Exploring Changes in Fishery Emissions and Organic Carbon Impacts Associated With a Recovering Stock

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International objectives for sustainable development and biodiversity conservation require restoring fish populations to healthy levels and reducing fishing impacts on marine ecosystems. At the same time, governments, retailers, and consumers are increasingly motivated to reduce the carbon footprint of food. These concerns are reflected in measures of the EU Common Fisheries Policy (CFP) and the CFP Reform Regulation, which highlighted a need to move from traditional single-stock management toward an ecosystem approach to fisheries management (EAF). Using publicly available landings and effort data combined with estimates of adult population biomass, we develop methods to explore the potential for lowering emissions intensity and impacts on organic carbon stocks through ending overfishing and rebuilding stocks. We use the recent recovery of European hake (*Merluccius merluccius*) stocks in the Northeast Atlantic as a case study. With a focus on the hake fisheries of France, Spain, and the United Kingdom, we compare 2008 and 2016 fishing years. We make an initial estimate of the influence of changing stock status on greenhouse gas emissions during the fishery phase from fuel use and investigate the potential disturbance of organic carbon in the ecosystem, specifically via identification of bottom trawling overlap with organic-rich muddy sediments, and directly on storage in hake biomass. Our findings indicate that recovery of the hake stock was associated with reductions in overall emissions intensity from fuel and proportional impact on hake populations, however, total emissions from both fuel and landings increased, as did likely disturbance of sedimentary organic carbon in surface sediments due to benthic trawling. Ultimately, the aims of this analysis are to further explore the climate impacts of fisheries and overfishing, and to inform development of EAF in the EU.

Keywords: fisheries, carbon emissions, hake (*Merluccius merluccius*), stock recovery, sedimentary organic carbon, sustainable fisheries, ecosystem based management (EBM), ecosystem based approach for fisheries management

INTRODUCTION

Unsustainable resource extraction, biodiversity loss, and climate change threaten the health and longevity of marine ecosystems and fish populations worldwide (IPBES, 2019). Reducing greenhouse gas emissions (GHGs) is essential for reducing the ecological and social impacts of climate change and remains an international priority (United Nations General Assembly resolution [UNFCCC], 2015). Simultaneously, restoring fish populations and marine ecosystems to achieve healthy oceans are cited as international objectives for sustainable development (United Nations General Assembly resolution [UNFCCC], 2015) and conservation of biodiversity (Convention on Biological Diversity, 2021). In the European Union (EU), these objectives are reflected in measures outlined by the Common Fisheries Policy (CFP) (European Union [EU], 2013). The latter reform of the CFP proposed a new framework to manage European fisheries, and amongst several new initiatives, it highlighted a need to move from traditional single-stock management towards an ecosystem approach to fisheries management (EAF) (Prellezo and Curtin, 2015). The CFP Reform Regulation defines the EAF as "... an integrated approach to managing fisheries within ecologically meaningful boundaries which seeks to manage the use of natural resources, taking account of fishing and other human activities, while preserving both the biological wealth and the biological processes necessary to safeguard the composition, structure and functioning of the habitats of the ecosystem affected, by taking into account the knowledge and uncertainties regarding biotic, abiotic and human components of ecosystems" (European Union [EU], 2013).

Ecosystem approach to fisheries management prioritises the wellbeing of ecosystems over economic and social objectives since ecosystem wellbeing is considered a prerequisite for the latter two objectives (Murawski et al., 2008; Baudron et al., 2019). While the current CFP advocates for the implementation of some form of EAF, it remains largely unclear how to include conservation objectives within fisheries management measures in practice. The CFP aims to fish at levels consistent with achieving Maximum Sustainable Yield (MSY) for all exploited stocks (European Union [EU], 2013), an approach which does not necessarily account for impacts on the ecosystem (Ulrich et al., 2017). In Northern European waters, these fishing levels are proposed by the EU's International Council for the Exploration of the Sea (ICES) which delivers scientific advice for the management of northern European fish stocks. This advice provides biological reference points for commercial stocks, including the level of fishing mortality (F) needed to achieve MSY (F_{MSY}). According to the latest Scientific, Technical and Economic Committee for Fisheries (STECF) CFP monitoring report, stock status of the NE Atlantic (both EU and non-EU waters) has significantly improved since 2003, although many stocks remain overexploited (STECF, 2020a). Among the stocks which are fully assessed, the proportion of those that are overexploited decreased from around 75% to close to 40% over the last ten years. This trend is promising, however, in 2019, the proportion of overexploited stocks (i.e., $F > F_{MSY}$) for which there are data increased slightly (STECF, 2020a).

Regarding the climate impacts of EU fisheries, many national governments, retailers, and consumers are increasingly motivated to reduce greenhouse gas emissions (GHGs) associated with food production, including fisheries, as a form of climate change mitigation (Iribarren et al., 2010). When considering direct emissions, such as fuel use, trawl fisheries are known to produce, on average, more GHGs per kilogram of catch than virtually any other fishing gear (Tilman and Clark, 2014). The carbon footprint of seafood landed using trawl nets may be similar to, and in some cases exceeds, the footprint of terrestrial staples such as poultry or pork (Tilman and Clark, 2014; Hilborn et al., 2018). Trawl fisheries are also known to have negative effects on the marine environment via significant alterations to abiotic and biogenic structure (Chuenpagdee et al., 2003). Evidence from vessel Automatic Information Systems (AIS) data suggests that the continental shelf surrounding the EU is among the world's most trawled, although the Celtic and Greater North Seas are slightly less impacted than the waters west of Iberia and within the Mediterranean (Amoroso et al., 2018a).

In addition to direct emissions, fishing activity can affect organic carbon (OC) stocks in the marine environment, with implications for both climate and ecosystem function. One such stock is held in marine sediments, which store substantial amounts of carbon (Atwood et al., 2020; Legge et al., 2020), the active burial of which provides a climate regulation service over thousand-year timescales (Berner, 2003). Where trawling gear interacts with marine sediments, it can introduce oxygen into sub-surface sediment layers, increasing the potential loss of buried carbon through aerobic remineralisation (Aller, 1994; Hulthe et al., 1998). Sediment type is an important factor in the storage of sedimentary OC (Diesing et al., 2017; Smeaton et al., 2021), where OC is largely controlled by the proportion of clay or mud (Hedges and Keil, 1995). Trawling has a larger physical impact on muddy-sediment environments in terms of resuspension, causing significantly higher volumes of OC to be resuspended compared to sandy-bottom environments (O'Neill and Summerbell, 2011), with implications for both carbon flux and the resilience of local biodiversity (Pusceddu et al., 2014; Paradis et al., 2017). There is currently a lack of comprehensive evidence to fully demonstrate the effects of trawling on sedimentary OC stocks, but one likely outcome of regular trawling is prevention of sediment settling processes and, in turn, localised carbon sequestration (Epstein et al., 2022 PREPRINT; Oberle et al., 2016). Furthermore, using the definition outlined in Scheffold and Hense (2020), fish populations are living pools containing stocks of OC. In addition to affecting OC stocks in sediments, by removing fish biomass, fishing activity may prevent OC from sinking in the form of fish carcasses and facilitate conversion of OC in biomass to atmospheric CO_2 (Mariani et al., 2020).

In this study, we make a first attempt at combining an established approach for estimating the fuel use of a specific fishery, with novel insights into the additional perturbation of OC stocks caused by fishing. We use landings and effort data associated with the Northern and Southern stocks of European hake (*Merluccius merluccius*) from 2008 and 2016, which enables a comparison of fishing emissions and OC impacts of the fishery

when the Northern stock was depleted (2008) and subsequently rebuilt (2016) (ICES, 2021a). The Northern stock of European hake (hereafter "hake") encompasses those populations living within the Greater North Sea, Celtic Seas, and the northern Bay of Biscay, while the Southern stock consists of those populations living in the southern Bay of Biscay and Iberian Coast (**Figure 1**). The combined range for Northern and Southern hake stocks is provided by ICES in terms of the following subareas and divisions: Subarea 4, 6, 7, Divisions 3.a, 8.a-d, 9.a (ICES, 2021a,b).

Hake are predatory, demersal fish, usually found at depths of 75–400 m, above muddy or sandy sediments (Lloris et al., 2005; Froese and Pauly, 2021). The Northern and Southern hake stocks may not be two distinct populations biologically but nevertheless are assessed separately for the purpose of fisheries management (Milano et al., 2014). The Northern stock is managed using the MSY approach and as such, the spawning stock biomass (SSB) is estimated during assessment of stock status by ICES. Conversely, the Southern stock is managed under the precautionary principle and SSB is not estimated. The Northern stock was overfished from at least the 1990s to the late 2000s (Murua, 2010; Villasante et al., 2011); on multiple occasions during this time, fishing mortality (F) substantially exceeded the agreed landings target (ICES, 2021a,b). However, in 2004, a recovery plan for hake was introduced which required a 70% reduction in F. Subsequently, the SSB of the Northern stock increased substantially, likely due to the reduced fishing pressure (Baudron and Fernandes, 2014). Between 2008 and 2016, SSB of the Northern stock increased by approximately six-fold, catches more than doubled, and F declined substantially (ICES, 2021a). Overall, catches of hake reported by ICES for 2016 were landed predominantly by long lines (39%), trawls (33%), and gillnets (24%) (ICES, 2017). Each gear type comes with trade-offs from varying levels of ease of use, to efficacy, to selectivity. Trawls, which trap fish as they scrape across the seafloor, are known as "active" gear types as they are continuously dragged by a moving vessel, while long lines and gillnets are considered "passive" gear types as they drift or hang idly in the current. It is worth noting that, despite modifications made to each of these gear types to increase selectivity, all three of these gear types have some issues.

In this paper we focus on the relationship between the carbon impact of the fishery, namely GHGs generated from vessel fuel use, and consider the potential perturbations to the OC stocks in the sediment and hake population, against the rebuilding of the Northern hake stock, from 2008 to 2016. We do not consider emissions from non-fuel inputs associated with fishing, for which estimates vary (for example Parker et al. (2018) assume 25% of total emissions arise from non-fuel sources). The purpose of including a preliminary ecological perturbation analysis in this paper is to introduce the impacts of fishing on OC stocks, in addition to the direct carbon footprint of boats on the water, and to advance information available for the development of ecosystem-based approaches for EU fisheries. Given the nexus between climate change, sustainable resource use, and biodiversity conservation (Sumaila and Tai, 2020), we consider whether the GHG footprint of the hake fishery overall and per tonne of catch were reduced by ending overfishing.

MATERIALS AND METHODS

We used publicly available data collected by STECF through the Fisheries Dependent Information (FDI) data call (STECF, 2017) in combination with data we requested from STECF (STECF, 2020b), which included detail on hake landings, fuel use and intensity (litres per tonne of total landings) at the level of individual fishing fleet segments (i.e., vessel size, gear type). The requested data, hereafter referred to as dataset 1, were extracted from the STECF database (STECF, 2020b) for every second year from 2008 to 2018 inclusive, according to the following selection criteria: (i) fleets operating in the North Atlantic Ocean (FAO Area 27 - NAO) and (ii) EU fishing fleet segments in which, in 2018, hake accounted for at least 1% of total landings. France, Spain, and the United Kingdom landed 91% of total hake landings in 2008 (27,416 tonnes), and 78% in 2016 (23,764 tonnes) (STECF, 2020b). Thus, fishing mortality of the hake population within the NEA was dominated by the activities of these three countries, indicating that hake was an important target species for these nations. As such, we used the landings, effort, and fuel data for these three nations to investigate the impacts of the hake fishery in terms of fuel use, sedimentary disturbance, and extraction of OC in biomass. To compare the carbon impacts of the European hake fishery eight years apart, with two vastly different estimates of SSB, we emphasised the relative fuel use and impacts on OC per kg of hake landings, as opposed to focusing on the total emissions and impacts of the fishery. Landings data from STECF (STECF, 2020b) were used in kilograms, and, unless otherwise stated, this is the basic unit of measure we refer to hereafter.

To analyse the GHG footprint associated with fishing activity we focused on the carbon generated by vessels' fuel use, which includes travel to and from fishing grounds and gear operation. These data were entirely available in dataset 1 (STECF, 2020b). We estimated fuel intensity (FI) (the amount of fuel burned while fishing hake per kilogram of hake landed), and emissions intensity (EI) (the estimated GHGs released while fishing hake per kilogram of hake landed) which is directly related to FI. Estimates for mean FI values were calculated for year and gear type. There were eight types of gear listed in dataset 1 (STECF, 2020b): (1) polyvalent passive gears (PGP), i.e. polyvalent nets, (2) drift/fixed-net gears (DFN), (3) gears with hooks (HOK), (4) demersal trawlers and seiners (DTS), (5) pots and traps (FPO), (6) vessels using active and passive gears (PMP), (7) vessels using "other" active gears (MGO), and (8) pelagic trawlers (TM). For this analysis, we grouped polyvalent passive gears (PGP) and drift/fixed-net gears (DFN) together as "DNGN". In addition to reporting the cumulative FI value for hake fished by all gear types in 2008 and 2016, we also report on FI values for the "DNGN", "HOK", and "DTS" gear types only, as these were relatively well sampled in both 2008 and 2016 ($n > 2$ for both years) and were responsible for the overwhelming majority of hake landed (>95% of total landings) in both years.

To estimate the disturbance of OC in muddy sediments caused by bottom-contacting otter-trawlers, we used swept area (SA), a measure of the seabed surface area that has been in contact with, or altered by, bottom-contacting fishing gear, such as trawls,
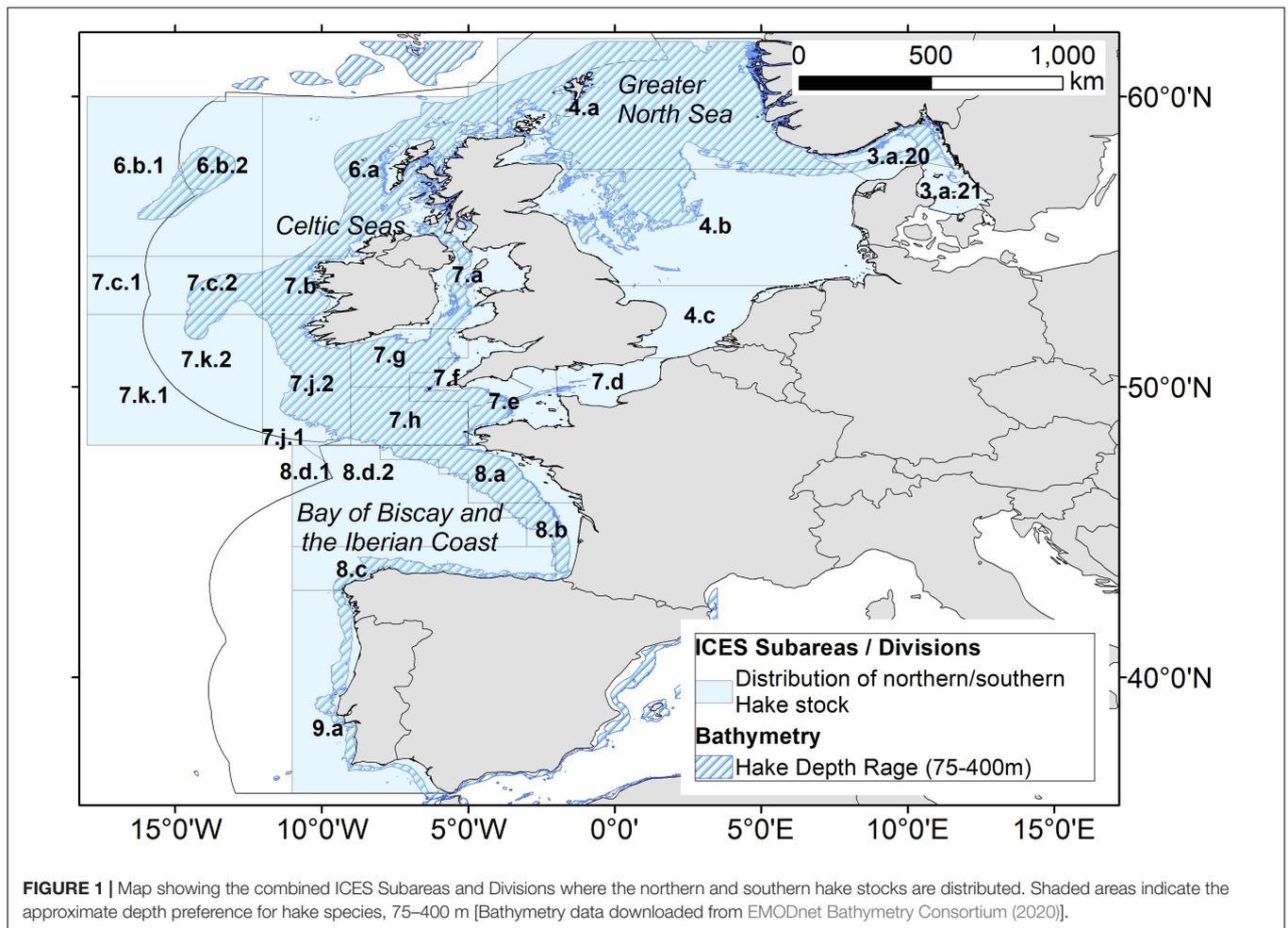
FIGURE 1 | Map showing the combined ICES Subareas and Divisions where the northern and southern hake stocks are distributed. Shaded areas indicate the approximate depth preference for hake species, 75–400 m [Bathymetry data downloaded from EMODnet Bathymetry Consortium (2020)].

and report SA per kg of hake landed. SA is determined by the width of the gear and vessel speed (Church et al., 2016). We calculated and mapped the total SA by country using publicly available FDI data (STECF, 2017), hereafter referred to as dataset 2. Although this calculation does not quantify the amount of OC lost or consider the specific mechanisms by which OC may be lost, the areal overlap provides spatial information about where the biggest impacts of the trawl fishery on surficial sedimentary OC stocks are likely to be.

We calculated SA per kg of hake landed for France, Spain and the UK using the landings data in dataset 1 (STECF, 2020b), which included hake landings, hake landings as a percentage of total landings, and effort by fishing segment (STECF, 2020b), but did not contain spatial data. Instead, dataset 2 (STECF, 2017), which included fishing effort available per ICES rectangle, was downloaded for annexes IIA, IIB, BOB, and CEL1 and years 2008 and 2016 (see **Table 1**). The data were filtered for otter trawling gears only (OT) and for the following countries: France, Spain, and the United Kingdom (data were available for England, Northern Ireland, and Scotland). Dataset 2, which provided effort, landings, and spatial data (STECF, 2017), did not contain hake landings for otter trawlers in France or Spain in 2008, or hake landings as a percentage of total landings. As such, all hake

landings data for both 2008 and 2016 for France, Spain, and the United Kingdom were used from dataset 1 (STECF, 2020b). Dataset 1 were filtered by gear type "DTS", which includes demersal trawlers and demersal seiners, on the assumption that these were mostly otter trawls, since, in European waters, effort by otter trawlers is an order of magnitude greater than that of demersal seiners (Eigaard et al., 2016; **Supplementary Table 1**). To see clearer differences in SA between depleted and recovered stocks it would be best to compare fleets that landed a high percentage of hake, as detailed in dataset 1, however, we were unable to disaggregate the effort of those fleets in dataset 2, which contained the spatial data. Therefore, for the purpose of making a comparison between two years with different stock statuses, the use of OT spatial data from dataset 2 with the total landings for France, Spain and the United Kingdom from the DTS segment in dataset 1 was the best possible approach given the limitations of the data.

Finally, to estimate the fishery's impacts on the OC stock of the hake population, we first calculated the carbon removed by each country and by the different fleet segments using the landings reporting in dataset 1 for 2008 and 2016. We again grouped polyvalent passive gears (PGP) and drift/fixed-net gears (DFN) together as "DNGN," and report OC removal values

TABLE 1 | International Council for the Exploration of the Sea (ICES) Annexes and the fishing areas they encompass.

Annex	ICES area
IIA	IV; VIId
IIB	VIIIc and Ixa
BOB	VIIIa; VIIIb
CEL1	VIIb, VIIc, VIIe, VIIf, VIIg, VIIh, VIIj and VIIk

for the "DNGN," "HOK," and "DTS" fishing segments for 2008 and 2016. We also estimated the OC stock in the adult hake population for 2008 and 2016 and the proportion of OC in hake stock removed by total landings by France, Spain, and the United Kingdom cumulatively using dataset 1 and SSB estimates for the northern stock only (ICES, 2021a). This analysis was limited to using SSB estimates for the Northern stock as a proxy for the adult hake population of both stocks as SSB estimates were not available for the Southern stock, and the landings data in dataset 1 could not be disaggregated spatially to ascertain whether landings were from the Northern or Southern stocks. We reasoned that this approach was appropriate for our purpose of comparison between the two years given that total landings estimated by ICES for the Northern stock were much higher at 47,822 tonnes in 2008, and 107,530 tonnes in 2016 (ICES, 2021a), than for the Southern stock, at 16,773 tonnes for 2008 and 12,443 tonnes for 2016 (ICES, 2021b). We note that our results are therefore underestimates of the OC stock in the adult hake population of the NEA for 2008 and 2016, and overestimates of the OC removed by landings as a proportion of the adult hake population in those two years.

Hake are caught as part of a mixed-species fishery with several other target species, which makes it challenging to partition and confidently assign impacts to hake versus other species that end up in the same net. Nonetheless, we provide estimates for FI, emissions intensity (EI), and SA for hake landed by all trawlers, noting that the figures reported herein are useful for comparing the fishery impacts between a depleted and recovered stock, and do not represent precise point estimates for hake's total carbon footprint. Estimates and statistical analyses were calculated in R version 4.0.3 (R Core Team, 2020), ArcGIS version 10.1, and Microsoft Excel.

Fuel and Emission Intensity Estimates Over Time
Extrapolating Fuel Use and Calculating Fuel Intensity (FI)

To estimate the amount of fuel consumed in the pursuit of hake, we assumed that the fuel used to land hake was directly proportional to the ratio of hake landings to total landings for that fishing segment. That is, for each fishing segment reported in dataset 1 (STECF, 2020b), we assumed:

$$\frac{F_{hake}}{F_{total\ L}} \alpha \frac{L_{hake}}{L_{total}} \qquad (1)$$

Where F is fuel and L is landings. Thus, we assumed that the quotient of total fuel consumption over total catch (i.e., the FI for

total catch) was a reasonable proxy for the FI of hake. On this basis, we estimated FI using the following equation:

$$FI_{hake} = \frac{F_{hake}}{L_{hake}} \alpha \frac{F_{total\ landings}}{L_{total}} \qquad (2)$$

Where F$_{hake}$ is estimated as:

$$F_{hake} = L_{hake} * \frac{F_{total\ L}}{L_{total}} \qquad (3)$$

Mean FI values for the three gear types were calculated by first summing the estimated values for F$_{hake,G}$ (in litres) and then the reported values for L$_{hake,G}$ (in kg), and subsequently dividing these as follows:

$$Mean\ FI_{hakeGY} = \frac{\Sigma\ estimated\ F_{hakeGY}}{\Sigma\ reported\ L_{hakeGY}} \qquad (4)$$

Where G is gear type and Y is year.

Converting FIs to Emission Intensity Estimates
To convert FI to emission intensity (EI), we assumed that most of the fishing vessels in the EU operate using marine diesel (Borrello et al., 2013), which has a published density of 890 kg/m^3 (ExxonMobil, 2021), equivalent to 890 g/L. The fuel-to-emissions conversion factor for marine diesel (MD), as published by the International Maritime Organisation (IMO, 2015), is 3.206 g of CO$_2$/g of MD. After converting between units, we arrived at the conversion factor of 2.853 kg CO$_2$/L of fuel. Note that this number does not account for the carbon-dioxide equivalent of: (i) other GHGs released during combustion, e.g., methane and nitrous oxide; (ii) upstream emissions associated with fuel production, e.g., drilling and refining; nor (iii) downstream emissions borne from processing, e.g., freezing, packaging, and distribution. In this respect, our estimates for GHGs released by fuel consumption are likely quite conservative.

Emission intensity estimates (reported as kg CO$_2$ per kg hake) were derived by multiplying FI values by a factor of 2.853 kg of CO$_2$/L of fuel, using the following equation:

$$EI_{hake} = FI_{hake} * 2.853 \left(\frac{kg\ CO_2}{L}\right) \qquad (5)$$

Sediment Disturbance
Calculating Swept Area
Swept area was calculated using standardised values for door width (km) and trawl speed (knots) for the Otter trawl class BENTHIS métier code: "OT_MIX_DMF_PEL," which is used to target hake (Eigaard et al., 2016). Following recommendations in the OSPAR CEMP guidelines (OSPAR Commission, 2017) (Agreement 2017-09) and Gerritsen et al. (2013), we used the equation:

$$Swept\ Area =$$

$$Effort\ (hours) \times 0.07621\ km \times 3.4\ knots \times 1.852 \qquad (6)$$

Where Effort (fishing hours) from dataset 2 (STECF, 2017) was provided with spatial data (standardised ICES rectangles), 0.07621 km is the reported average door width and 3.4 knots

is average trawl speed (ICES, 2016; OSPAR Commission, 2017); and 1.852 is the conversion factor for knots to km/hr. The final SA estimates between the countries and two fishing years are compared on a relative basis. Only the average door width and vessel speed were reported by ICES (2016) and OSPAR Commission (2017), yet the width of the trawl doors is a function of the vessel size and length of the sweeps, which can vary between 25 and 250 m, and the towing speed can vary from 2 to 4 knots (Eigaard et al., 2016). Thus, there is a degree of uncertainty within the estimated SA results.

Resulting SA estimates were spatially mapped for individual countries and as combined totals for 2008 and 2016, using a Natural Breaks Classification scheme (Holt, 2008). Swept Area Ratios (SAR), i.e., the proportion of each grid cell area that is trawled, were not deemed a suitable metric for this study due to the large area of the ICES rectangles (at $0.5° \times 1°$, these are approximately 4,000 km^2) in combination with the low spatial resolution of dataset 2 (STECF, 2017), as it was not possible to determine where within the ICES square the reported activity occurred (Amoroso et al., 2018b). As outlined above, SA per kg of hake was calculated using total annual estimated SA (km^2) and hake landings (kg) data for each country as reported in dataset 1 (STECF, 2020b).

Combining With Sediment Type

Shapefiles for seabed substrate classified to the simplified Folk 5 classification were downloaded from EMODnet Geology (EMODnet Geology, 2016; **Supplementary Figure 1**). The total SA polygons for 2008 and 2016 were overlaid with the classified sediment layers and a spatial analysis was performed that extracted the areas of 'mud to muddy sands' (having the highest relative OC contents; e.g., Smeaton et al., 2021) directly swept by the otter trawls, and therefore considered to be impacted. We calculated the total area of the sediments considered to be impacted for both years.

Carbon Stock in Hake Populations

Using carbon measurements from six hake, 15–20 cm long and 25–35 g in wet mass, as recorded by Czamanski et al. (2011), where dry weight was $42.9 \pm 6\%$, we calculated that OC was approximately 11.33% of hake wet weight. Dataset 1 was used to estimate the OC removed from the hake population (combined Northern and Southern stocks) in landings by country for France, Spain and the UK (STECF, 2020b), using the equation:

$$OC_{Removed} = Landings_{CY} \times 0.113256 \qquad (7)$$

Where Landings are in kg, C is country, and Y is year. Using a 94% conversion rate of landed OC to CO_2 emissions described by Mariani et al. (2020), CO_2 emissions from total hake landings for gear type (DNGN, HOK, and DTS), for all three countries cumulatively, for 2008 and 2016 were calculated using the following equation:

$$Emissions_{Landings} = Landings_{GY} \times 0.113256 \times 0.94 \qquad (8)$$

Where G is gear type and Y is year. To calculate the OC stock in the adult hake population for 2008 and 2016, estimates of SSB

were used for Northern stock only (ICES, 2021a), since ICES does not estimate the SSB for the southern stock, using the equation:

$$OC_{SSB} = SSB_Y \times 0.113256 \qquad (9)$$

Where Y is year. The range of OC in SSB was calculated using the high, mean, and low estimates of SSB reported by ICES (2021a). Finally, to make a meaningful comparison between 2008, when the stock was considered overfished, and 2016, when it was considered rebuilt, the proportion of OC removed in total hake landings for the three countries was calculated as a percentage of the total OC stock in the hake population, again using the SSB for Northern stock only and the years 2008 and 2016. For this, we used the equation:

$$\frac{OC_{Removed}}{OC_{SSB}} \qquad (10)$$

Again, the range was calculated using the high, mean, and low estimates of SSB.

RESULTS

Fuel Use, FI, and EI

Between 2008 and 2016, the total fuel consumption for all fishing segments that landed hake for France, Spain, and the United Kingdom increased by 29% (from ~49M litres to ~63M litres), relative to hake landings more than doubling (from ~45M kg to ~95.5Mkg). Simultaneously, the FI (and by extension, EI) for hake landed by the gear types DNGN (polyvalent passive gears and drift/fixed-net gears), HOK (gears with hooks), and DTS (demersal trawlers and seiners) decreased by 11–54% (**Figure 2** and **Table 2**). Additional analyses on these differences are included in the **Supplementary Information**. The sample size was extremely small for those fishing segments that landed primarily hake (i.e., where hake accounted for $\geq$50% of the total landings), and therefore not particularly viable for statistical analyses. However, there was a declining trend in FI over time (**Supplementary Figure 2**) and, as FI is directly related to EI, the same can very likely be said for emissions per kg of hake.

The CO_2 produced in pursuit of hake (and, realistically, other species associated with the fishery) was influenced by the type of gear used to target them. For example, in 2016, hake that was landed using demersal trawlers or seiners (DTS) was approximately 37% more carbon intensive than the mean FI for the entire fishery and approximately 65% more carbon intensive than hake landed by vessels using polyvalent-, drift-, or fixed-net gears (DNGN) (**Figure 2** and **Table 2**).

Disturbance of Sediment

An increase in effort by vessels using otter trawls, and subsequently total SA, occurred for all three nations from 2008 and 2016, although the hake landings by otter trawl decreased overall (**Figure 3**). Vessels that landed hake for France, Spain, or the United Kingdom using otter trawls swept a cumulative total area of 230,103 and 520,856 km^2 in 2008 and 2016 respectively. Conversely, the total reported landings of hake by otter trawls were reduced from approximately 27,416 tonnes in 2008, to
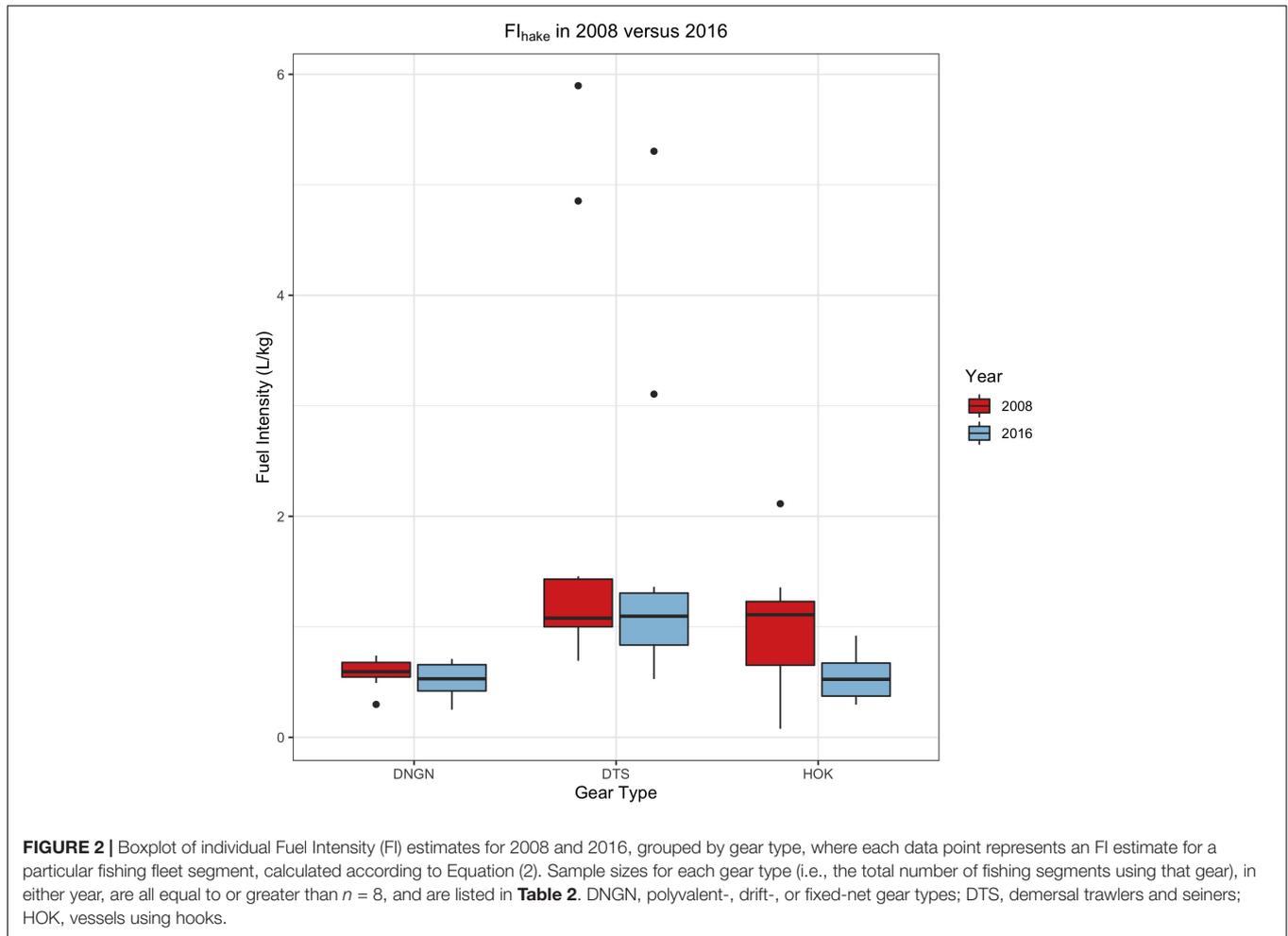
FIGURE 2 | Boxplot of individual Fuel Intensity (FI) estimates for 2008 and 2016, grouped by gear type, where each data point represents an FI estimate for a particular fishing fleet segment, calculated according to Equation (2). Sample sizes for each gear type (i.e., the total number of fishing segments using that gear), in either year, are all equal to or greater than *n* = 8, and are listed in **Table 2**. DNGN, polyvalent-, drift-, or fixed-net gear types; DTS, demersal trawlers and seiners; HOK, vessels using hooks.
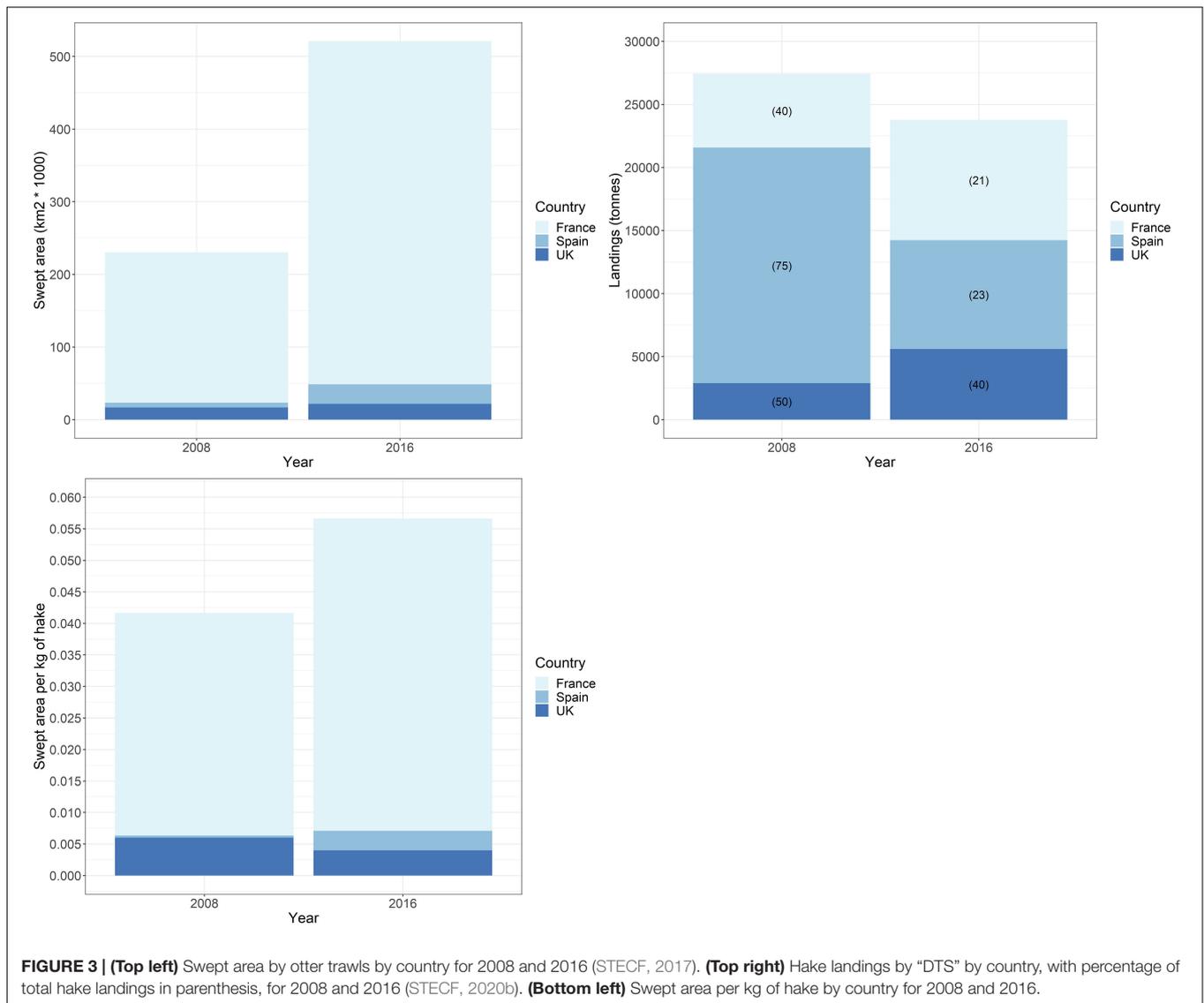
TABLE 2 | The reported total landings and estimated total fuel, mean Fuel Intensity (FI), and mean Emission Intensity (EI) for hake landed by vessels equipped with particular gear types (DNGN, HOK, DTS, or all gear types) in years 2008 and 2016.

Year	Measure	DNGN	DTS	HOK	All gear types
2008	Number of Individual fishing segments	12	10	8	37
	Total Fuel$_{Gear}$ (L)	6,150,847	32,894,188	8,903,432	49,195,015
	Reported Total Landings$_{Gear}$ (kg)	10,000,827	27,416,490	6,230,559	44,973,215
	Mean FI (L of fuel/kg hake)	0.615	1.200	1.429	1.094
	Mean EI (kg CO_2/kg hake)	1.755	3.423	4.078	3.121
2016	Number of Individual fishing segments	12	10	8	37
	Total Fuel$_{Gear}$ (L)	26,726,954	21,546,642	12,364,812	63,110,975
	Reported Total Landings$_{Gear}$ (kg)	48,654,256	23,763,605	18,743,699	95,547,292
	Mean FI (L of fuel/kg hake)	0.549	0.907	0.660	0.661
	Mean EI (kg CO_2/kg hake)	1.567	2.587	1.882	1.885
Change in FI and EI estimates from 2008 to 2016 (%)		−11	−32	−54	−40

Here we use "fishing segment" to refer to the combined gear type and size of vessel. DNGN = Polyvalent-, drift-, or fixed-net gear types; DTS, demersal trawlers and seiners; HOK, vessels using hooks. Respectively, units for FI and EI estimates are: litres of fuel per kg of hake landed, and kg of CO_2 per kg of hake landed. Percent changes in mean FI and EI estimates from 2008 to 2016 are listed at the bottom of each column. Mean FI estimates were calculated according to Equation (4). Note that, mechanistically, EI estimates are directly related to FI estimates by a factor of 2.853 kg CO_2/L fuel.

23,764 tonnes in 2016. The total SA values for the two annual snapshots are presented spatially in **Supplementary Figure 3**. In terms of SA per kg of landed hake, when comparing the depleted stock of 2008 to the rebuilt stock of 2016, only the United Kingdom exhibited a lower result (33% decrease), while SA per kg of landed hake increased for France by 40% and Spain

FIGURE 3 | (Top left) Swept area by otter trawls by country for 2008 and 2016 (STECF, 2017). **(Top right)** Hake landings by "DTS" by country, with percentage of total hake landings in parenthesis, for 2008 and 2016 (STECF, 2020b). **(Bottom left)** Swept area per kg of hake by country for 2008 and 2016.

by 8-fold (**Figure 3**). For France, this is a result of a combined increase in effort and landings; however, for Spain, while there is a large increase in effort in 2016, reported hake landings were greatly reduced: less than 50% of 2008's catch.

As we have emphasised throughout the text, it is important to note that this is a mixed fishery and that hake forms a percentage of the overall landings, thus the SA is not attributable to the hake fishery alone. However, irrespective of which species were caught, the area of sediment swept represents the disturbance caused in relation to the hake landed. The spatial distribution of SA per individual nation for each year is shown in **Supplementary Figure 4**. Overall, the total spatial distribution of effort is quite similar for both years. The most intense activity occurred within the Bay of Biscay, following the western coastline of France, and within the Moray Firth region of the Greater North Sea. The English Channel sees increased effort in 2016, albeit consistent in distribution. In 2008, there was activity within the southern North Sea and along the northern and western coastline of Spain

which is not seen in 2016; instead, in 2016, a larger distribution of activity in the Celtic seas to the south-west of Ireland occurred. Using a somewhat crude area calculation provided by the spatial resolution of the ICES rectangles, we calculate an increase in the area of specifically muddy sediments disturbed by otter trawls from 5.72 km^2 in 2008 to 31.82 km^2 in 2016 (**Figure 4**). In 2008, disturbance of muddy sediments occurred off the west coast of France; northern coastline of Spain and west coast of Portugal; within the northern North Sea; and in the Celtic Sea to the west of Ireland. In 2016, there was less disturbance, and less activity generally, around the coasts of Spain and Portugal and the North Sea, and relatively consistent disturbance on the west coast of France. However, disturbance of a larger area of muddy sediments occurred in the Celtic Sea to the west of Ireland.

Impacts on Carbon Pool in Hake Stock

The total OC in hake landings increased between 2008 and 2016 for all three countries, with an additional 5,728 tonnes of
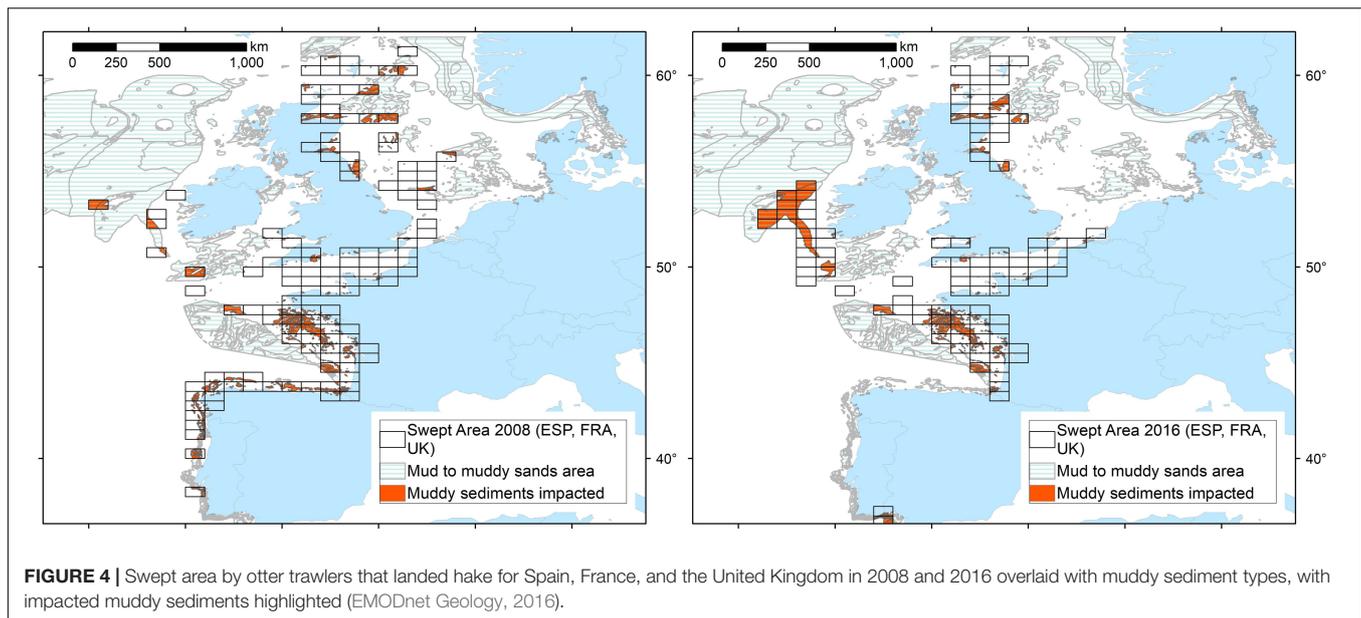
FIGURE 4 | Swept area by otter trawlers that landed hake for Spain, France, and the United Kingdom in 2008 and 2016 overlaid with muddy sediment types, with impacted muddy sediments highlighted (EMODnet Geology, 2016).

OC landed in 2016 cumulatively compared to 2008 (**Table 3**). Subsequently, total CO_2 emissions from OC in landed hake increased from 4.8M kg in 2008, to 10.2M kg in 2016, including increases in CO_2 emissions from hake landed using polyvalent passive gears, drift/fixed-net gears, and gears with hooks (**Figure 5**). However, a decrease of 0.4M kg CO_2 was observed for hake landed using demersal trawlers and seiners, as fewer hake overall were landed using that gear type in 2016. Despite total OC removal and emissions from OC in hake landings increasing between the two years, the proportion of the OC stock in the hake pool removed by landings in 2016 was much lower (31%) than that in 2008 (96%) (**Table 3**), and the OC stock in the adult hake population was approximately 6.5 times larger in 2016 than in 2008 (**Figure 5**).

DISCUSSION

Despite the limitations of the data, comparisons between the relative impacts of the fishery when the stock was overfished, as in 2008, and rebuilt, as in 2016, were possible. We have demonstrated improvements in efficiency and proportional OC storage in living stocks in 2016 compared to 2008. However, increased fishing in 2016 also resulted in increased total emissions from both fuel and landed hake, and increased ecosystem disturbance. First, we found that all gears were more fuel efficient in 2016 compared to 2008, suggesting an increase in catch per unit effort, where the unit of effort is fuel. Second, in 2016, when stocks had been rebuilt, more OC remained in the living pool of hake compared to when stocks were depleted in 2008, both in terms of total biomass and proportionally. Third, increased fishing effort in 2016 using bottom trawling resulted in higher disturbance of sedimentary OC, however, the hake catch from trawling was lower in 2016, suggesting this increase may have been due to trawls targeting other species than hake. Finally,

as may be expected with increased landings, higher total fuel emissions and CO_2 release from hake landings in the Northeast Atlantic occurred once stocks were rebuilt. However, this analysis does not consider the displacement of effort and catch that may occur when a stock in one geographic location is depleted, while demand for that seafood remains constant. For instance, in 2008 frozen hake imported to Spain from outside the EU was higher than imports reported for the five subsequent years (EUMOFA, 2015), which suggests that the full emissions and OC impacts borne from the depleted stock may be higher, perhaps substantially so, from a global perspective. Likewise, we did not consider post-processing differences in our analysis, which may undergo changes when fish are imported rather than landed and marketed fresh. While our aim was to provide insights on the impacts of fisheries that will ultimately be useful for the development of EAF, such additional assessments would also improve the information available to the consumer at the point of purchase.

Overall, the increase in available hake biomass once the stock was rebuilt correlates with increased efficiency across passive gear types and proportional reduction of fishing impacts on the living pool of OC. We found that the volume of CO_2 emissions produced by vessels landing hake was influenced by the type of gear used, with the passive gillnets, hook and line, and polyvalent gears generally outperforming trawls in terms of emissions and EI. With regard to sediment disturbance, the rebuilt fishery (2016) performed better than the depleted fishery (2008) in instances where hake landings produced by trawlers were more-or-less consistent between the two years (in France and the United Kingdom for example), compared to instances where the landings from trawlers between 2008 and 2016 were substantially reduced (as in the case of Spain). These observations are likely linked to the improved stock status of hake in 2016 compared to 2008, however, the hake fishery is a mixed fishery, thus the changes in EI and impacts of the benthic trawl gear

TABLE 3 | Organic carbon (OC) impacts of hake fisheries in France, Spain, and the United Kingdom.

OC estimates	Year	Country			Total
		France	Spain	UK	
OC in landings (tonnes)	2008	1,633	2,805	656	5093
	2016	5,005	4,221	1,596	10,821
OC in stock (tonnes)	2008	5,280 (±375)			
	2016	34,780 (±2671)			
Proportion of OC stock landed (range)	2008	96% (90–100%)			
	2016	31% (29–34%)			

OC in stock refers to Northern hake stock only as SSB not estimated for Southern stock.
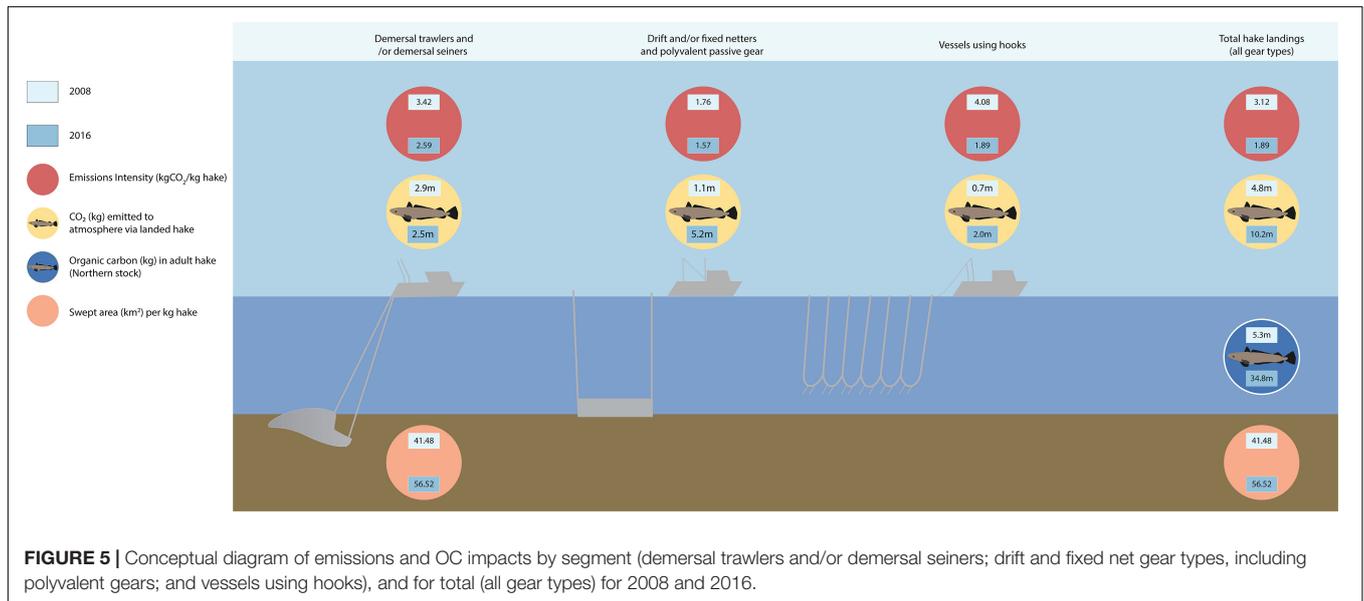
FIGURE 5 | Conceptual diagram of emissions and OC impacts by segment (demersal trawlers and/or demersal seiners; drift and fixed net gear types, including polyvalent gears; and vessels using hooks), and for total (all gear types) for 2008 and 2016.

on sediment cannot be attributed to hake stock status and hake landings alone. A greater proportion of the overall disturbance due to trawling effort in 2016 is likely to be attributable to other species, given the decline in hake landings by trawlers observed in 2016, particularly for the Spanish fleet. Unfortunately, we were unable to explore this observation further due to the limitations of the datasets. Nevertheless, the SA analysis provides useful insights into the potential disruptions to sedimentary OC posed by trawlers that land hake. Notably, hake habitat typically encompasses muddy sediments, which generally hold more OC (Diesing et al., 2017; Smeaton et al., 2021) and are resuspended for longer periods of time relative to other sediment types (O'Neill and Summerbell, 2011), implying a greater potential for OC loss via remineralisation or lateral transport offshore (Paradis et al., 2019; Epstein et al., 2022). This is not to suggest, however, that other types of seabed sediments are impervious to the impacts of trawling, both in terms of carbon and biodiversity— impacts relevant to EAF. For example, while both muddy and gravelly sediments experience relatively high benthic community depletion rates following a trawl, recovery rates for infaunal benthic communities are higher in mud than gravel due to the presence of faster-growing species (Pitcher et al., 2022).

As an early attempt to consider fishery impacts on OC in sediments and biomass using current publicly available data, there are limitations to what we could surmise. Firstly, we recognise the limitations of using two datasets which cannot be consistently filtered either by gear type or by landings with spatial data and, as such, note that the final estimates for SA per kg of hake are unreliable. Furthermore, our estimates of SA are likely to be over-estimated, not least because of the overlap of ICES rectangles with land area along coastlines (**Figure 3**). This is a function of the spatial scale of available data. We carried out a comparative analysis using a recent, much higher resolution dataset to illustrate this point (i.e., 0.05° × 0.05° as opposed to 0.5° × 1), however, we note that the SA data themselves are not comparable due to differences in the way that STECF (2017) and ICES (2021c) aggregate data. For instance, while landings data for hake are available at a country level by year from STECF (2020b), the data are aggregated into a broader gear type, for example "demersal trawls and seines" are categorised simply as "DTS." Conversely, while the ICES data are disaggregated into specific designs of otter trawl (seven spatial layers exist for otter trawls within the high-resolution ICES dataset), the data comprise all landed species and for all countries per year.

To illustrate the advantages of high-resolution spatial data, we compared our 2016 SA calculated using dataset 2 (STECF, 2017) with the ICES (2021c) dataset of the 2016 spatial layer for the BENTHIS métier code "OT_DMF," which refers to otter trawling of demersal fisheries. This BENTHIS métier code includes hake as a target species according to Eigaard et al. (2016) although hake is not specifically mentioned for this gear type by ICES (2021c). We compared the spatial distribution of SA for the area of high-intensity SA values off the west coast of France and north coast of Spain using these two datasets (**Supplementary Figure 5**). The higher resolution ICES dataset visibly reduced the estimated footprint and provided a much-improved spatial analysis of areas that are heavily impacted by trawling. An analysis of this nature might inform highly targeted management interventions, if required. The second analysis relates to estimates of the overall area of muddy sediment impacted using data of different scales/resolutions (**Supplementary Figure 6**). When we extracted the areas of muddy sediment that overlap with the SA data from dataset 2 and the ICES data (ICES, 2021c), we did not see a large difference in the disturbed area estimated by the two different resolutions. Overall, despite the data limitations described above, it is evident that the results of any spatial analysis strongly depend on the spatial scale of the dataset (Amoroso et al., 2018b) and highlights the importance of data resolution when estimating and considering fishing impacts. Therefore, with finer spatial resolution of effort data, combined with sediment maps and OC content estimates, quantification of disturbance to sediment OC are likely to improve.

Our analysis of fishing impacts on the living OC stock is focused on hake biomass only, due to the data available. Including dynamics between the target species, competitors, predators, and prey would improve the analysis and better inform management of living OC stocks under different fishing conditions. Consideration of the fishing impacts on bycatch and, when assessing a mixed fishery such as hake, other target species would be necessary, thus reporting catch composition and bycatch by segment would enable a more thorough analysis of fishing impacts on living OC stocks. Furthermore, better understanding and incorporation of a target species' natural history and trophic dynamics into the analysis could shed further light on the impact of fisheries on OC in living stocks. For instance, consideration of the age at which a species is fished may provide insights on the longevity of the OC stock in that population. The recorded maximum longevity for hake ranges from 20 to 25 years (Vitale et al., 2016); if individuals live for 20 years, they can effectively store OC for two decades. Hake occupies different trophic levels as their diet changes throughout their life stages, thus the prey controlled by juvenile and adult hake are different. Adult hake over 30cm in length, which are the target of hake fisheries, prey on demersal fishes such as blue whiting and, where adult and juvenile hake distributions overlap, they show a preference for cannibalism (Mahe et al., 2007). Removal of large hake may therefore release smaller hake from predation, increasing the chances that juveniles will reach adulthood and recruit to the fishery, while a reduction in fishing pressure on larger hake could have the opposite effect (Mahe et al., 2007). At the same time, larger hake females may facilitate faster rebuilding where stocks are depleted, as they have a higher fecundity than smaller hake females and produce more eggs (Cerviño et al., 2013). Overfishing of predators can cause widespread changes in the ecosystem as prey are released from predation, with implications extending beyond the biomass of the target population, to food webs, habitats, and ecosystem services (Östman et al., 2016; Norderhaug et al., 2021). While they are not considered a deep-sea species, hake can be found at depths down to 1000m (Morales-Muñiz et al., 2018), thus may provide a link between shallower and deep sea habitats, which play a key role in global ecological and biogeochemical processes (Danovaro et al., 2008).

The objectives of this study were to explore how ending overfishing of hake and stock recovery affected (i) the carbon emissions from fuel use during fishing activity; (ii) disturbance of OC in sediments by trawling; and (iii) impacts on the OC stocks in the population of the target species. Earlier analysis of emissions from the hake fishery in Spain considered the entire life cycle of the fishery, from extraction to processing and consumption (Vázquez-Rowe et al., 2011). However, our approach was to consider the fishery from the perspective of EAF, and thus, the only fuel emissions we considered were those caused by fishing activity directly. Our study was also limited to a snapshot view of fisheries impacts when the hake stock was depleted, in 2008, and rebuilt, in 2016. As such, we did not seek to establish the reasons for stock depletion and recovery, thus, the effects we report are not necessarily a product of ending overfishing. However, it is likely that reduced fishing pressure, required by the recovery plan introduced in 2004, contributed to the increase in hake biomass of the Northern stock (Baudron and Fernandes, 2014).

Exploration of the OC impacts of fisheries is timely given that the interaction between trawl fishing activity and sediments is increasingly recognised as an important impact for consideration in EAF (De Borger et al., 2021); recent research has highlighted the roles of fish in the carbon cycle and flux (Bianchi et al., 2021; Saba et al., 2021); and there is significant overlap between fishing grounds and areas of high productivity (Cavan and Hill, 2021). Furthermore, EU targets to end overfishing by 2020 have not been met, yet overfishing is known to affect the resilience of fish stocks to climate change and other stressors (Sumaila and Tai, 2020). During this study, we used only publicly available fisheries data and, as such, found various limitations which have resulted in unreliable estimates, particularly for SA and OC in hake stock. Improving the reliability and accuracy of estimates is necessary. Ensuring that data can be consistently disaggregated across public databases, such as by country, fishery segment, BENTHIS métier, effort, and landings, would go a long way toward improving the accuracy of estimates of the impacts of fishing on landed populations and the environment. In addition, spatial data at finer scale resolutions than ICES rectangles are especially important for generating estimates of impacts on benthic environments.

The need for EAF which can lead to better outcomes for climate, biodiversity, and people is widely recognised but not easily operationalised (Link et al., 2020). Climate-based fisheries management must go beyond a target of MSY to include climate-based objectives in EAF. This would, presumably, call for management decisions based on consideration of emissions from fuel, disturbance to OC in sediments and living pools, and the carbon functions of the ecosystem. Reference levels for what constitutes sustainable fishing and desirable stock size could then be decided across priorities, such as carbon sequestration, harvest, ecosystem health, and social and cultural facets. This analysis represents a first step towards ensuring that relevant information from emerging fields of research can be included in the development of EAF approaches and has illuminated some of the complexity involved when using publicly available data to assess fisheries impacts on ecosystems.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study and are referenced. The data provided by STECF (2020b) upon our request can be found here: https://github.com/angela-m/Hake-fishery-recovery-and-climate.

AUTHOR CONTRIBUTIONS

AM, EF, and SV contributed to the initial discussion. AM and EF led the writing of the manuscript. AM, EF, CH, and KB designed the figures and compiled the tables. All authors contributed to the literature survey, drafted and reviewed the manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.788339/full#supplementary-material

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