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Spatial restrictions inadvertently doubled the carbon footprint of Norway's mackerel fishing fleet

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ABSTRACT

The ocean is increasingly used for industry, energy and recreation or protected for conservation, resulting in increasing spatial restrictions for fisheries. Simultaneously, producing seafood with a low climate footprint is becoming increasingly important. Despite this, the effects of spatial restrictions on the emissions of fishing fleets are poorly known. In the Northeast Atlantic, the withdrawal of the United Kingdom from the EU (Brexit) meant that the UK regained autonomy in its Exclusive Economic Zone (EEZ). This suddenly imposed a spatial restriction for several foreign fishing fleets targeting Northeast Atlantic mackerel (*Scomber scombrus)*. Here, we use this natural experiment and open fisheries data to investigate how Brexit affected the performance and emissions of the Norwegian mackerel fishery. As the fleet was excluded from fishing grounds in the UK, the catch per fishing trip almost halved, while the number of trips per vessel doubled. As a result, fuel use intensity (FUI) more than doubled from ~0.08 to ~0.18 L fuel per kg mackerel. We estimate that this shift required an additional 23 million liters of fuel per year, causing additional fuel costs of ~€18 million annually and emitting an additional ~72,000 tonnes CO_2 per year. The policy change undid ~15 years of improved fuel efficiency in Norwegian pelagic fisheries. These findings provide rare empirical evidence on how spatial restrictions can undermine progress towards decreasing greenhouse gas emissions in fisheries, highlighting the need to monitor and account for emissions in fisheries management and consider these trade-offs in marine spatial management.

1. Introduction

Spatial restrictions of capture fisheries are becoming increasingly common, both as a tool for improving fisheries sustainability and as an effect of the intensifying competition for ocean space. Marine protected areas (MPAs) are being implemented as a complementary tool to conventional fisheries management, with a recent target set to 30% MPA cover by 2030 to address overfishing and biodiversity decline [1]. Simultaneously, energy production, mineral mining, and aquaculture are expanding into the ocean, adding to other growing activities like shipping and recreation [2]. Emerging extractive and use interests in the sea are also shaping the evolution of national and international ocean jurisdiction [3]. This race for ocean space means that the potential displacement of fishing from historical fishing grounds is becoming an increasingly important issue (e.g. [4]). Overall, the new spatial arrangements for marine sectors bring yet unknown net effects to the sustainable use of marine space.

While new marine spatial restrictions are emerging, producing nutritious food with low greenhouse gas emissions is a core sustainability challenge. Global demand for seafood is projected to double by 2050 [5], while emissions must reach net zero in 2050 to reach the 1.5 °C target of the Paris Agreement. Marine fisheries emit 180 million tonnes of CO_2 equivalents annually – mainly from their fossil fuel use [6] – but wild-caught seafood can have both low emissions and high nutritional value [7]. Fisheries for small pelagic species are particularly fuel efficient, typically with a carbon footprint of one tenth of other fisheries [6,8,9]. This efficiency is attributable to their high productivity, schooling behavior, and pelagic niche. But since the spatial biology and behavior of a fish stock determine where the fish can be caught most efficiently, spatial restrictions of fishing fleets may limit fisheries from acting optimally [10]. This could have a significant impact on a fishery's performance and in turn on its carbon footprint.

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Despite these growing concerns, empirical studies that demonstrate causal effects of spatial restrictions on fisheries outcomes are scarce [10–12]. Theoretical scenario analyses indeed indicate that spatial management decisions can impact seafood sustainability [13], but controlled experiments at the necessary scale are complicated to perform. In real-world settings, the mobility of species and fishing fleets often make it difficult to isolate cause and effects [11]. In addition, despite the importance of reducing CO_2 emissions, emissions are generally not tracked and regulated in current fisheries management. This hinders evaluating the impact of spatial closures on emissions.

To overcome these challenges and begin to quantify the potential scale of these effects with empirical data, this study makes use of a real-world spatial restriction experiment. The withdrawal of the UK from the European Union, "Brexit", meant that the UK no longer was bound to the access agreements for third countries in the Common Fisheries Policy [14]. Consequently, the Norwegian mackerel fishing fleet lost access to UK waters for the 2021 and 2022 fishing seasons. Northeast Atlantic (NEA) mackerel is a transboundary pelagic stock that supports one of the most important fisheries in the Atlantic, with catches averaging ~1 million tonnes yr^{-1} (~1% of the annual global marine fish catches) in the last decade. Norway and the UK catch the largest shares of about 20% each [15]. The area restrictions imposed under Brexit create a rare opportunity to better understand how spatial restrictions and fishing fleet displacement affects a pelagic fishing fleet. Here, we used openly available sales slip, logbook, and vessel monitoring system (VMS) data (https://www.fiskeridir.no/Tall-og-analyse/AApne-data) to investigate how Brexit influenced the behavior (spatial distribution, gear type) and performance (trip numbers, catch size and quality) of the Norwegian mackerel fleet, and to quantify the effect on the fleet's CO_2 emissions. We also evaluate alternative potential drivers of change.

2. Materials and methods

Open-access logbook, VMS, and sales slip data [16] from 2014 to 2022 were used to assess multiple performance indicators in the Norwegian mackerel fishery. The VMS and logbook data sets were combined to estimate fuel use intensity (FUI; liters of fuel used per kg mackerel landed), while sales slip data was used to calculate other performance indicators (number of trips, catch size, catch month and gear used). Previous studies have used reported fuel consumption data to estimate FUI in Norwegian fisheries [17–19], but such data are not yet available for the two complete years with post-Brexit mackerel regulations to date (2021–2022). Therefore, we estimated FUI from logbook and VMS data in line with the methodology in Sala et al. [20] and Coello et al. [21]. We only included the vessel size group "≥28 m" in the analysis since small vessels that fish along the Norwegian coast are unlikely to be directly impacted by the access restrictions to the UK EEZ, and vessels <28 m catch only <13% of Norwegian mackerel catches (Fig. S1). Performance indicators were aggregated by trip, vessel, year, or period (pre-Brexit = 2014–2020, post-Brexit = 2021–2022) depending on purpose. Data analysis was performed in RStudio (Posit team, 2023). One-sided (larger/smaller) Wilcoxon rank sum tests were used to test differences between years. The code for analyses and the processed data sets are available in the zenodo repository https://doi.org/10.5281/zenodo.8406422.

2.1. Identifying mackerel fishing trips in logbook and VMS data

Logbook information is electronically reported by fishers to the Norwegian Directorate of Fisheries and covers four different types of logbook messages. Departure messages (DEP) report the time and location of departure; detailed catch and activity messages (DCA) report fishing and steaming activity; arrival messages (POR) report time and location of arrival to port; and transshipment messages (TRA) report transshipment of catch. We collected all types of logbook messages and sorted them by message number to identify individual trips. Vessels were identified by their radio call signal. We assumed that each new departure message of a given vessel indicated the beginning of a new trip. For each vessel and year, all consecutive messages after one departure message until the next departure message were assigned the same trip ID.

The time span of each trip (from departure time to last arrival time) in the logbook was used to match a logbook trip with the VMS data, thus removing idle or non-fishing transportation time from the VMS data set. VMS observations that fell just outside of the time span of a trip were included in the analysis if they were closer to the start (or end) time of the trip than to the previous (or subsequent) VMS observation. Logbook trips that had no corresponding VMS observations were excluded from the analysis.

Mackerel trips were then identified using the "main species" (in catch and activity messages) and "target species" (in departure messages) indicators in the logbook. All trips with mackerel as main species in the catch were included, as well as trips that stated mackerel as target species but that caught nothing. Thus, all trips where mackerel was by-catch (minor species) were excluded. Trips undertaken for research purposes were detected and removed from the data set using the "Activity" categories and landing sites from the logbook data, and information about research cruises ([22]; A. Slotte, personal communication 2023). Further details on the number of trips, trip lengths and number of VMS points by trip are shown in Figs. S2, S3, and Table S1, respectively.

2.2. Fuel use intensity

Fuel use intensity was estimated at the trip level by estimating the fuel consumption of each mackerel trip and dividing it by its mackerel catch. We also calculated total annual FUI by summing the fuel consumption of each year and dividing it with the annual mackerel catch. Fuel consumption, FC [g], was estimated using a similar approach as in Sala et al. [20] and Coello et al. [21] and references therein, where FC in a mackerel fishing trip i, is

$$FC_i = \sum_{j_{start,i}}^{j_{end,i}} P_i \times SFC \times LF_{i,j} \times T_{i,j}$$

T is the time span [hours] associated with each VMS position (data row), j, in a trip, and FC was calculated by summing over all positions in a mackerel fishing trip. Engine power of the vessel in that trip, P [kW], was taken from the logbook and VMS data. Specific fuel consumption, SFC, was assumed to be 250 [g kWh^{-1}] for Norway [20]. The load factor LF, which represents the fraction of maximum engine power used, was calculated for each VMS position, j, as

$$LF_{i,j} = \begin{cases} L_{\max} \times \dfrac{\left(\frac{v_{i,j}}{d_i}\right)^3 + \dfrac{L_{\min}}{L_{\max} - L_{\min}}}{1 + \dfrac{L_{\min}}{L_{\max} - L_{\min}}} \\ 0.75 \quad \text{when towing gear} \end{cases}$$

where v is the instantaneous speed of the vessel as given in the VMS data, and $L_{min} = 0.2$ and $L_{max} = 0.9$, respectively, are the minimum load when idling and maximum load assumed when a vessel operates at design speed d [knots]. To reflect the higher fuel consumption when towing gear, LF was set to 0.75 in time intervals when a vessel signalled fishing with any type of trawl [21]. The design speed is calculated from the empirical formula from Sala et al. [20]

$$d_i = 10.4818 + 1.2 \times 10^{-3} P_i - 3.84 \times 10^{-8} P_i^2$$

We used linear interpolation to fill the gaps in the fuel consumption estimates that stemmed from missing instantaneous speeds in the VMS data (< 0.2% of data points).

When estimating the fuel use intensity (FUI; [L kg^{-1}]) of a trip, fuel associated with non-mackerel bycatch was removed by weighting the FC in each trip with the ratio of mackerel catch, $C_{mac,i}$, to total catch, $C_{tot,i}$. Simplifying reduces the calculation as in equation 4. We used the density of marine diesel (MDO; 0.8691 g cm^{-3}) for conversion from mass to volume.

$$FUI_{mac,i} = \frac{FC_{tot,i}\frac{C_{mac,i}}{C_{tot,i}}}{C_{mac,i}} \times \frac{1}{0.8691 \times 1000} = \frac{FC_{tot,i}}{C_{tot,i}} \times \frac{1}{0.8691 \times 1000}$$

For Fig. 1g, we calculated the mean FUI of each vessel in each year (blue or red dots), as well as the median FUI across vessels (open black circles). For calculation of the total annual FUI of mackerel, we similarly summed the fuel consumption of all trips in each year and divided with the total annual catch, resulting in the numbers (pre- and post-Brexit averages) presented as black horizontal lines in Fig. 1g. In total, FUI estimates were made for n = 7206 mackerel trips, comprising between 113 and 124 vessels each year, out of which 52 vessels had FUI estimates in all nine years 2014–2022 (Table S1, Fig. S4).

The estimates of fuel consumption hinge on models, with uncertainty about the true values of SFC, L_{min}, L_{max}, and d. For our purposes, this approach provides a realistic and consistent estimate of FUI that is comparable over the relatively short time span covered. We underline, however, that although the values agree well with the range of FUIs estimated in other studies (Fig. 1g), the FUI estimates in this study are not intended to replace FUI derived from collected and specific fuel consumption data (e.g. [17]; [19]).

2.3. Other performance indicators

Other performance indicators (trip numbers, catch size, catch month, and gear used), were derived from sales slip data 2014–2022. The data set was filtered with equivalent criteria as in the FUI analysis. Here, trips were defined as observations (rows) from the same vessel with identical “Last catch date”, which specified the last fishing day in a trip. Trips targeting mackerel were identified by summing the catch by species in each trip, retaining in the analysis only trips where mackerel made up more than 50% of the total catch. Trips for research purposes were removed (Table S2). The final filtered sales slip data set consisted of n = 5830 mackerel trips. The smaller sample size compared with the FUI sample size is explained mainly by the fact that 1184 of the trips in the VMS and logbook data caught nothing, thus not generating sales slips. The sales slip data set included between 111 and 130 vessels per year (Table S1), with 51 vessels having data from all nine years (Fig. S5). The total annual mackerel catches in the filtered sales slip data set were between 90% and 100% of the annual mackerel catches in the VMS and logbook data depending on the year (Table S1), implying that inferences can be drawn across the data sets.

As an alternative measure, we estimated the catch per unit effort (CPUE; tonnes per day) of each trip from the catch, and trip duration in the logbook data. To calculate CPUE by area, polygons for the Norwegian and British EEZ from the R “terra” package were used in combination with the catch location specified in the logbook.

2.4. Impacts on costs and emissions

To assess the impacts of the increased FUI in the Norwegian mackerel fishery after Brexit, we estimated the additional annual fuel costs and emissions associated with the increased FUI. Additional annual fuel consumption, FC_{add}, was calculated as

$$FC_{add} = \Delta FUI \times C_{mac}$$

Where $\Delta FUI = FUI_{post\text{-}Brexit} - FUI_{pre\text{-}Brexit}$ and C_{mac} is the average annual mackerel catch after Brexit. We assumed a fuel price range of €0.5 - €1.0 L^{-1} [23] to estimate the upper and lower bound of the additional fuel costs, and used a conversion factor of 3.17 from L fuel to kg CO_2 equivalents [24]. For comparison with within-Europe air flights, we assumed a CO_2 emission of 106 kg per return trip between Amsterdam Schiphol and London Heathrow airport [25].

2.5. Testing alternative drivers of fuels use intensity

To infer a causal link to Brexit, we evaluated whether alternative drivers of FUI had recently changed in this fishery. Other studies have found that FUI is lower when fish stock biomass is high (the fish are easy to find and catch) or when the total catches are high (the fishery can operate efficiently) [17,26,27]. FUI has also been found to correlate negatively with fuel price, quota size, and technology level, and positively with fish price [17,26]. We therefore tested the correlation between our total annual FUI and 1) spawning stock biomass of mackerel [15], 2) total annual mackerel catch (from sales slips), 3) the sum of unilateral quotas (there has not been an agreement on total allowable catch since 2008; [15], 4) fuel price [28], and 5) mackerel price (from sales slips), using linear regression. Data on the technology level was lacking but we find it very unlikely that there was a sudden drop in the technology level of the Norwegian mackerel fleet in 2021 and 2022.

3. Results

The Norwegian mackerel fishing fleet clearly shifted its spatial distribution after Brexit. VMS vessel trajectories (colored lines) and mackerel catches (circles) in Fig. 1a-b show how the ocean-going fleet (≥28 m) followed the clockwise migration of mackerel from their foraging areas in the Norwegian Sea, south along the Norwegian coast. While the fleet continued into British waters during September-November in 2014–2020, it never entered the UK’s EEZ due to lack of rights after Brexit (2021–2022). As a result, the fleet fished closer to home and in a smaller area. The few catches shown within the UK zone after Brexit appear there due to the coarse reporting resolution in the sales slip data. Note how the winter fishery north of Scotland in December-January also ceased for Norwegian vessels after Brexit (Fig. 1b, e).

The sales slips reveal how the exclusion from the British EEZ has affected multiple performance indicators for the Norwegian mackerel fleet (Fig. 1c-f; Table S1). The average catch per trip almost halved, from 290 tonnes per trip pre-Brexit to 160 tonnes post-Brexit (Fig. 1c). Concomitantly, the average number of trips per vessel and year approximately doubled from 4 trips to 10 trips per vessel (Fig. 1d). Small catches also made up a larger fraction of the total catch (Fig. 1c; Fig. S6). Together, the increased trip number and reduced catch per trip demonstrate that more effort was required to catch a given amount of mackerel.

The fishing season shifted earlier in the fall after Brexit, with most catches occurring in August-September, compared to September-October as was normal before Brexit (Fig. 1e). Norwegian vessels also prolonged the season, and fished more in November, but stopped fishing north of Scotland in December-January. After Brexit, a larger fraction of the catch was taken with pelagic trawl, instead of purse seine (Fig. 1f). Purse seine requires less engine power but is only efficient when fish are in dense schools, while pelagic trawl requires more engine power but is more efficient when fish are more dispersed [29]. We note that the Norwegian mackerel quota increased substantially in 2021 and 2022 [30,31]. Consequently, the total annual mackerel catch of the Norwegian fleet (≥ 28 m) increased from an average of 170 000 tonnes yr^{-1} before Brexit (2014–2020) to an average of 240 000 tonnes yr^{-1} after Brexit (2021-2022; Table S1).

The lowered performance of the Norwegian mackerel fishery from the sales slip data is mirrored in the fuel use intensity (FUI) estimated from the VMS and logbook data. Total annual FUI approximately doubled from an average of 0.083 L kg^{-1} before, to 0.178 L kg^{-1} after Brexit (Fig. 1g; Table S1). In Fig. S7, the whole range of FUI values is shown together with the average median FUI by vessel (which increased from 0.076 to 0.15 L kg^{-1}). The increase in FUI by vessel was

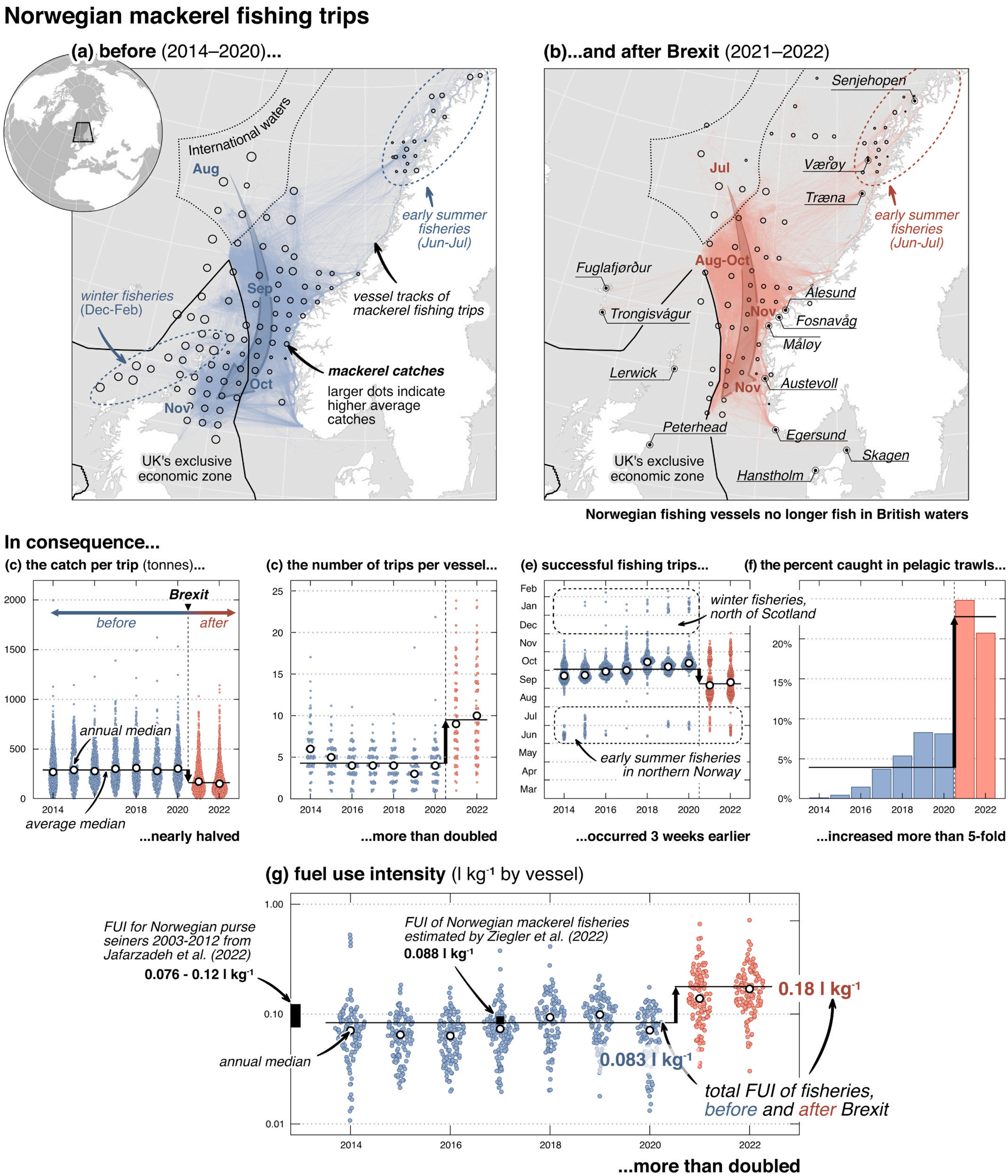

Fig. 1. Changes in the Norwegian Northeast Atlantic mackerel fishery after Brexit spatial closures. Panels at the top show the spatial distribution of Norwegian mackerel fishing in the period (A) before (blue; 2014–2020) and (B) after (red; 2021–2022) Brexit. Colored lines show VMS tracks of mackerel fishing trips. Marker size indicates the average catch per year and grid cell according to sales slips. Large transparent arrows indicate the southward movement of mackerel and the fleet over the main fishing season in autumn. Panels in the middle show the consequences for fisheries performance (from sales slip data); (C) the number of trips per vessel, (D) the average catch per trip, (E), time of the fishing season and (F) the fraction of catch taken with pelagic trawl instead of purse seine. Finally, (G) shows the estimated fuel use intensity by vessel based on the VMS and logbook data. Open black circles show the annual median, and horizontal black lines show the pre- and post-Brexit average of the medians except for in **G**, where the lines denote the total FUI of the fisheries. Note that four outliers are not shown in panel G (see Fig. S7).

statistically significant when comparing year 2021 ($W = 87{,}064$, p-value < 0.0001) and 2022 ($W = 99{,}705$, p-value < 0.0001) with all other years (Table S1). The efficiency in terms of the catch per unit effort (CPUE; here catch per day at sea) also decreased substantially after Brexit. In the Norwegian EEZ, where it is possible to compare CPUE before and after the spatial restriction, the average CPUE decreased by 56% (66% for pelagic trawl, 55% for encircling nets; Fig. S8).

The increase in FUI has incurred additional monetary costs and CO_2 emissions in the Norwegian mackerel fishery post-Brexit. As the increase in fuel use intensity, ΔFUI, is 0.094 L kg^{-1} and the Norwegian mackerel catch of vessels ≥28 m, C_{mac}, has been on average 240 000 tonnes yr^{-1} in the post-Brexit period, the additional fuel required due to Brexit was ~23 million liters annually. This amounts to between €12 to €23 million in additional fuel costs per year (see Methods). We underline that additional operating costs, including labor and increased maintenance and depreciation as the fleet spent more time at sea (Table S1) are not considered here. The additional fuel consumption in the two years after Brexit generated additional emissions of ~72 000 tonnes CO_2 yr^{-1} from the studied fleet. Since the annual mackerel catch increased significantly after Brexit, the total annual fuel consumption and emissions tripled (Table S1).

Alternative drivers beyond the shift in spatial distribution were unable to explain the sudden increase in FUI in 2021 and 2022. While the post-Brexit years did coincide with low spawning stock biomass of NEA mackerel, the biomass was even lower in 2020, and there was no statistically significant correlation between our annual FUI and spawning stock biomass (Fig. S9a) or total allowable catch (Fig. S9b). Contrary to expectations, there was a weakly significant and positive correlation between FUI and total mackerel catch (Fig. S9c), but this positive relationship became insignificant when removing the two post-Brexit years. For all three variables the two post-Brexit years deviate from the general trends (Fig. S9). Fuel prices have been *higher* than normal in the autumns of 2021–2022 [28] which normally should incentivize fuel efficiency, and the price of mackerel in 2021 was normal compared with previous years (Fig. S10). The COVID-19 pandemic did not have a negative impact on Norway's pelagic fisheries and would have had the largest impacts in 2020–2021 [32]. Altogether, this implies that other known drivers suggested by the literature (e.g. [26]; [33]; [34]) are unlikely to have caused the marked increase in FUI shown here and leaves Brexit as the most plausible explanation.

4. Discussion

We identified a marked shift in the performance of the Norwegian mackerel fishing fleet since Brexit and the resultant new spatial arrangements. The large impact on the fleet's fuel use is best explained by the shift in fished area and the biology of the Northeast Atlantic mackerel stock. The stock spends different parts of its life cycle across the NEA [35–38], but after tracking the spring bloom and peak abundance of zooplankton in the north [37,39], the mackerel migrate south along the Norwegian coast. From August onwards, the mackerel gather in larger groups off the Norwegian coast before they migrate to the wintering areas east of Shetland [40], where the greatest catches have been taken historically [41]. Fishers report that mackerel were abundant in large schools in Norwegian waters up to 2018, after which the fish has become more dispersed (Roald Oen, personal communication, November 2023). Consequently, Norwegian fishers have shifted their effort to the British EEZ, harvesting much of their quota by efficient purse seine on these dense schools in British waters (see Fig. S8 and S11). When the access to the British EEZ was revoked in 2021, these Norwegian vessels were displaced to fish on less dense aggregations. This explains why the fleet had smaller catches per trip after Brexit, used pelagic trawl more often, compensated with more fishing trips, and started the fishing season earlier when the mackerel were still within the Norwegian EEZ. The impact was large enough that the fleet's fuel efficiency declined despite that fishing activities took place closer to home ports after Brexit.

Our analysis demonstrates effects of fishing displacement that are highly relevant for evaluating trade-offs in marine spatial planning. The study offers a rare empirical complement to the largely model-based literature on displacement effects on fishing fleets [10], and highlights some counterintuitive principles. It demonstrates that shorter distance to fishing grounds does not necessarily result in lowered fuel use intensity, a finding also supported by Ziegler et al. [42]. It further suggests that policies that aim to reduce the efficiency of fishing fleets for the sake of protecting the stock can have unwanted side effects in the shape of increased emissions. Climate-driven range shifts (e.g. [43]) are likely to interact with these principles. For example, if a country's fleet is prevented from following a poleward shifting fish stock, but retains a share of the quota, similar mechanisms as the ones demonstrated here may cause increased emissions. The shifts in the high-density mackerel areas, as noted by the Norwegian fishers, illustrate this issue.

It is important however to consider the context of the study when generalizing the findings. The Norwegian mackerel fishery targets a migratory stock and has a high-capacity fleet with high operating margins [44]. This makes it both possible and feasible for the fleet to catch a large amount of fish even when it is excluded from the best fishing grounds. In addition, the quota system and incomplete transboundary management of the NEA mackerel fishery likely makes this fleet's behavior economically rational. An international agreement on how to allocate the advised mackerel quota between countries is lacking, and quota allocation generally accounts for the recent distribution of catches and indicators of regional abundance [45]. This makes it strategically beneficial for Norwegian mackerel fishers to catch the quota (or more) in Norwegian waters, and may explain why the fleet's behavior does not seem to match simple bio-economic predictions [46].

The increase in fuel use intensity (FUI) due to Brexit is strikingly large in relation to previously measured changes, and has likely had economic consequences beyond those included in our analysis. Fisheries management often has diffuse effects on fuel use that are difficult to quantify. The increase in FUI after Brexit, however, was almost twice as large as the observed progressive reduction in FUI for Norwegian purse seiners between 2003 and 2012 (−0.05 L kg^{-1}; [17]), suggesting that Brexit undid the equivalent of ~15 years of progress towards lower fuel use intensity. In further comparison, Kristofersson et al. [26] found a 30–40% reduction in the FUI of Icelandic demersal fisheries over 20 years, and Jafarzadeh et al. [17] a 30% reduction in the FUI of Norwegian factory trawlers over 10 years. Given that labor costs and fuel generally make up the largest shares of variable costs in European fisheries, followed by running and repair costs [47], our estimated €12 to €23 million in additional annual fuel expenses likely cover only a fraction of the total additional expenses. We note that Norwegian purse seiners and pelagic trawlers experienced a drop in operating margin in 2021 [48], signaling reduced profitability in fleet segments that targeted mackerel in the first post-Brexit year.

This analysis has focused on Norwegian fisheries, which take ~20% of the total NEA mackerel catch. To understand whether Brexit has had a negative effect on the FUI of the whole NEA mackerel fishery, perspectives from other nations are necessary. In the Faroe Islands, the mackerel caught per unit fuel was greatly reduced from 2019 to 2021–2022, following a similar restriction in access to fishing grounds [49]. Yet in the Scottish mackerel fisheries, shorter steaming times and improved flexibility to follow mackerel migrations have been noted after Brexit, thanks to the removal of a requirement for Scottish fishers to catch 40% of their quota west of 4° (Ian Gatt and Steve Mackinson 2023, personal communication). This further highlights the impact of spatial restrictions and has likely reduced FUI in UK fleet, potentially mitigating some of the additional emissions in the Norwegian and Faroese mackerel fisheries but through a different and not mutually exclusive mechanism. We note however that this additional change in spatial fisheries restrictions after Brexit may make it difficult to quantify how the exclusion of foreign mackerel vessels from the British EEZ impacted the fuel efficiency of the British mackerel fleet.

We underline that our method for estimating FUI (VMS-based FUI) is different from using directly reported fuel use. Our pre-Brexit estimates of FUI are, however, in line with earlier estimates of FUI based on reported fuel use for Norwegian mackerel fishing in 2017 (Ziegler et al. [19], black square in Fig. 1g) and Norwegian purse seining 2003–2012 (Jafarzadeh et al. [17], black square along *y*-axis in Fig. 1g). Yet an evaluation of whether VMS-based FUI estimates can replace the reported fuel use for analyzing Norwegian fisheries is still needed, and we caution readers from using the FUI values obtained here in further analyses without considering the differences in methodology and scope. Since this study focuses on relative changes, we are confident that the difference in VMS-based FUI can be used for estimation of cost and emission changes. An alternative approach would be to apply the relative change in VMS-based FUI to a representative, directly reported pre-Brexit FUI value. The relevant pre-Brexit FUI data are limited to one observation for Norwegian mackerel in year 2017 [19], but using that value (0.088 L kg^{-1}) instead of our modeled pre-Brexit average (0.083 L kg^{-1}) would yield very similar results.

These findings demonstrate that political and spatial management decisions (or lack thereof) can greatly undermine the carbon efficiency of a fishery, highlighting the importance of including low emissions as an explicit management objective. While effective fisheries management may indirectly promote low FUI by increasing stock abundance [26,34], the ways by which management decisions can directly impact emissions are more rarely discussed (but see e.g., [13]; [50]). Quota shares and access agreements for internationally shared marine resources are contentious political issues, but when decision-makers try to solve them, minimizing greenhouse gas emissions need to become one of the management objectives. For this, it will be necessary to systematically and routinely quantify these emissions from fisheries, and model the impact of different management decisions (see e.g. [51]). Fuel use data from fisheries is collected e.g. in EU fisheries through the Data Collection Framework but is not available for research at a high level of detail due to confidentiality and/or reported with a significant delay (years) [27], while VMS and logbook data are more readily available. Therefore, we believe that the VMS-based approach used here shows promise for making real-time estimates of fuel use, and to monitor variability, shifts, and irregularities. If applied broadly, additional climate consequences of other regulations can hopefully be detected and rectified.

This analysis shows that the international political context can have a substantial impact on the emissions of a fishery. Despite its small contribution to the UK economy, a key issue in the Brexit campaign was “taking back control” of British waters [52], and for NEA mackerel, there has been an international conflict about quota allocations since 2008 [53]. This history of disagreement can explain the political trajectory that led UK to revoke the access rights for mackerel fishing, but the impact of access rights for fuel use has likely been overlooked. In a systems perspective, the additional 72,000 tonnes of CO_2 that were emitted annually in Norway’s mackerel fishery after Brexit exemplify an emission leverage point; a place in the system where a small change of rules leads to large changes [54]. More such leverage points in fisheries management systems surely remain to be identified. In this case, the emission cuts from restoring a bureaucratic regulation about fishing access must be easier (and fairer) for governments to achieve than, for example, persuading citizens to cut half a million within-Europe flights each year, or preventing ~46,000 people from increasing their living standard from a low-income to a lower-middle income category (and thus get daily access to electricity; [55]). Indeed the UK and Norway reached a bilateral agreement in time for the 2023 mackerel season, granting Norwegian fishers again access to the autumn fishing grounds in the British waters. That governments that are signatories to the Paris agreement avoid squandering emissions is especially important at a time when there is an urgent need to inspire climate action across society.

CRediT authorship contribution statement

Kim J.N. Scherrer: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Tom J. Langbehn:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Software, Visualization, Writing – review & editing. **Ljungstrom Gabriella Ljungström:** Conceptualization, Funding acquisition, Writing – review & editing. **Katja Enberg:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Sara Hornborg:** Funding acquisition, Methodology, Writing – review & editing. **Gjert Dingsør:** Investigation, Methodology, Writing – review & editing. **Christian Jørgensen:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Visualization, Writing – review & editing.

Declaration of Competing Interest

Gjert Dingsør is employed at Fiskebåt, an interest group and employers’ organization for the Norwegian ocean-going fishing fleet. GD has helped align the methods and quantification with the practicalities of the mackerel fishery (including temporal development), pointed to openly available data sources, has commented on but not written the manuscript, and has not influenced results or conclusions. The other authors declare no competing interests.

Data availability

The dataset produced and used in this study, as well as the R-code used for analysis and visualization, is provided in the online repository https://doi.org/10.5281/zenodo.8406422.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2024.106014.

References

[1] UN environment programme, & CBD, 2022. Decision 15/4. Kunming-Montreal Global Biodiversity Framework. https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf.

[2] J.-B. Jouffray, R. Blasiak, A.V. Norström, H. Österblom, M. Nyström, The blue acceleration: the trajectory of human expansion into the ocean, One Earth 2 (1) (2020) 43–54, https://doi.org/10.1016/j.oneear.2019.12.016.

[3] S. Ranganathan, Ocean floor grab: international law and the making of an extractive imaginary, Eur. J. Int. Law 30 (2) (2019) 573–600, https://doi.org/10.1093/ejil/chz027.

[4] Scottish Government, 2022. Assessing fisheries displacement by other licensed marine activities: Good practice guidance—Literature review (A303088-S00-REPT-001-A02). Marine Scotland Science. ⟨http://www.gov.scot/publications/good-practice-guidance-assessing-fisheries-displacement-licensed-marine-activities-literature-review/pages/3/⟩.

[5] R.L. Naylor, A. Kishore, U.R. Sumaila, I. Issifu, B.P. Hunter, B. Belton, S.R. Bush, L. Cao, S. Gelcich, J.A. Gephart, C.D. Golden, M. Jonell, J.Z. Koehn, D.C. Little, S. H. Thilsted, M. Tigchelaar, B. Crona, Blue food demand across geographic and temporal scales, Nat. Commun. (2021) 1, https://doi.org/10.1038/s41467-021-25516-4.

[6] R.W.R. Parker, J.L. Blanchard, C. Gardner, B.S. Green, K. Hartmann, P. H. Tyedmers, R.A. Watson, Fuel use and greenhouse gas emissions of world fisheries, Nat. Clim. Change 8 (4) (2018) 333–337, https://doi.org/10.1038/s41558-018-0117-x.

[7] J.Z. Koehn, E.H. Allison, C.D. Golden, R. Hilborn, The role of seafood in sustainable diets, Environ. Res. Lett. 17 (3) (2022) 035003, https://doi.org/10.1088/1748-9326/ac3954.

[8] J.A. Gephart, P.J.G. Henriksson, R.W.R. Parker, A. Shepon, K.D. Gorospe, K. Bergman, G. Eshel, C.D. Golden, B.S. Halpern, S. Hornborg, M. Jonell,

M. Metian, K. Mifflin, R. Newton, P. Tyedmers, W. Zhang, F. Ziegler, M. Troell, Environmental performance of blue foods, Nature (2021) 7876, https://doi.org/10.1038/s41586-021-03889-2.

[9] R. Hilborn, J. Banobi, S.J. Hall, T. Pucylowski, T.E. Walsworth, The environmental cost of animal source foods, Front. Ecol. Environ. 16 (6) (2018) 329–335, https://doi.org/10.1002/fee.1822.

[10] M.N. Reimer, A.C. Haynie, Mechanisms matter for evaluating the economic impacts of marine reserves, J. Environ. Econ. Manag. 88 (2018) 427–446, https://doi.org/10.1016/j.jeem.2018.01.009.

[11] P.J. Ferraro, J.N. Sanchirico, M.D. Smith, Causal inference in coupled human and natural systems, Proc. Natl. Acad. Sci. 116 (12) (2019) 5311–5318, https://doi.org/10.1073/pnas.1805563115.

[12] D. Ovando, J.E. Caselle, C. Costello, O. Deschenes, S.D. Gaines, R. Hilborn, O. Liu, Assessing the population-level conservation effects of marine protected areas, Conserv. Biol. 35 (6) (2021) 1861–1870, https://doi.org/10.1111/cobi.13782.

[13] A. Farmery, C. Gardner, B.S. Green, S. Jennings, Managing fisheries for environmental performance: the effects of marine resource decision-making on the footprint of seafood, J. Clean. Prod. 64 (2014) 368–376, https://doi.org/10.1016/j.jclepro.2013.10.016.

[14] Bjørndal, T., & Munro, G.R., 2020. Brexit and the consequences for fisheries management in the North Sea. Centre for Applied Research at NHH Bergen, Norway. ⟨https://snf.no/media/ufrd1qql/a03_20_-2.pdf⟩.

[15] ICES, Mackerel (Scomber scombrus) in subareas 1–8 and 14, and in Division 9.a (Northeast Atlantic and adjacent waters), ICES Advice Recurr. Advice (2022), https://doi.org/10.17895/ices.advice.19772392.v1.

[16] Norwegian Directorate of Fisheries, 2023a. Åpne data. Fiskeridirektoratet. ⟨https://www.fiskeridir.no/Tall-og-analyse/AApne-data⟩.

[17] S. Jafarzadeh, H. Ellingsen, S.A. Aanondsen, Energy efficiency of Norwegian fisheries from 2003 to 2012, J. Clean. Prod. 112 (2016) 3616–3630, https://doi.org/10.1016/j.jclepro.2015.06.114.

[18] E.M. Schau, H. Ellingsen, A. Endal, S.Aa Aanondsen, Energy consumption in the Norwegian fisheries, J. Clean. Prod. 17 (3) (2009) 325–334, https://doi.org/10.1016/j.jclepro.2008.08.015.

[19] F. Ziegler, S. Jafarzadeh, E. Skontorp Hognes, U. Winther, Greenhouse gas emissions of Norwegian seafoods: from comprehensive to simplified assessment, J. Ind. Ecol. 26 (6) (2022) 1908–1919, https://doi.org/10.1111/jiec.13150.

[20] E. Sala, J. Mayorga, C. Costello, D. Kroodsma, M.L.D. Palomares, D. Pauly, U. R. Sumaila, D. Zeller, The economics of fishing the high seas, Sci. Adv. 4 (6) (2018) eaat2504, https://doi.org/10.1126/sciadv.aat2504.

[21] J. Coello, I. Williams, D.A. Hudson, S. Kemp, An AIS-based approach to calculate atmospheric emissions from the UK fishing fleet, Atmos. Environ. 114 (2015) 1–7, https://doi.org/10.1016/j.atmosenv.2015.05.011.

[22] Nøttestad, L., Høines, Å., Stenevik, E., Diaz, J., Tonheim, S., Salthaug, A., Ólafsdóttir, A., Kennedy, J., Jacobsen, J., Smith, L., Eliasen, S.K., Jansen, T., Post, S., Sethsen, J., & Wieland, K., 2022. International Ecosystem Summer Survey in Nordic Seas cruise report 2022.

[23] Hafsås, K.O. 2022. Prisene halverer driftsmarginene i fiskeflåten [Nett.no]. https://nett.no/synspunkt/prisene-halverer-driftsmarginene-i-fiskefl%C3%A5ten.

[24] Statistics Norway, 2017. Emission factors used in the estimations of emissions from combustion. https://www.ssb.no/_attachment/291696/.

[25] The Guardian, 2019. Carbon calculator: Find out how much CO2 your flight will emit. The Guardian. https://www.theguardian.com/travel/2019/jul/31/carbon-calculator-find-out-how-much-co2-your-flight-will-emit.

[26] D. Kristofersson, S. Gunnlaugsson, H. Valtysson, Factors affecting greenhouse gas emissions in fisheries: evidence from Iceland's demersal fisheries, ICES J. Mar. Sci. 78 (7) (2021) 2385–2394, https://doi.org/10.1093/icesjms/fsab109.

[27] F. Ziegler, S. Hornborg, Stock size matters more than vessel size: the fuel efficiency of Swedish demersal trawl fisheries 2002–2010, Mar. Policy 44 (2014) 72–81, https://doi.org/10.1016/j.marpol.2013.06.015.

[28] SSB, 2023. 09654: Prices on engine fuel (NOK per litres) 1986M08 - 2023M01. Statbank Norway. SSB. https://www.ssb.no/en/system/.

[29] R.W.R. Parker, P.H. Tyedmers, Fuel consumption of global fishing fleets: current understanding and knowledge gaps, Fish Fish 16 (4) (2015) 684–696, https://doi.org/10.1111/faf.12087.

[30] Naerings- og fiskeridepartementet, 2022. Norge fastsetter endelig makrellkvote for 2022 på 278 222 tonn [Pressemelding]. Regjeringen.no; regjeringen.no. https://www.regjeringen.no/no/aktuelt/norge-fastsetter-endelig-makrellkvote-for-2022-pa-278222-tonn/id2920278/.

[31] Regjeringen, 2022. Meld. St. 8 (2021–2022) [Stortingsmelding]. Regjeringa.no; regjeringen.no. https://www.regjeringen.no/nn/dokumenter/meld.-st.-8-20212022/id2903591/.

[32] Bertheussen, B.A. 2022. Robuste sjømatinntekter også under COVID-19 pandemien (1891–0998/32:1–2022/1–13; Økonomisk fiskeriforskning). Nofima AS. ⟨https://okonomiskfiskeriforskning.no/wp-content/uploads/sites/4/2022/05/Robuste-sjomatinntekter-ogsa-under-COVID.pdf⟩.

[33] S. Hornborg, A.D.M. Smith, Fisheries for the future: greenhouse gas emission consequences of different fishery reference points, ICES J. Mar. Sci. 77 (5) (2020) 1666–1671, https://doi.org/10.1093/icesjms/fsaa077.

[34] S. Waldo, F. Jensen, M. Nielsen, H. Ellefsen, J. Hallgrimsson, C. Hammarlund, Ø. Hermansen, J. Isaksen, Regulating multiple externalities: the case of Nordic fisheries, Mar. Resour. Econ. 31 (2) (2016) 233–257, https://doi.org/10.1086/685286.

[35] O.S. Astthorsson, H. Valdimarsson, A. Gudmundsdottir, G.J. Óskarsson, Climate-related variations in the occurrence and distribution of mackerel (Scomber scombrus) in Icelandic waters, ICES J. Mar. Sci. 69 (7) (2012) 1289–1297, https://doi.org/10.1093/icesjms/fss084.

[36] T. Brunel, C.J.G. van Damme, M. Samson, M. Dickey-Collas, Quantifying the influence of geography and environment on the northeast Atlantic mackerel spawning distribution, Fish. Oceanogr. 27 (2) (2018) 159–173, https://doi.org/10.1111/fog.12242.

[37] N. Nikolioudakis, H.J. Skaug, A.H. Olafsdottir, T. Jansen, J.A. Jacobsen, K. Enberg, Drivers of the summer-distribution of Northeast Atlantic mackerel (Scomber scombrus) in the Nordic Seas from 2011 to 2017; a Bayesian hierarchical modelling approach, ICES J. Mar. Sci. 76 (2) (2019) 530–548, https://doi.org/10.1093/icesjms/fsy085.

[38] A.H. Olafsdottir, A. Slotte, J.A. Jacobsen, G.J. Oskarsson, K.R. Utne, L. Nøttestad, Changes in weight-at-length and size-at-age of mature Northeast Atlantic mackerel (Scomber scombrus) from 1984 to 2013: effects of mackerel stock size and herring (Clupea harengus) stock size, ICES J. Mar. Sci. 73 (4) (2016) 1255–1265, https://doi.org/10.1093/icesjms/fsv142.

[39] T. Jansen, S. Post, T. Kristiansen, G.J. Óskarsson, J. Boje, B.R. MacKenzie, M. Broberg, H. Siegstad, Ocean warming expands habitat of a rich natural resource and benefits a national economy, Ecol. Appl. 26 (7) (2016) 2021–2032, https://doi.org/10.1002/eap.1384.

[40] T. Jansen, A. Campbell, C. Kelly, H. Hátún, M.R. Payne, Migration and fisheries of North East Atlantic Mackerel (Scomber scombrus) in autumn and winter, PLoS One 7 (12) (2012) e51541, https://doi.org/10.1371/journal.pone.0051541.

[41] K. Ono, A. Slotte, S. Hølleland, S. Mackinson, S. Þ Jónsson, J.A. Jacobsen, A. H. Ólafsdóttir, Space-time recapture dynamics of PIT-tagged Northeast Atlantic mackerel (Scomber scombrus) reveal size-dependent migratory behaviour, Front. Mar. Sci. 9 (2022). ⟨https://www.frontiersin.org/articles/10.3389/fmars.2022.983962⟩.

[42] F. Ziegler, E.A. Groen, S. Hornborg, E.A.M. Bokkers, K.M. Karlsen, I.J.M. de Boer, Assessing broad life cycle impacts of daily onboard decision-making, annual strategic planning, and fisheries management in a northeast Atlantic trawl fishery, Int. J. Life Cycle Assess. 23 (7) (2018) 1357–1367, https://doi.org/10.1007/s11367-015-0898-3.

[43] J. Palacios-Abrantes, T.L. Frölicher, G. Reygondeau, U.R. Sumaila, A. Tagliabue, C. C.C. Wabnitz, W.W.L. Cheung, Timing and magnitude of climate-driven range shifts in transboundary fish stocks challenge their management, Glob. Change Biol. 28 (7) (2022) 2312–2326, https://doi.org/10.1111/gcb.16058.

[44] Fiskeridirektoratet. 2022. Redusert lønnsomhet for fiskeflåten. Fiskeridirektoratet. https://www.fiskeridir.no/Yrkesfiske/Nyheter/2022/redusert-lonnsomhet-for-fiskeflaten.

[45] P. Gullestad, S. Sundby, O.S. Kjesbu, Management of transboundary and straddling fish stocks in the Northeast Atlantic in view of climate-induced shifts in spatial distribution, Fish Fish 21 (5) (2020) 1008–1026, https://doi.org/10.1111/faf.12485.

[46] H.S. Gordon, The economic theory of a common-property resource: the fishery, J. Political Econ. 62 (2) (1954) 124–142.

[47] V.W.Y. Lam, U.R. Sumaila, A. Dyck, D. Pauly, R. Watson, Construction and first applications of a global cost of fishing database, ICES J. Mar. Sci. 68 (9) (2011) 1996–2004, https://doi.org/10.1093/icesjms/fsr121.

[48] Norwegian Directorate of Fisheries, 2023b. Lønnsomhetsundersøkelse for fiskeflåten—Tidsserier. Fiskeridirektoratet. ⟨https://www.fiskeridir.no/Yrkesfiske/Tall-og-analyse/Loennsomhet/Tidsserier⟩.

[49] Sjókovin Blue Resource, 2023. Ársfrágreiðing Sjókovans 2022. https://www.sjokovin.fo/fiskivinnan2022.

[50] J. Driscoll, P. Tyedmers, Fuel use and greenhouse gas emission implications of fisheries management: the case of the new england atlantic herring fishery, Mar. Policy 34 (3) (2010) 353–359, https://doi.org/10.1016/j.marpol.2009.08.005.

[51] F. Bastardie, J.R. Nielsen, T. Miethe, DISPLACE: a dynamic, individual-based model for spatial fishing planning and effort displacement — integrating underlying fish population models, Can. J. Fish. Aquat. Sci. 71 (3) (2014) 366–386, https://doi.org/10.1139/cjfas-2013-0126.

[52] Has the Brexit fishing promise come true? 2023. BBC News. https://www.bbc.com/news/64430216.

[53] T. Gray, Normative theory of international relations and the 'mackerel war' in the North East Atlantic, Mar. Policy 131 (2021) 104620, https://doi.org/10.1016/j.marpol.2021.104620.

[54] Meadows, D., 1999. Leverage points—places to intervene in a system. The Sustainability Institute.⟨https://donellameadows.org/wp-content/userfiles/Leverage_Points.pdf⟩.

[55] Ritchie, H., Roser, M., & Rosado, P. 2020. CO_2 and Greenhouse Gas Emissions. Our World in Data. https://ourworldindata.org/co2-and-greenhouse-gas-emissions.