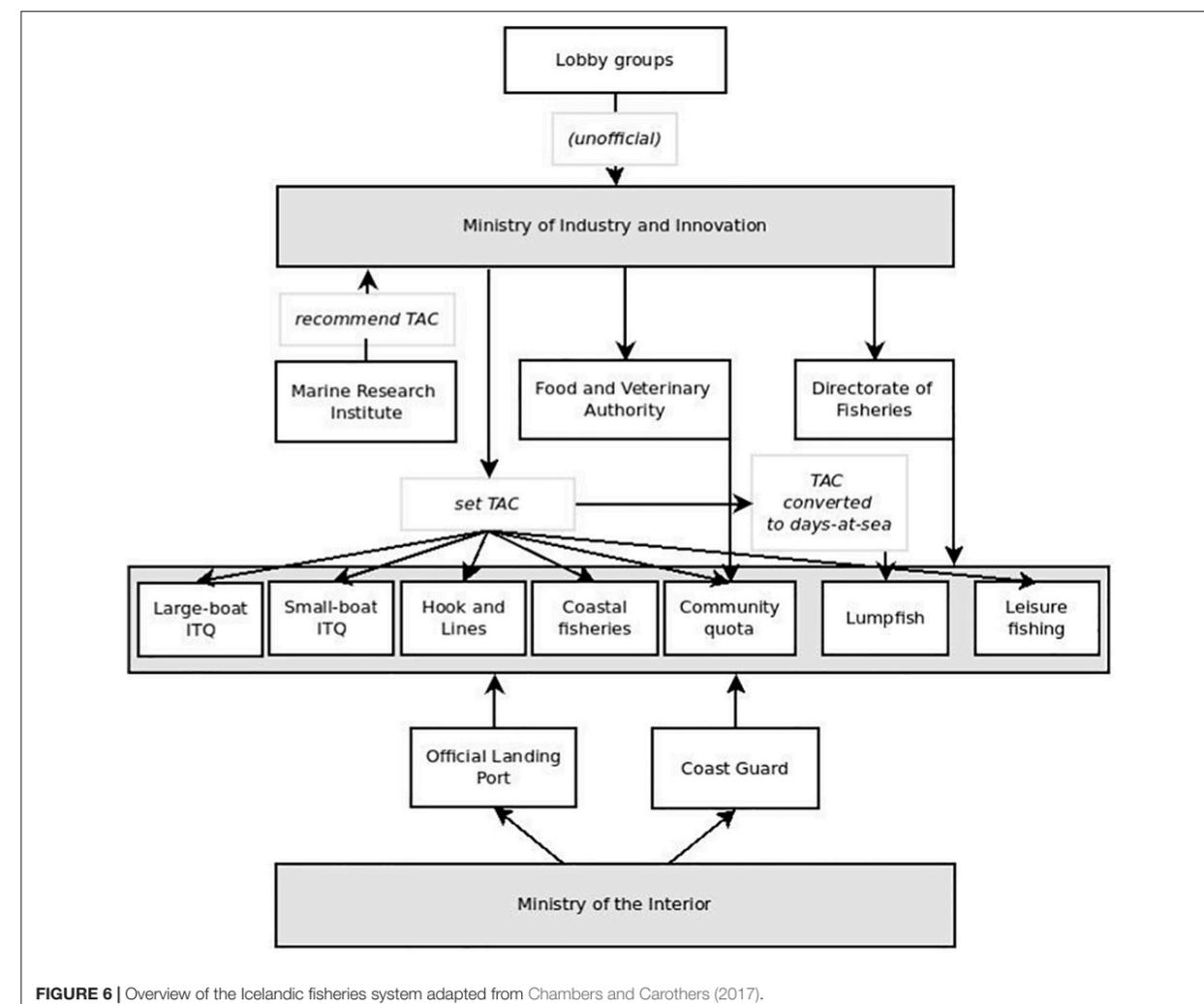


FIGURE 6 | Overview of the Icelandic fisheries system adapted from Chambers and Carothers (2017).

south/southwest Iceland), in which the fisheries were allowed to take place, each having its own monthly TAC. This was, however, only a small proportion of the general TAC used in the Icelandic ITQ fisheries (Icelandic Directorate of Fisheries, 2017; Gunnlaugsson et al., 2021). Since 2020, a general TAC instead of an area-specific TAC was established, hence for example, a max. of 10,000 t of cod are allowed to be fished in general, but the vessels are still only allowed to fish within their area to which they have been registered (Fiskistofa, 2021). It is not possible to fish in both coastal fisheries and quota fisheries simultaneously, hence the yearly quota must be fished out before being able to participate in the coastal fishery with an entrance fee of 72,000 ISK or approximately 600 US\$ (Chambers et al., 2020; Fiskistofa, 2021). At the end of the coastal fishery season, those vessels can then rejoin the ITQ system (Icelandic Directorate of Fisheries, 2019). The coastal fishery and lumpfish fishery together only account for approximately 1% of the total Icelandic catch (Chambers, 2016b).

Even though SSF is still considered essential in coastal communities, several problems started to occur with the introduction of the ITQ system (Chambers et al., 2017). As vessel and species-specific quotas were distributed according to each vessel's catch history during the mid-1980s, several SSF vessels were not able to remain profitable with what they received and were forced to sell their quotas (Karlisdóttir, 2008; Mariat-Roy, 2014; Kokorsch, 2018). Hence, quota concentration occurred rapidly toward larger companies operating from urban areas, and with it, processing and associated jobs also started to vanish, which largely affected women (Skaptadóttir, 2007; Karlisdóttir, 2008; Chambers et al., 2017). Fleet consolidation is actually thought to be a well-known by-product when establishing an ITQ system because more efficient firms are expected to buy quotas from less efficient firms, which in turn increases the overall economic performance of the sector. Indeed, the profitability is now thought to account for 40% of the total value of exported goods in Iceland (Gunnlaugsson, 2020).

Yet, rural transmigration increased considerably, resulting in a significant loss of young people. Especially the Westfjords area, where the fishing industry still is the main income source, was largely impacted with individuals under the age of 40 transmigrating by up to 40% (Mariat-Roy, 2014; Statistics Iceland, 2016; Kokorsch, 2018). This was also shown by Edvardsson et al. (2018), who mapped the increased geographical consolidation of fishing activities in Iceland and found that many small fishing communities around Iceland are vulnerable to changes in the industry, especially in the Westfjords area. The importance of SSF varies with region, and while the total catch of some communities might seem small, it may be significant compared to the population size and absence of other economic activities in this region (Chambers et al., 2017, 2020; Edvardsson et al., 2018). In areas where it is possible, fishermen also try to supplement their incomes by being employed in other part-time jobs, which can also mean working on large-scale fishing vessels (Chambers and Carothers, 2017). Half of the SSF fishermen do not actually own quota anymore, some do rent quota, but most participate in the non-privatized coastal fishery. The ones who do own quota often also have the financial possibility to rent more and, therefore, are able to obtain most of their salary directly from SSF (Chambers and Carothers, 2017).

The discard ban provides additional difficulties for non-quota owners: They are forced to rent additional quota for a day depending on their catch composition, discard illegally or pay a penalty when landing species for which they did not rent any quota. Besides, the lack of decision-making power and disregard of SSF in the political sector generated a high level of distrust and dissatisfaction (Kokorsch, 2018). The only exception in which the SSF has a strong lobby is the seasonal lumpfish fishery. As a possible solution, SSF fishermen would promote tighter restrictions on quota transferability and quota decentralization in general, although they acknowledge the importance of the ITQ scheme for the overall profitability of the fisheries system (Chambers and Carothers, 2017). Additionally, the Icelandic fisheries sector continues to be economically extremely important, and the strong large-scale fishery lobby also significantly influences international policy decisions, which do not always have to be in favor of the Icelandic SSF.

However, according to the Marine Management Law Code (Fiskveiðistjórnun), the economic viability and sustainability of rural areas have to be ensured (Iceland, 2006; Mariat-Roy, 2014). Therefore, several national programs have been tested and established in order to support the Icelandic SSF and coastal communities, hence counteracting the problems that arose with the introduction of the ITQ scheme. One such program was the reimplementation of the previously described longline fisheries in the late 1990s (Mariat-Roy, 2014). It now even became “a national symbol of fishing for survival,” especially in the Westfjords area, making it possible to rebuild social structures (Mariat-Roy, 2014). An additional program was further established to support small-scale, manually baiting longliners that fish on a daily basis. They now received the right to land an additional 20% of their quota, which impacted 202 vessels in 2013 (Þórðarson and Viðarsson, 2014). A third program was the introduction of

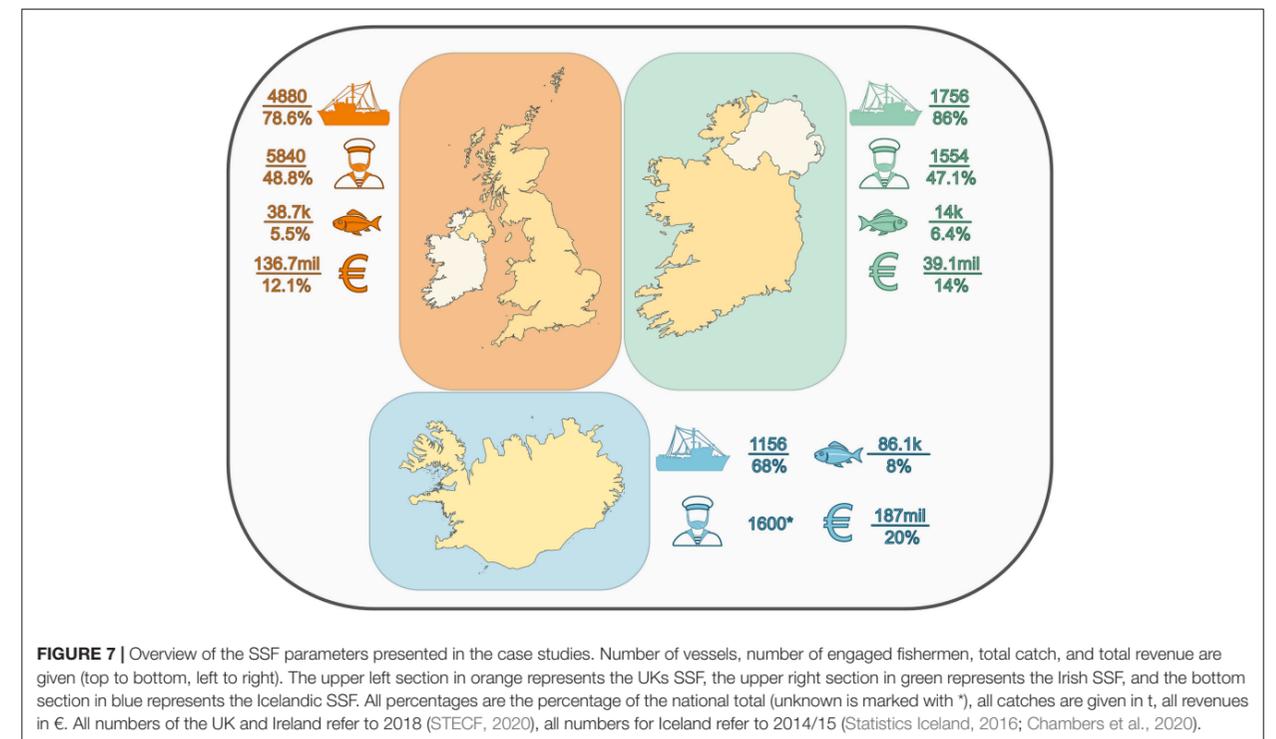
the already mentioned coastal fishery (strandveiðar). It is only seasonal but does bring more jobs to the coastal communities and is now also considered to be essential for rural communities (Einarsson, 2011; Gunnlaugsson et al., 2021). However, it does not seem to make the entry for younger fishermen any easier (Chambers and Carothers, 2017). There has also been a lot of criticism from quota owners of both SSF and large-scale fishers, stating that the non-privatized coastal fishery gains support without having to make a return since they do not have to pay for any quota. Additionally, there has been a lot of tension between the coastal fishers themselves because of a resulting race-for-fish during the relatively short fishing season (Chambers et al., 2020; Gunnlaugsson et al., 2021). In order to reduce the race for fish and therefore risk to go fishing in bad weather, vessels can choose to go fishing for 12 days per month (still Monday to Thursdays only) since 2018, and the four-area division was essentially suspended. Moreover, the 12-day option leads to a more consistent fish supply, which in turn leads to higher fish prices (Gunnlaugsson et al., 2021). At the same time, catch of saithe by coastal fisheries was not included in the 650 kg limit anymore in order to counteract high-grading as only about 11% of the average catch consists of saithe, which makes it a choke species. Yet, this program seems to primarily maintain the livelihood of already successful but rather overaged fishermen. It, however, does not necessarily simplify the entry and capital building for newcomers. A fourth program was the introduction of community quotas (byggðakvóti) in 2003/2004 (Figure 6; Chambers et al., 2020). For SSF fishermen, who are willing to land their catch in certain communities and within community-specific regulations, this provides the opportunity to receive an additional quota. Primarily, it was implemented as a temporary measurement only, in which quotas were given to the community leaders first. They then further distributed the quotas to the most viable vessels because these would gain the most returns and, therefore, would also strengthen the economic situation of the community most (Icelandic Directorate of Fisheries, 2019). Now fishermen can apply directly to the Fishery Directorate, which is responsible for distributing community quotas to vessels in specific communities. This program is thought to be very important for supporting local communities and receives the highest support in the Capital Region and Westfjords area (Chambers, 2016b; Kokorsch, 2018). Yet, Kokorsch and Benediktsson (2018) state that a dependency in terms of employment should be added as a criterion for having access to the community quota as the number of fisheries-related jobs on shore has been continuously decreasing over time. At the same time, a fishing fee was introduced in addition to the usual corporate taxes (Figure 5; Gunnlaugsson et al., 2018; Gunnlaugsson, 2020). The main purpose is to compensate for resource managing costs as well as to redistribute a share of the resource rent to the public in order to improve the general welfare. This seems very similar to how the resource rent made by the Alaska pollock fisheries is used when leasing CDQ. In the beginning, the fee was fairly low, but in 2012 it was increased substantially due to the significant increase in resource rent production after nearly two decades (Figure 5). The fee applies to all commercial fisheries, although significant

deductions are possible for firms that are highly in debt as well as for smaller firms (Gunnlaugsson et al., 2018). In general, the Icelandic coastal fisheries are not considered to be efficient or profitable from an economic point of view, but as they inhabit such a special position in terms of cultural and social significance, they could be considered an additional cost larger firms must pay in order to access the fishing resource (Gunnlaugsson, 2020). The debate about the level of taxation, however, still remains.

DISCUSSING COMMUNITY DEVELOPMENT QUOTAS AND THE SUPPORT OF SMALL-SCALE FISHERIES IN THE CONTEXT OF BLUE GROWTH

Three out of the four case studies illustrate the difficult position and precarious economic situation of SSF. SSF vessels account for more than two-thirds of all fishing vessels in the case studies, and in the UK and Ireland, nearly half of the fishermen are engaged in SSF (Figure 7). In all three case studies, however, they only account for < 10% of the total national catch. This is at least partly due to insufficient quota allocation. Such a development should concern managers, scientists and decision-makers, because SSF is an integral part of traditional coastal living, comprises the majority of a nation's vessels and engaged fishermen (Figure 7), and is “merely a job, [but] a way of life” (Symes and Phillipson, 2013). The romanticized image of local, small-scale fishing boats

and the possibility of consuming fresh fish almost directly from a vessel is a pull factor for coastal tourism, and the SSF benefit from the added value generated by selling their products as local delicacies (Lowitt, 2012). They are part of daily life and tradition in port areas and maintain knowledge of their hereditary waters. Therefore, SSF are also ideal as employees for coastal tourism, e.g., tour guides. Governmental programs promoting such synergies have been successfully implemented on various occasions (Chen, 2010; Lopes et al., 2015) and can help to diversify the economic opportunities in coastal communities (European Commission, 2014). The improvement of “human well-being and equity, while significantly reducing environmental risks and ecological scarcities” is, in fact, one of the main goals of Blue Economy or Growth (Pauly, 2018). SSF has the potential to combine both of these aspects because it does not only provide the described benefits to their communities but also passes on traditional knowledge and, furthermore, uses selective fishing techniques with a comparably small impact on the marine environment (Kolding et al., 2014). As pointed out in the case studies, small-scale fisheries are often challenged by administrative and financial hurdles. Targeted funding and adjustments in fisheries management hold the potential to make the sector more profitable and resilient, creating full-time jobs and livelihoods for families where fishermen are now working on a part-time or even subsistence basis. By those means, SSF should play a more relevant part in a Blue Growth strategy. Currently, the EU's Blue Growth focus is directed on expanding and supporting the aquaculture sector. The added value of fisheries is considered to be relatively small, and fisheries are thought



to play a minor role in the future of the EU's economic sector (European Commission, 2019) and in Blue Growth Strategies in general (Said and MacMillan, 2020). We, however, argue that the added value of specific fisheries sectors can indeed continue to grow in terms of Blue Economy, although the total catch is unlikely to increase any further. Increasing the added value can be achieved by promoting coastal communities, generating a higher number of jobs, as well as funding labels specifically designed for resulting products illustrating their sustainability and uniqueness, as the certification for sustainable fisheries of the marine stewardship council (MSC) or the Protected Geographical Indication (PGI) and Protected Designation of Origin (PDO) of the EU. Consumer awareness for sustainability and fisheries increases, and studies showed that they are willing to pay a considerably higher price for MSC-certified products. An exact price premium for certified seafood products is hard to determine but can be estimated to be around 10–15% (Roheim et al., 2011). The SSF in the presented case studies is predestined to receive MSC status since they are already specialized in high-value seafood products, reflected by their share in national catch revenue being much higher than their share in national catch weight (Figure 7). The regulations to receive and hold an MSC certification are strict, and the certification of some large, commercially extremely valuable stocks (e.g., in case of Northeast Atlantic mackerel and herring) have been or will most likely soon be suspended because of political disputes (MSC, 2020a). Especially for SSF, a sustainability-certification like MSC holds numerous potential advantages like better fish prices (Wakamatsu and Wakamatsu, 2017), preferences in funding and lobby-building, as well as an improved management and scientific framework (Lopuch et al., 2008). Yet, SSF often not only struggle to meet the financial requirements of the certification (Wakamatsu and Wakamatsu, 2017) but also lack the necessary scientific data on stock health and a sufficient management (Lopuch et al., 2008). The MSC started to address this issue by launching targeted certification programs for SSF (Marine Stewardship Council, 2019) and for the UK inshore fishery in particular (Huntingdon, 2015). An example of successful certification of SSF in the UK is the Cornish sardine (*Sardina pilchardus*) fishery, a data-poor SSF, which was certified in 2010 and recertified in 2017, after developing a management framework together with retail partners, local authorities, and fisheries research (Marine Stewardship Council, 2019). The first collaboration project of the MSC and the Seafish organization "Project inshore" evaluated England's inshore fisheries sector and concluded that only two of their top fifteen most valuable species have, at their current state, the potential for an MSC certification. This was due to overexploitation and the lack of a management framework as well as sufficient stock data (Huntingdon, 2015; Davies et al., 2018). The organizations launched successor projects to address these issues and develop a strategic plan for the future of SSF in the UK. In October 2019, a conference on the "Future of Inshore Fisheries" was held involving fishermen, managers, and scientists (Seafish, 2019b). Seafish published the summary action plan created from the content of this conference and presented five main themes that emerged from the conference: Co-management,

collaborative Science, credible fisheries management, rights and access, and effective compliance. One of the priority tasks of the fourth theme, rights, and access, is to "explore the feasibility of Community Quota Ownership schemes..." (Seafish, 2020b). Complementary to the MSC certification, the concept of PGI's has been successfully applied for fish products in several cases, for example, the bleak roe of vendace (*Coregonus alba*) in Sweden (Boonstra et al., 2018) or "Aischgründer" Common carp (*Cyprinus carpio*) in southern Germany (Lasner et al., 2020). In both cases, the certification added value to the traditional production system and increased profitability. The Swedish bleak roe fishery still generated high value in recent years, even though landings approximately halved. This is due to a steep incline in prices (STECF, 2019) and successful marketing of not only the bleak roe itself but also the byproducts of the MSC-certified fishery (e.g., vendace filet (Boonstra et al., 2018). The UK has left the EU, and therefore its certification scheme for PGI was lost as well, but the UK Government announced that a UK-specific geographical indication system would be launched in the near future (UK Government, 2020b).

In general, most UK fishermen euphorically welcomed Brexit because it provided the opportunity to decrease administrative and financial hurdles when implementing management measures such as CDQs, but it holds both chances and risks for the SSF. Deregulation of fisheries management and an adaptation of the zonal attachment system could provide new catch opportunities. On the other hand, the withdrawal from the European Maritime and Fisheries Fund (EMFF) could leave the fishery with a lack of funding (Symes et al., 2020). In the last EMFF funding period from 2014 to 2020, the UK received a total of 4.28% of the EMFF means, equaling 243 million €. The largest share of that funding (40%) was designated for the implementation of the CFP and more than a fourth (27.8%) to support sustainable fisheries (European Commission, 2020b). Both of these funding targets held the potential of supporting SSF, as they were also used to establish the Coastal PO, exclusively created for SSF vessels in England, which comprise the largest SSF in the UK (Davies et al., 2018). The EMFF funding is not only used for funding infrastructure development such as port facilities and scientific data collection, but individual fishermen can also apply for funding and have investments in their vessels or gear refunded (European Commission, 2017). In the future, these and several other possibilities will be inaccessible for the UKs SSF. Hence, an independent economic development scheme should be implemented in order to substitute this lack of aid for fishermen and fishing communities. In such considerations, not only should direct funding be considered as a trajectory for financial support of SSF, but also indirect funding *via* discounts needs to be taken into account. The Icelandic fishing free provides a good example for it. SSF could, for example, be excluded from further increases of the fee or even be granted discounts. In addition to monetary aids, fisheries management needs to establish a framework in which SSF are adequately represented. If POs play a vital role in the management structure, SSF needs to be enabled to form POs with the same rights and duties as other fisheries POs to guarantee fair and even market conditions in the fishing sector. In an ideal framework, a coastal or SSF PO would be

integrated into the management of a CDQ program to make sure that local SSF receives the necessary share of the CDQ quota and is integrated into decision-making. This kind of priority to local residents and businesses is an integral part of the Alaska CDQ program, which has significantly improved socio-economic circumstances for both community members as well as the corresponding fishery. Job availabilities in rural areas increased, also reducing transmigration toward larger cities (Strong and Criddle, 2013). CDQ members have been enabled to buy and operate their own vessels with the earnings coming from CDQ quota leasing, and large-scale Alaska pollock fisheries can extend their fishing season and gain limited access to areas restricted for fishing (Haynie, 2014). The Alaska CDQ scheme has significant positive effects on the income and fishing infrastructure of Alaska's communities and training of their residents. It should be mentioned, though, that the introduction of this scheme was not without controversy and several lawsuits were filed in the process. Initially, re-allocating 7.5% of pollock TAC from offshore to inshore fisheries was a concession in order to secure the deciding vote of Western Alaska in the North Pacific Fisheries Management Council negotiations (National Research Council, 1999). The subsequent increase to 10% of pollock TAC was only accepted by the inshore and offshore sectors because authority was given through the AFA to self-organize as cooperatives. The consequent ability to sub-allocate the sectors allocations as individual quotas led to substantial cost savings and an increase in revenue, which led to the acceptance of the CDQ scheme (National Research Council, 1999). Therefore, when the CDQ scheme was expanded to other species, it was increasingly welcomed overall.

In contrast, the UK's, Irish, or Icelandic fishing industries do not have the economic volume of Alaska's fishing industry, which had total revenue of around 1.5 billion € in 2018 (National Marine Fisheries Service, 2020), yet fisheries are an important economic pillar, especially for the coastal communities. In such a CDQ system, SSF could diversify their dwindling target species portfolio if it grants them prioritized access to quota. Furthermore, they could benefit from improved harbor, processing, and wholesales infrastructure resulting from CDQ revenues as well as from a general economic uplift of their communities, similar to the CDQ scheme in Alaska (Strong and Criddle, 2013). One has to keep in mind, though, that fisheries systems are complex networks of socio-economic and ecological influences. In such systems, management tools like CDQs should not be considered as panaceas but have to be evaluated with respect to their sociocultural and bioeconomic side-effects and drawbacks and in interplay with other management measures (Young et al., 2018). The UK is no longer a part of the EU, its legislation, conservation- and development strategies, yet it has similarly ambitious goals for the protection of its coast and the strengthening of the fishing sector (UK Government, 2020a). In fact, it is one of the largest fishing sectors in Europe, and in the light of recent political changes, it is likely to grow further. Therefore, it is legitimate to assume that a well-designed CDQ program could have similar positive socio-economic effects in the UK. Furthermore, it could include measures to specifically support small-scale fisheries, a fraction of the fisheries that has

been struggling to survive but, in our view, holds potential to be a viable and recognized part of the Blue Economy. Iceland, on the other hand, is a good example in which many different measures were implemented in order to support local communities. These are still considered to be the main economic drivers for several areas around Iceland and are therefore also extremely valuable in the context of cultural identification. Although quota concentration, as well as rural migrations, seem to continue at a slower pace, the willingness to invest and support SSF with the corresponding communities also seems to be significant. Chambers et al. (2020) suggest three important aspects that should be considered in the future to continue strengthening SSF: (a) more possibilities to allow easier access of newcomers into the fisheries, (b) stronger representation of SSF in the political sector as well as better arrangements in general with more equitable power-sharing, and (c) stronger development policies for rural communities. These aspects align with the management and funding strategies we identified for the UK and Ireland, representing the EU fisheries management. This highlights that even though local requirements may be specific, the measures we described in this discussion can be considered as a general strategy for the empowerment of SSF and the strengthening of coastal communities in the context of Blue Growth. Boonstra et al. (2018) differentiated two growth trajectories for fisheries: Extensive growth, meaning an increase in the means of production like the number of vessels or extension of fishing grounds, and intensive growth, which is defined by output (i.e., fish revenues) growing more relative to input. This can be achieved by technological innovation increasing catch per unit of effort or by implementing labels for sustainable fisheries, which increase product prices. Following these definitions, we can state that the measures described in the previous sections have the potential to stimulate both extensive and intensive growth in SSF. When fishing opportunities for SSF are improved by preferential access to a CDQ quota pool, it is possible that more fishermen engage in the small-scale sector and invest in small boats, especially when they are backed up by public funding. Funding can also be used to promote extensive growth trajectories like CPUE optimization by using more efficient gear or increasing product value with a certification. We, therefore, argue, in accordance with Boonstra et al. (2018), that capture fisheries and, in particular, SSF in the global north can grow along both identified growth trajectories and be a valuable part of a Blue Economy, which is ecologically and socio-economically sustainable.

CONCLUSION

"We want our waters back," claimed the pro-Brexit movement among UK fishermen (Boffey, 2017). This phrase inherits some of the fishermen's general paradigm: A feeling of exclusive use right for the resources in a country's territorial waters and a strong sense of connectedness with their fishing grounds. It highlights their self-perception as an integral part of their coastal landscape and communities. We argue that those beliefs, which are deeply anchored in the mindset of fishermen, are a

key factor supporting the establishment of CDQs as the case study of the Alaska pollock fishery highlights, a lucrative and technologically advanced fishery can be managed successfully, providing income and fostering growth in a fishery-dependent region. The management scheme also prevented labor outflow from remote coastal communities and excessive consolidation in fishing opportunities. These two problems also occur in island nations of the Northeast Atlantic, as we presented in the three case studies from the UK, Ireland, and Iceland. We described the attempts of those three nations to implement community-managed quota schemes.

In Ireland and the UK, these schemes conflicted with the laws of the EU and were never operational, while in Iceland, the community quota scheme was subject to major transformations in recent years and today does not play a significant role in fisheries management. Even though the reasons for the absence of relevant CDQs in the three nations are complex and multifarious, the Alaska pollock provides an excellent example of the factors needed for the successful implementation of such a scheme. We argue that given a solid regulatory framework supported and enforced by the communities, sufficient quota allocation, close scientific support, and long-term legal protection, such programs could also be successful in member states of the EU, the UK, Iceland, and other fishing nations. Managers and decision-makers could use such schemes to stop and, at best, overturn issues like quota consolidation and the workflow exodus from coastal communities.

As we described in the case studies, the Alaska pollock CDQ TAC is fully harvested by technically highly advanced catcher-processor vessels. Therefore, highlighting the chances CDQs hold for SSF might seem contradictory at first glance. We, however, argue that such schemes hold the potential for significant benefits for SSF. First and foremost, SSF would profit tremendously from more favorable quota allocation and easier access to quota. Nowadays, the CDQ program not only covers Alaska pollock but a number of other species, such as Pacific halibut, sablefish, and cod. In contrast to the Alaska pollock fishery, these are usually fished from longline (or also jig in case of cod) vessels < 10 m, < 15 m, and < 20 m, respectively (NOAA, 2018a). Additionally, CDQs also own and operate large vessels in the trawl and pot fisheries (NOAA, 2018a).

As we pointed out, quota allocation processes, especially in the UK and Ireland, disfavor SSF. The additional quota share needed to ensure their economic survival is often small and, we hypothesize, would not endanger the survival of large-scale fisheries. Secondly, the SSF would also indirectly profit from the economic upswing of their coastal communities from CDQs royalties or revenues. A well-functioning local fishing industry leads to improved harbor infrastructures, more established value chains, and a more stable local economy. As in the Alaska CDQ scheme, revenues could be reinvested in the training of local personnel such as fishermen, mechanics, and dock workers, who are an equally essential part of coastal infrastructure as well. From those factors, SSF would benefit directly in the form of easier access to the harbor, processing, and marketing infrastructure as well as from a generally improved economic situation. Since their operational radius is small due to the

small size of their vessels, they are dependent on access to structures at their home ports. Thirdly, SSF would benefit from the establishment of a regional management organization that administers the CDQ and acts as a representative instrument in political negotiations. Increasing the inclusion of SSF stakeholders into the CDQ management decision processes as well as the scientific support projects would help to gain more visibility amongst decision-makers. This appears to be of large importance in order to design a management framework that meets the SSF's needs. Despite all possible benefits of CDQ systems highlighted here, we want to put concluding emphasis on the point that such systems can never be panaceas in fisheries management. Even though some authors promote community self-organization of fisheries as the most powerful tool in coastal fisheries management (Venkatachalam, 2004), a CDQ system will never solve all issues affecting the SSF. It will take time and effort to establish it, requires major investments of public resources, and the advantages will take years, possibly decades, to become apparent. Therefore, it has to be undermined by robust and accessible research and included in a framework of interconnected management measures. This could be supported by establishing an open online toolkit for fisheries governance, like Young et al. (2018) suggest. In addition to the inclusion of SSF in a CDQ scheme, we discussed support strategies and growth trajectories for SSF, such as certification and targeted funding, in the third section of our review. As we stated in our introduction, these strategies can be effective when implemented individually. Yet, we see the potential for mutual reinforcement if they are combined and with when including SSF, for example, by using a CDQ scheme as described above. Through targeted funding and certification, SSF is enabled to improve and ensure the ecological sustainability of their fishing operations, which would then lead to higher revenues. We state that a successful certification is much more likely if the SSF is included in a CDQ program, in which it is closely monitored and subject to a descent management plan. Therefore, funding would not be a pure subsidy but more of an investment into a fishery that has the proven potential to be ecologically and economically sustainable if the right circumstances are created. As Blue Growth is commonly defined as a holistic management approach, we argue that SSF has a significant potential to contribute to any Blue Economy. It provides income for thousands of coastal residents lacking other economic opportunities. Harvested with more sustainable fishing methods, it is cross-linked with other sectors of the Blue Economy, especially coastal tourism, and it is an integral part of the culture and tradition of coastal communities. The UK and Iceland are yet to implement a Blue Growth strategy. In the EU's strategy, capture fisheries play a secondary role so far. The case studies we provide in this review highlight the importance for nations and unions to establish new Blue Growth strategies, in which the importance of SSF is acknowledged, and effective measures are taken to ensure its survival and solidified position in a modern Blue Economy. In our opinion, the trajectories described in this review hold significant potential to be an effective instrument of Blue Growth strategies, even though they are most certainly neither the only recipe for success nor applicable to every fishery.

AUTHOR CONTRIBUTIONS

ES and SR conceptualized the review and wrote the review chapters. ES created the figures which were not cited from other publications. Both authors contributed to the article and approved the submitted version.

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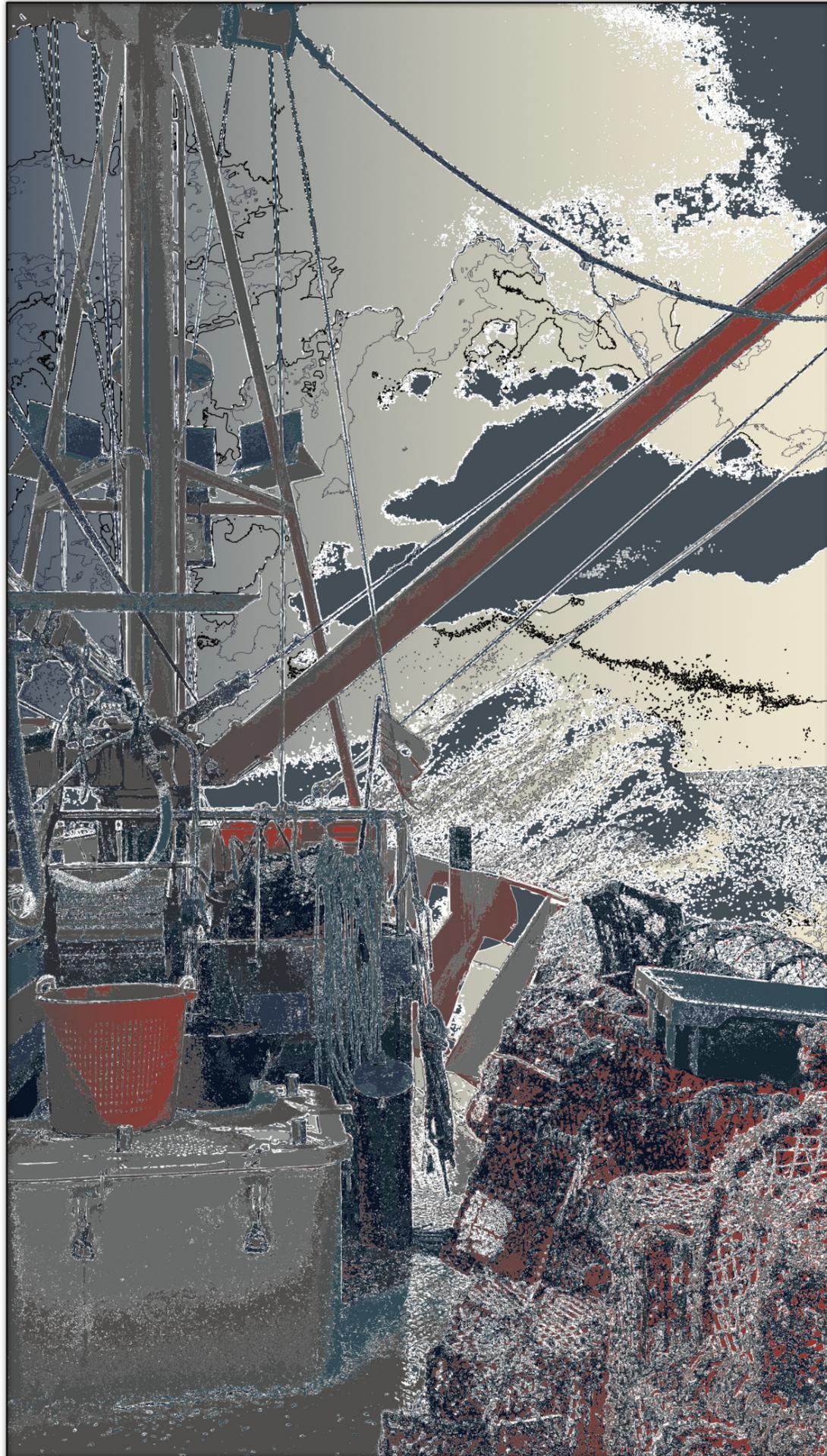
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Discussion

Discussion

Improvements in data collection to facilitate realistic fishing fleet models

In the first chapter, the novel approach to fleet segmentation was presented, and its advantages were highlighted. Combining multivariate statistics with machine learning and translating the approach into a freely available, extensively documented R package (Sulanke, 2021), it was well received and swiftly adopted by the scientific community. The identified fleet segments of the German fleet were further analyzed by subsequent research, as Knöpfel et al. (2025) analyzed fishing inefficiency trends of the German Brown shrimp fisheries, while Niemann and Lasner (2025) conducted analyses on the value chain of this fleet and the profitability of mechanized shrimp shelling technologies. In the National Fisheries Profile (NFP) of Germany, a novel document mandated by the EU, which aims to give a comprehensive overview of the national fisheries economic sectors with special emphasis on economic and social data, the results were also extensively cited (Barz et al., 2025). In a study on Icelandic demersal fisheries dynamics, the versatility of the approach was demonstrated, as the clustering methods were transferred to assess métier-based dynamics, clustering compositions of single hauls rather than annual catch profiles of fishing vessels (Oostdijk et al., 2024). Grigoraş et al. (2023) utilized the approach to provide the first holistic characterization of the Romanian fishing fleet. Yet, this widespread scientific recognition is likely to be only one side of its versatility, as it has proven to be particularly useful in MSE and national advisory work. These are very common tasks in departmental research that can consume an immense amount of resources, but the results rarely find their way into scientific publishing. This can be due to confidentiality issues, political strategy, or simple time constraints. The novel approach has proven to create more homogeneous fleet segments, especially with regard to cost structure, activity patterns, and quota distribution. When the Brexit negotiations took place, these advantages became particularly apparent.

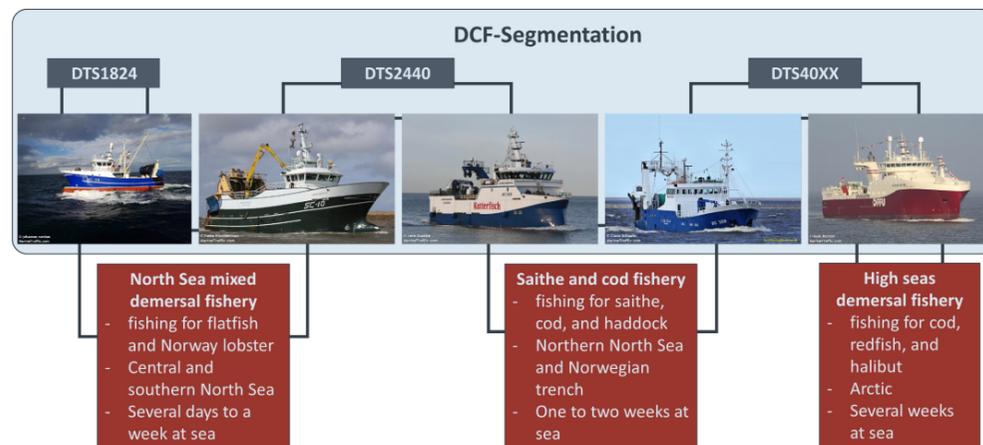


Fig.4: Examples of German demersal trawlers and the respective segments they were assigned to under both the DCF and the novel segmentation approach. All pictures were taken from MarineTraffic.com, copyright is held by (from left to right): Johannes Romkes, Hette Kloosterman, Jens Grabbe, Claus Schaefer, Maik Richter.

alternative approach allowed for precise calculations of the economic impacts of the agreement. Especially the demersal trawling segments, which harvest very different stocks, were impacted by the agreement in very different ways. German high seas demersal fisheries lost fishing opportunities in Arctic Waters, as Norway took advantage of the political vacuum, re-negotiating access to Spitzbergen cod and redfish quota. In the agreement, the EU gave up shares of North Sea cod and saithe quota to the UK, particularly affecting the German saithe and cod fishery in the Norwegian trench. German mixed demersal fisheries only lost little quota in the agreement, but were impacted by another, less obvious consequence of Brexit. This fishery relies heavily on Norway lobster fisheries for revenue generation, a species for which Germany, under the key of relative stability, has nearly no quota and only gains access to by swapping quota for it with cod quota with the UK (Letschert et al., 2021). Until the final days of the negotiations, it was unclear whether or not this system would still be legal after Brexit. Therefore, the aforementioned fleet segments, which are partly mixed by the DCF-segmentation, were affected by Brexit very differently, but each in its own serious way. Applying the novel approach allowed for precise economic impact assessments in the advisory work related to Brexit. And Brexit was not the last crisis or exceptional situation that German fisheries went through. As outlined in the introduction of this thesis, the Russian invasion of Ukraine made fuel prices surge globally, MSP and conservation efforts put especially coastal fleets under continuous pressure, and fishing pressure and stock health are not at the desired levels for all target stocks. In summer 2025, the North Sea saithe fishery voluntarily withdrew its MSC certificate to avoid official decertification. After a benchmark process, the target fishing mortality was missed by 0.004% - enough for one of the independent assessors to advise decertification (McBride, 2025a, 2025b). The certificate is a source of additional wealth generation and, maybe even more importantly, a requirement to be listed by many retailers, giving it immense market power (Ponte, 2012; Bellchambers et al., 2016). The socio-economic impacts of such developments can only be assessed by segmenting fisheries and collecting their data based on their operational reality and targeted stocks, not purely on their technical parameters.

Even though the approach had the highlighted advantages, its novelty lay in the emphasis on transferability, standardized statistical procedure and widespread applicability rather than technical innovation. As described in the discussion of Chapter One, many previous studies used clustering (Pelletier and Ferraris, 2000; Holley and Marchal, 2004; Jiménez et al., 2004; Tzanatos et al., 2006; Pérez-Jiménez and Mendez-Loeza, 2015) and other multivariate approaches like PCAs (Rogers and Pickett, 1992) to identify groups and patterns in fishing fleet data. Yet, all these approaches were tailored to fit specific datasets. By modifying assumptions and technical details, like data preparation, dissimilarity coefficients, clustering method, fusion algorithm, diagnostics on the number of clusters, and post-hoc processing of the clusters, results can be shaped immensely. Approaches can emphasize production volume by clustering catch quantities or transformed catch quantities rather than catch composition, and thereby focusing on separating scales of fisheries rather than target species, or even apply Factor Analysis of Mixed Data (FAMD) and analyze quantitative and qualitative data simultaneously. One of the major advantages of the alternative segmentation approach is the utilization of stock-based catch data as a basic input variable. Yet, acquiring such data can be challenging. The term stock, as a group of fish that lives in the same geographic area and is self-sustaining in terms of reproduction, is rather loose, and many stocks have been documented to mix considerably with

neighbouring stocks (Utter and Ryman, 1993; Begg et al., 1999; Campana et al., 2000). For many areas in the world, no stock databases are available, disabling any spatial dimension of the novel approach, which is only implicitly included via the recommended structure of the input data. Even in the well-researched Greater North Sea Ecoregion, the stock concept is still subject to shifts and changes, as the recent splitting of the North Sea cod stock into three substocks demonstrated (ICES, 2025a). Furthermore, even though the novel approach is as standardized as possible, which was achieved through extensive collaborative work during three fleet segmentation workshops hosted by the Regional Coordination Group for Economic Issues (RCGECON) of the EU (Sulanke et al., 2021; Sulanke et al., 2022; Sulanke and Berkenhagen, 2024), a substantial level of expert knowledge, and therefore subjectivity, is required to make the decisions necessary to perform the post-hoc processing of the clusters created by the approach, particularly the joining into meaningful, homogeneous fleet segments. This level of subjectivity and expertise should not be considered a significant disadvantage of the method, as the approach is primarily designed to be an assisting tool for fleet experts. The implemented machine learning approach, which has been proven to be able to perform the fleet segmentation based on very few years of pre-segmented reference data, is an additional measure to reduce subjectivity, but it is not a panacea for full automatization of fleet segmentation. Novel species will challenge any machine learning approach trained on a historic data set. With ongoing climate change, fisheries target species will change, and there have already been numerous examples of novel fishing strategies appearing in North Sea waters and elsewhere. Only detailed knowledge of the involved fleets and fishing companies, their cost structure, and operational reality will allow data collectors to correctly classify them within the existing national and supranational fleet segments. Ongoing close collaboration with the fishing sector, scientific exchange and method standardization among national fisheries data collection delegates, and continuous adaptation of novel data analysis and machine learning methods are keys to providing fisheries economic data suitable for scientific and advisory work and should be the focus of all initiatives in this field.

One of the original intents of acquiring funding to develop a novel approach to fleet segmentation was to provide a better linkage between the economic fleet data collected by the DCF and published in the Annual Economic Report of European Fishing fleets (STECF, 2024b), and the Fisheries Dependent Information collected and published by the STECF, which is a crucial data source of fisheries effort and catches, and the foundation of many modeling applications (STECF, 2024a). In the retrospective, only minimal steps towards this goal were achieved, yet, upon closer inspection, the technical details of these two data calls reveal the limited possibilities for harmonization. FDI data is based on level 6 métiers, which combine information on the vessel length, specific gear type, target assemblage of the respective fishing activity, and the mesh size of the utilized net (EU, 2016). The information is activity-based, meaning that one vessel can be assigned with a multitude of métiers in one calendar year, or even use various métiers during one fishing trip. The information on the number of vessels, of which trips were aggregated to produce the métier-based information, is not given. Conversely, the economic data collected and reported for the AER is vessel-based. Data is collected for single vessels through surveys or national sampling programs and then extrapolated to the fleet segment level. Disaggregating segment cost structures to a métier-level to join these two datasets relies heavily on assumptions on the influence different métiers have on the variable costs of the associated segments. Fuel costs, which account for a significant fraction of fisheries variable costs (Cheilari et al., 2013; Bastardie et al., 2022), for example,

could be disaggregated to the métier level based on their proportion of the overall effort of the segment. However, different fishing techniques vary considerably in their fuel intensity (Davie et al., 2015), and on board fuel use measurements during fishing operations have revealed significant differences between steaming and fishing operations (Sala et al., 2011; Sala et al., 2022). Novel approaches to onboard data collection, including live assessment and reporting of fuel use (EU, 2018), could provide information vital for the disaggregation of cost data to different fishing activities, but these approaches are still under development and far from being implemented universally in fisheries. Close collaboration with the fishing sector, rigorous reality checking, and critical reviews of model assumptions, therefore, remain essential in all modeling approaches, independent of the underlying data set.

A bio-economic modeling approach to simulate the impact of climate change on fishing fleets

In the second chapter of this thesis, the application of the bio-economic simulation and optimization model Fishrent to the demersal roundfish fleets of three North Sea fishing nations is described. The model results revealed the intricate effects that climate-induced changes in prices and management policies, as well as MSP scenarios, can have on the profitability of fishing fleets. Price developments and target stock health were found to be the major factors influencing fleet profitability, while MSP scenarios played only a secondary role. This was also the case for the spatial dynamics of the fleets, where fuel costs and the development of fuel-saving strategies to reduce operational costs were the main factors shaping effort distribution in space and time. These results are well in line with similar modeling approaches. Bartelings et al. (2013) found prices and stock health to be the most influential factors for fleet profitability as long as spatial flexibility was given, while Simons, Döring and Temming (2014) demonstrated a shift of spatial activity to low-cost areas and the economic importance of healthy fish stocks Simons and Bartelings et al. (2014). Rybicki et al. (2021) found spatial fleet dynamics to be inherently shaped by the stock distribution of the modeled Northeast Atlantic mackerel (*Scomber scombrus*) stock, which distribution was density dependent in the model, i.e., the larger the stock, the further east- and northward it spread. This biological mechanism has been proven to be a predominant cause of the range extension of this mackerel stock into Icelandic waters, with elevated temperatures favoring the process (Olafsdottir et al., 2019). Prolonged high fishing pressure exceeding scientific advice led to a severe decline in SSB and a subsequent reduction in scientific advice (ICES, 2025b). Due to the reduced density, the stock has again shifted eastward (Olafsdottir et al., 2019). The mechanism of density-dependence included in the model of Rybicki et al. (2021) is a sophisticated reflection of this biological reality, leading to the interesting phenomenon. Larger, and therefore for the model result more influential, fleets purposefully pressuring the stock with high catch rates, keeping the stock density low, and by these means, the distribution of mackerel within their operational range. This is a very interesting and, in the context of industrialized fishery for pelagic species with a proven density-dependent distribution, highly versatile modeling technique. Yet, it would not be appropriate to use it in the case of the modeled demersal fleets presented in the second chapter. The distribution of the three modeled

stocks, particularly the cod stock, which drove the modelling result because of the high market value of cod, has not been proven to be density-dependent but rather influenced by environmental factors and their respective cascading effects. Tagging studies of adult cod revealed that the individuals showed only a limited response to unfavorable temperatures (Neat and Righton, 2007). The northwestward shift of the cod stock observed is rather attributable to the settlement dynamics of juvenile cod, which might have higher settlement and survival rates in the northern North Sea (Righton et al., 2010). Recently, ICES has proposed splitting the North Sea Cod stock into three sub-stocks, of which the southern stock is in a severely depleted state and likely has undergone a systemic regime shift (Cecapolli et al., 2025). Yet, since the degree of mixing between the three sub-stocks is unknown, ICES has most recently recommended zero catches for all three stocks (ICES, 2024a). This announcement was taken with the utmost concern by the fishing sector, declaring it a possible economic disaster (Welling, 2025). It is a vivid reflection of one of the key model results of Chapter II, in which continuous unsustainable management strategies and excessive fishing pressure led to the collapse of the cod stock, jeopardizing fleet profitability.

Spatiotemporal bio-economic simulation models of multiple fishing fleets targeting multiple fish stocks are complex, and cause and effect can be difficult to determine from the model outputs, especially since there are no standardized model diagnostics and post-hoc tests for these kinds of models. In the model version presented in Chapter II, no climate effects on stock distribution were included. This is a major model weakness, which was critically discussed in the chapter and by the reviewers of the submitted manuscript. Not including distribution effects was chosen to maintain model parsimony and focus on the results of price and MSP developments, not as a deliberate neglect of scientific evidence. In the future, an additional model version should be configured, focusing on this aspect by applying appropriate mechanistic connections between the three modelled species' distribution and climate change. To maintain model parsimony, other aspects of the model, which were found to be of minor influence, could be simplified, like MSP development. This tailored approach will allow for testing the economic consequences of climate-induced distribution changes of target species, which are a proven reality in the North Sea (Perry et al., 2005; Rose, 2005; van Hal et al., 2010; Engelhard et al., 2014), yet difficult to replicate in simulation models. Nonetheless, bio-economic simulation models like FishRent have unique advantages over similar models. As they are spatially explicit and contain refined information on fleet cost structures, both aspects that other frequently used fisheries simulation models like FLBEIA commonly lack (Rybicki, 2020). The spatial explicitness of FishRent is created by allocating fishing effort in space and time until an overall optimum in the simulated objective function, most commonly in overall fleet profit, is reached. Optimizing overall profit was also the objective function applied in the model version presented in this thesis. While this assumption sufficiently emulates the operational reality of highly industrialized, very mobile fishing fleets applying modern fish detection technology (Rybicki, 2020), it has been criticized to be insufficient when it comes to less mechanized, coastal fisheries operating on a rather individual basis. Human behavior and strategy building, particularly spatial choice, are a major source of insecurity in fisheries modeling (Fulton et al., 2011), and various approaches have been developed aspiring to better reflect such behavior. The introduction of métiers, which have been discussed in the previous section, was a step towards fisheries behavioral characterization by the EU, yet métiers also do not fully reflect fisheries behavior (Ulrich et al., 2012). To mimic the unique combination

of experience, technological aids, and stochastic uncertainty influencing fishing ground choice, fisheries modelers have used Random Utility Models (RUMs). These are modeling frameworks simulating the spatial choice of fisheries by partitioning each possible fishing location into an observable component (e.g., expected catches, steaming distance, and associated fuel costs, etc.) and an unobservable randomized component. Such models have been applied to analyze the effect of closures on effort displacement (Hynes et al., 2016) or spatial choice of trawl (Holland and Sutinen, 2000) or pelagic fisheries (Rybicki et al., 2025), with the latter utilizing economic and ecological conditions to achieve high predictive power of spatial choice simulation.

Even though RUMs represent a considerable step towards realism in simulating spatial choice of fisheries, they are unable to reflect to simulate behavior on the individual level of fishers or vessels, for they are based on statistical utility rather than on explicit decision rules enabling sequential choices. This is only achieved by agent-based models (ABMs) and their basic principle of applying a set of rules followed by all the individual agents. In most fisheries ABMs, the agents are single fishing vessels, and these models can mimic all forms of fishing behavior and even incorporate factors of learning and interaction (Haase et al., 2023). ABMs have been applied to various kinds and aspects of fisheries, including spatial choice (Cabral et al., 2010), the impact of fishing behavior on stock assessments (Alós et al., 2019), and the influence of MSP on spatial choice as well as fishing gear choice (Letschert, 2024). Setting meaningful socio-economic rules for fisheries operations is a powerful tool, yet, to realistically mimic operational styles, data collection needs to be thorough and incorporate robust qualitative methods. Boonstra and Hentati-Sundberg (2016) conducted extensive surveys and interviews, defining three fishing styles relevant for the fisheries operating in the analyzed region before transferring this knowledge into a socio-ecological ABM Wijermans et al. (2020). The kind of qualitative sampling necessary for socio-ecological parametrization is resource-consuming and requires knowledge and techniques not very common in fisheries sciences, as particular details like habitus and interview location can distinctively shape the data gathered in such sampling (Albrecht, 2025). Ultimately, no single modeling style has the capacity to overcome all disadvantages and provide a holistic, realistic 'digital twin' of an operation so diverse, heterogeneous, and complex as fisheries. Rather than striving for a panacea violating the principle of model parsimony, ensemble modeling, like Letschert (2024) proposes, should be used to simulate fisheries behaviour, perform MSE, and test the effects of future scenarios. A variety of modeling styles should be applied to approach the same research question, utilizing the strengths of each model family while being cognisant of their respective disadvantages.

Species redistribution and its economic implications: Squid in the southern North Sea as a case study

After discussing the difficulties of implementing species distribution changes into fisheries models, the implications of the third chapter's case study become even more apparent. In a comprehensive approach to assess recent changes from a fisheries perspective, data analysis and spatial statistics were combined with interviews and onboard sampling of commercial fisheries to gain insights into targeted squid fisheries emerging in the Southern North Sea. Although the magnitude of the sudden rise in economic relevance of cephalopods for North Sea fisheries was striking even for scientists and managers, researchers have predicted the increasing importance of cephalopods in the North Sea for some years now. With their short, commonly semelparous life cycle, high adaptability, and given their efficiency as predators (Clarke, 1996; Piatkowski et al., 2001), cephalopods are often thought to benefit from the consequences of climate change (Lipiński et al., 1998; Doubleday et al., 2016), and many species have been documented to shift their distribution poleward (Schickele et al., 2021; Boavida-Portugal et al., 2022). In the North Sea, the fishery for *Loligo forbesii*, a species closely related to the target species of southern North Sea squid fishing (*Loligo vulgaris*), has been targeted by a specialized seasonal coastal fishery. In the Moray Firth in Eastern Scotland, this species has been fished for more than two decades during its winter spawning aggregations in the Firth (Godwin A. Otego, Sansanee Wangvoralak, Graham J. Pierce, Lee C. Hastie, Beth Scott; Young et al., 2006). Recently, fishing in the Moray Firth has slowed, and the species has been reported to aggregate further north, at the Shetland Islands, where it is again targeted by the well-developed local trawl fleet (McBride, 2025c). Simultaneously, in the southern North Sea, the common Octopus (*Octopus vulgaris*) has extended its distribution towards the western English Channel, where it causes major economic damage (Jansen, 2025; Through the Gaps, 2025). The intelligent and adaptable octopi have learned to prey on lobsters caught in lobster traps and also prey on scallops (mainly King scallop *Pecten maximus* and queen scallop *Chlamys opercularis*), which are both highly valuable and therefore sought-after target species for coastal fisheries. Some fishermen decided to make virtue of necessity and target Octopus instead, which is not only a highly marketable species itself, but does not fall under any quota or technical regulations in both the EU system of relative stability and the UK fisheries management (Through the Gaps, 2025). As highlighted in Chapter III, the same factors allowed the rapid development of squid fishing for *L. vulgaris* a little further to the west, in the Eastern English Channel and the southern North Sea. Fishers did not need a quota for squid, only for the bycatch species, no license, and no other form of regulatory requirement. All it takes to participate in the fishery is the vessel, the custom-made trawling net, and the knowledge of the fishing grounds. Of all the aspects highlighted in the first description of the emerging German squid fishery in the second part of Chapter III, the spatial concentration of fishing hot spots was one of the most striking. As convincing as the data analysis was, the personal experience of sampling a trawler fishing an approximately 125 NM² trawl stretch with more than 20 trawlers in proximity left a lasting impression of a different magnitude. As supported by the spatial clustering analysis, the fishermen stated that the trawlers stay at the exact same location until catches decline, and then move further south and east to the next productive fishing ground.

From an ecological perspective, this phenomenon raises two questions: 1) why are squid aggregating in the specific area, and 2) how is the replenishment of the trawled area taking place? The field sampling revealed many indications of feeding interactions, with sampled whiting caught as a bycatch showing not only bite marks from squid beaks but also having an unusually high number of individuals with very full stomachs. Random visual examination of the stomach contents revealed sandeels (*Ammodytes* sp.) to be the most common prey item, but also squid individuals and unidentified fish eggs were found. Sandeels have been identified as a common food source for squid before (Wangvoralak et al., 2011), and the fishing area is a known spawning ground of Downs herring during the squid fishing season (Hufnagl et al., 2015). Herring spawning has been demonstrated to attract various predators such as haddock and cod (Toresen, 1991).

Overall, the availability of forage fish in the form of sandeel as well as herring spawn could present a rich feeding ground to the squid, which might also feed on other predators like whiting, although the observed bite marks could also be attributed to a panic reaction during trawling. No sandeels were detected in the trawl catches, which might indicate a low catchability of sandeel in the squid trawl. Therefore, prey availability would be maintained even under high fishing pressure, providing an ongoing incentive for squid to aggregate in the area and form an intricate, size-dependent predation hot spot (see Fig. 5A). Even though this is an overall possible theory given the predation efficiency of squid and the availability of suitable prey items, the phenology of *L. vulgaris* makes a spawning aggregation appear to be highly likely as well. The rocky area southeast of the fishing area, where no trawling is possible, would be a suitable spawning area for the species (Laptikhovskiy et al., 2021), and the individuals might travel through the deeper Strait of Dover located to the Northwest, possibly utilizing currents, and avoiding predators. Therefore, the fished area would represent a transition area that squid individuals use to reach their spawning grounds (see Fig. 5B). Fishing squid individuals that aggregate at their spawning grounds is a common squid fishing strategy around the world, which holds the risk of severe overfishing (Iwata et al., 2010). Even though squid life cycles are short and stock sizes display strong fluctuations,

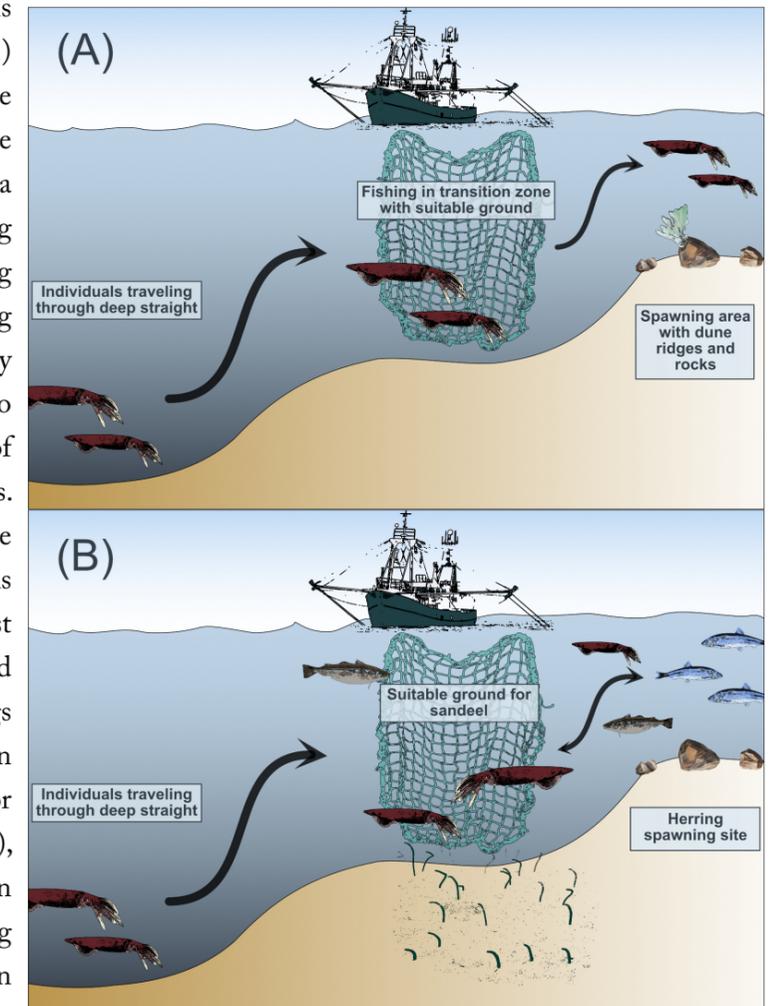


Fig.5: Conceptual depiction of possible reasons for squid aggregating on the fishing grounds. (A) Transition from Dover Strait to spawning grounds. (B) Feeding aggregation on sandeel and herring eggs.

unsustainable use of them in fisheries is still possible, and unfortunately, a common reality (Arkhipkin et al., 2015). These developments should serve as a warning to European fisheries management that these resources require cohesive action and specifically designed management plans, not in a distant future, but immediately.

The consequences of climate change and the subsequent changes in species distribution are manifest in the North Sea, and the fishing sector is already adjusting by harvesting these novel resources. Management has not been able to prepare for the situation and develop robust plans in advance, but the least it has to do is to match the pace of these developments, as squid are not the only species favored by the warming of the North Sea. Lusitanian clupeids like Sardines (*Sardina pilchardus*) and Anchovies (*Engraulis encrasicolus*) are increasingly targeted in the North Sea, the described Octopus fishery in the English Channel is emerging, cuttlefish (*Sepia officinalis*) are fished in the English Channel, showing not only climate-induced changes in their phenology but also signs of overfishing (Laptikhovskiy et al., 2023; Laptikhovskiy et al., 2024), and red mullet (*Mullus surmuletus* and *Mullus barbatus*) are increasingly targeted in the southern North Sea and the English Channel. During the interviews held in the preparation of the second chapter, fishermen stated that up to 50% of their revenue during the late stage of the squid fishing season (February and March) is generated by red mullet, which fetch similarly high market prices as squid. Just like them, red mullet is not managed by TACs in the EU or the UK, and ICES has only limited knowledge on the state and structure of their stock and considers *M. surmuletus* in the North Sea as category 3, where survey assessments indicate stock size trends, but quantitative information on the stock size can't be given (ICES, 2025e). Additional effort and resources need to be allocated to research on the various ecological and management implications of distribution changes. The emergence of novel fishing strategies must be studied, and their sustainability safeguarded. Only with in-depth scientific knowledge, robust MSE can be provided, and realistic future scenarios for modeling applications can be developed. Otherwise, North Sea fisheries are likely to continue their decline and remain in their niche role in ocean governance, being perceived as largely unsustainable and having little to no room for development and growth.

Fisheries in the Blue Economy and the Potential of Alternative Management Measures

This common notion of fisheries having little to no potential for sustainable Blue Growth was extensively discussed in the fourth chapter. In addition to the aforementioned hardship caused by climate change affecting the distribution of established target species, lack of access to and concentration of quotas were highlighted as significant pressures, especially for small-scale fisheries. As discussed in the chapter, the definition of the term small-scale fisheries itself is highly debated, as the socio-economic reality of coastal fisheries does not follow the technical separation criteria made by the EU. For example, the vast majority of German coastal North Sea fisheries are small, family-owned businesses operating one vessel,



Fig.6: Deck of a former brown shrimp fishing vessel converted for pot fishing. The fishing pots are visible in the bottom right corner.

or two to three in rare cases (Goti-Aralucea et al., 2021; Quiroga, 2025). They are facing pressures typical for SSF, like a lack of access to sales channels and limited bargaining power against highly industrialized processing companies (Knöpfel et al., 2025; Niemann and Lasner, 2025). Similar to the Alaskan, British, Irish, and Icelandic SSF described in the chapter, they are struggling with access to quota, and the Brown Shrimp fishery, which is the backbone of today's German North Sea coastal fleet, used to be an unpopular alternative, only reverted to in times of hardship, when catches of more valuable target species like plaice and sole were dwindling (Seidel, 2025). In the research work leading to the results presented in Chapter III, economic alternatives for German Coastal fisheries were explored, and pot fishing for lobster (*Homarus gammarus*) and brown crab (*Cancer pagurus*) was identified as an alternative fishing strategy pursued by several fishermen. After prolonged periods of low brown shrimp catches, a few shrimp fishermen converted their vessels and acquired pot fishing gear (see Fig. 6)

after realizing that the once severely depleted lobster stocks of the German Bight had recovered significantly (Goemann, 1990).

This fishery, even though its target species are not subject to quota management, would also benefit from a community quota allocation scheme in another, less obvious way. One of their major sources of expense is bait for the lobster pots, as lobsters are scavengers and are more attracted to baited pots. Bait availability is crucial for many pot fisheries worldwide and can account for the largest share of their variable costs (DiFiore et al., 2025). As the German pot fishermen do not hold a quota for suitable baitfish such as mackerel or herring, even though these species occur in sufficient numbers for the purpose in coastal waters, they have to rely on buying bait. As residual material processing in Germany is highly efficient (Barrelet et al., 2025), they often have to buy food-grade fish at immense prices, accelerating their bait costs even more. A minor assignment of bait fish quota, like, e.g., 10t of mackerel per year, pooled in all coastal communities, would relieve economic pressure from this emerging fishery. This measure would not hamper the profitability of German High Seas mackerel fisheries, which fish the vast majority of the German mackerel quota, as the pooled bait quote would reflect a reduction of approximately 0.1% (STECF, 2024b). Simple and often subtle measures like these hold the potential of increasing the profitability of coastal fisheries and securing their livelihood, and transdisciplinary processes of strategy building, as well as field surveys following socio-ethnographic principles, like the

sampling undertaken in the field phase leading to the results presented in Chapter III, are highly efficient in identifying such measures. The Thünen Institute hosted a series of transdisciplinary workshops, the ‘Future Workshop Coastal Fisheries 2045’, in which nine core elements affecting the livelihood of coastal fishing folk were discussed: Diversification strategies for fishers, fishers’ training, technological advancements, fisheries management, fleet capacity, recreational fisheries, aquaculture, marine protected areas, and offshore wind farms (BMEL / Zukunftskommission Fischerei, 2025). The selection of these criteria and the subsequent, controversial development of a common vision highlight how the pressures affecting small-scale fisheries differ from those faced by industrialized fisheries. Beyond resource availability, they are struggling with spatial conflicts with OWFs, marine conservation, and recreational fisheries, with which they also compete for resources (Guyader et al., 2013; Lloret et al., 2018; Letschert et al., 2021; Stelzenmüller et al., 2021; Di Cintio et al., 2024; Letschert, 2024), while most of these issues do not affect industrialized distant-water fisheries. They also struggle with generational replacement, while industrialized fisheries commonly belong to multinational corporations offering comparably high pay and often hiring international crews. In addition, they commonly have difficulties establishing reliable sales channels and rely heavily on direct sales (Pascual-Fernández et al., 2018; Mantziaris et al., 2025), or, in the case of German brown shrimp fisheries, have only limited bargaining power against an oligopoly of wholesalers (Goti-Aralucea et al., 2021; Niemann and Lasner, 2025). One of the fishers participating in the aforementioned emerging pot fishery had to go out of business because the quantities he landed were too low to establish reliable sales channels. This is another example of the difficulties SSF have in monetizing their catch. As discussed in the chapter and in accordance with Boonstra et al. (2018), supporting SSF in acquiring certification and participating in high-value marketing strategies, such as the protected geographical indication of the EU, is a promising strategy in ensuring their long-term economic viability. By increasing the revenues they generate from their catch, they can be a part of Blue Growth without putting additional pressure on marine ecosystems. Additionally, the Marine Stewardship Council (MSC), which is the most widespread and influential certificate for fisheries products, can facilitate alternative management options by introducing voluntary self-management schemes to certified fisheries. A good example of that is the certified fraction of North Sea brown shrimp fisheries, where a voluntary CPUE threshold is applied. If weekly CPUEs of the fleets fall below a certain threshold, maximum fishing effort is reduced (Neumann et al., 2025). In theory, this is an effective system of management for non-quota species and ensuring the sustainability of the certified fishery. Yet, many fishers have vocalized their dissatisfaction with it, criticizing not only differing ways of fishing effort estimation in the respective national fleets, but also the economic infeasibility of reducing their fishing time below the set threshold.

An additional way to secure income for coastal fisheries is diversification of business. As discussed in the aforementioned ‘Future Workshop Coastal Fisheries 2045’, the ‘Sea Ranger’ program for Baltic SSF allows fishers to receive funded additional training, qualifying them to carry out research, perform monitoring obligations of protected areas, and offer guided tours for tourists (Sea Ranger, 2025). Not only does this approach allow fishers to gain additional income, but transdisciplinary approaches from other areas have demonstrated how acceptance of conservation measures is increased in fisheries when they are included in the management and monitoring. One rather famous example is the Torre Guaceto marine reserve in Apulia, southern Italy, where local fishers enjoy territorial use rights, participate in

monitoring, ensure compliance, and report violations by other fishers (Russi, 2020). Additionally, they can market their catch as a locally sourced, sustainable product, generating increased value and public acceptance. It is a model example of inclusive, transdisciplinary design and management of a protected area and extensive growth in fisheries, like Boonstra et al. (2018) propose. It also highlights how the core of fisheries, despite all constructive initiatives of co-use and diversification, is to harvest seafood from the ocean. Thus, the central obligation of effective fisheries management is to provide a framework guaranteeing the sustainable use of available marine resources. As described in Chapter III and the previous section of this discussion, dramatic shifts in the distribution of target species and reduced fishing opportunities caused by political turmoil are already a day-to-day reality in North Sea fisheries. Bycatch species are subject to management measures, while the target species are unmanaged, like in the case of squid. Quota-managed species like hake become ‘choke species’, and the economic backbone of entire fleets is maintained by quota swapping, an opaque process that is largely based on self-management and endangers equity in the sector (Hoefnagel et al., 2015). Ongoing climate change and the accelerating shift in species distribution will intensify this problem, and authors have argued that the EU’s principle of relative stability, in which a fixed share of the annual TAC is allocated to each member state, will not be feasible anymore in the near future (Hoefnagel et al., 2015; Döring, 2023). If no alternative is found in time, unilateral advances, as they became a reality in the mackerel crisis, leading to severe overfishing of the Northeast Atlantic’s most valuable fish stock (Spijkers and Boonstra, 2017; Østhagen et al., 2020), will become an increasingly common phenomenon. Without the flexibilization of management strategies, multilateral cooperation between EU and non-EU states, and specific, directed funding, North Sea fisheries indeed have little perspective for Blue Growth.



Conclusion

Conclusion

This thesis was intended to provide a holistic collection of solutions for problems of all levels of fisheries research and management. As North Sea fisheries are facing a multitude of pressures in a dramatically changing natural environment and in times of political turmoil, pragmatic and contemporary solutions utilizing modern techniques are urgently needed. In the first chapter, a novel approach to the segmentation of fishing fleets was presented, holding the potential to refine data collection and enable management strategy evaluation and advisory work better suited to the operational reality of fisheries. It became apparent that, on the one hand, modern data analysis techniques like machine learning applications can significantly aid data collection work, but on the other, in-depth knowledge of the operational characteristics and cost structure of fishing fleets is still a necessity for fisheries data collection. These two factors should not be viewed as contradictory but rather as complementary.

The novel fleet segmentation approach was applied to facilitate the second chapter of the presented thesis, a detailed bio-economic simulation and optimization model designed to simulate the socio-economic consequences of climate change for demersal roundfish fisheries of the North Sea. The model results illustrated how price increases and unsustainable fishing pressure levels are a substantial threat to long-term fisheries profitability and supported the necessity of governmental financial aid to ensure a transition to sustainable fishing practices. The influence of marine spatial planning on fleet profitability was comparably limited, yet many potential negative effects of spatial effort concentration and offshore windfarm development, like additional routing costs, habitat degradation, and localized overfishing effects, could not be included in the model for mechanistic and parsimony reasons. This was also the case for climate-driven changes in species distribution, which are a scientifically proven reality, but hard to implement in bio-economic models in a biologically convincing and technically sound way. Including such distribution changes is, without a doubt, an essential field of improvement for bio-economic models, yet the complexity and variety of the presented model results and limitations support the idea of ensemble modelling approaches. Instead of pursuing more and more complex models, bio-economic modelling in fisheries should focus on applying different modeling approaches for answering the same research question. The reality of North Sea fisheries and their ecological and socio-economic dynamics are too complex for a single model to emulate, and only a diversity of approaches is capable of providing robust projections.

This complex reality of North Sea fisheries was illustrated and analyzed in the third Chapter, where the emergence of targeted squid fishing in the southern North Sea and the Eastern English Channel served as a case study. Data analysis of international landing statistics revealed a surge in directed squid fishing in the area by numerous nations, namely the Netherlands, France, and the UK. The German mixed demersal fleet is comparatively small in size and was rather unobtrusive in a multinational dataset, but the specific data analysis and field sampling campaign described in the second part of the chapter also highlighted the role that squid fishing plays in German North Sea mixed demersal fisheries. Within just two fishing seasons, squid catches rose to unprecedented values, accounting for 21% of revenue generated by the fleet in 2024 and passing traditional key species like plaice and cod in value. Geospatial statistics

and hot spot analysis revealed distinct clusters of fisheries following a seasonal dynamic in fishing activity, a phenomenon indicating within-season dynamics of squid aggregation. The reason for squid individuals to aggregate in the area is yet to be fully understood, even though onboard sampling provided valuable insights, showing not only a single squid species, *Loligo vulgaris*, to dominate the squid catches, but also indicated feeding dynamics between the squid, whiting, and sandeels. Further research needs to be dedicated to unveiling the details of these ecological interactions, while management needs to focus on a common strategy to safeguard this valuable novel resource in the long term. Given the short life cycle and semelparous nature of squid, such management strategies need to be closely coordinated with scientific experts and utilize novel approaches tailored to dynamic resources like squid.

Such alternative management strategies were the topic of the fourth and final chapter of this thesis, in which community quota schemes and directed support of small-scale fisheries were analyzed, putting emphasis on their potential for integrating fisheries in Blue Growth strategies. Given the stagnating catches and dwindling capacities of many European fishing fleets, the European Union has not identified fisheries as a sector with potential for Blue Growth. It was argued that, given appropriate support measures like community-based quota allocation schemes, targeted funding of small-scale fisheries, and easier access to certification schemes, extensive growth in fisheries is possible. This extensive growth will facilitate adding value to fisheries rooted in coastal communities dependent on them, without putting additional pressure on the ecosystems they depend on.

In its entirety, this thesis offers solutions and pathways to improvement, yet it also clarifies the need for additional research, both ecologically and socio-economically, as well as the need for cooperation, modernization, and flexibilization in European fisheries governance. The North Sea has fed the people living at its shores for generations, and it is the responsibility of fishers, scientists, and managers to safeguard this ecosystem and the riches it has to offer for future generations. Sustainable fisheries are possible, but they can only be facilitated by all involved parties continuously working together, improving with every challenge presented to them.

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Bremerhaven, den 11.12.2025
Unterschrift



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