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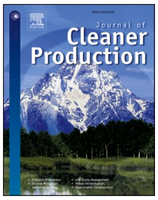

Is renewing Icelandic demersal trawling vessels resulting in lower greenhouse gas emissions?

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ABSTRACT

Understanding and reducing the greenhouse gas emissions of bottom trawl fisheries is of importance, as it directly impacts efforts to mitigate climate change and promotes sustainable fishing practices. As a considerable part of global landings is fished using demersal trawls and vessel renewal is often mentioned as an important mitigation measure. This study compares the greenhouse gas emissions of older and newer trawlers in the Icelandic fleet, using Life Cycle Assessment methodology with the functional unit “1 kg of demersally trawled fish at landing”. The global warming potential (kg CO2-eq) from older Icelandic bottom trawlers was assessed and compared to the newer ones, where older vessels were in some cases being decommissioned. A total of 11 trawlers were assessed, providing a cross section of the Icelandic bottom trawler fleet, with respect to age, size, catch composition and onboard operations. The results show that freezer trawling was more energy-intensive compared to trawlers landing their catches chilled/superchilled. Fleet renewal alone does not explain the reduction in fuel use and greenhouse gas emissions in the Icelandic bottom trawl fleet between 2012 and 2022, highlighting the need for a comprehensive approach considering multiple factors such as catch composition, fishing ground, and vessel characteristics, which explained 87% of the emissions. Catching indicated increased fuel consumption compared to steaming. The greenhouse gas emissions allocated to each demersal fish species ranged on average from 0.5 to 1.0 kg CO2-eq/kg of the weight of demersal fish landed, and from 1.4 to 2.7 kg CO2-eq/kg of the edible part of demersal fish landed (mass allocation), where redfish stood out as having the highest emissions.

1. Introduction

Fisheries contribute significantly to global food security, providing about 17% of global animal proteins and 7% of all proteins in 2019 (FAO, 2022). Aquatic foods constituted a minimum of 20% of animal protein intake for approximately 3.3 billion people (FAO, 2022). Research has also shown that seafood generally has a relatively limited climate impact in comparison to most other animal protein sources, such as beef, pork and chicken, along with a higher nutritional value per climate impact (Hallström et al., 2019). Marine captured species amounted to 78.8 million tons in 2020 (FAO, 2022), caught by around 4.1 million fishing vessels. Although total catches have remained relatively stable, the number of fishing vessels has decreased (FAO, 2022). Catches being landed by fewer fishing vessels leads to improved fuel efficiency in fishing operations, and fuel consumption has been identified as the most important input in fisheries (e.g. Ziegler et al., 2022).

Currently, fisheries depend on fossil fuels, and demersal trawl fisheries are among the most energy-intensive operations in comparison with other fishing methods (Byrne et al., 2021; FAO, 2022), where the stock abundance has great impact on the greenhouse gas (GHG) emissions. Indeed, rebuilding of fish stocks has been shown to be the primary contributing factor reducing GHG emissions in Iceland’s demersal fisheries from 1997 to 2018 (Kristofersson et al., 2021), and significantly improved fuel efficiency and hence GHG emissions in Sweden from 2002 to 2010 (Ziegler and Hornborg, 2014). However, bottom trawling has been reported to impact the marine ecosystems significantly in some

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places, which has particularly been debated in recent years with respect to the impact of bottom trawling when it comes to resuspending carbon that is stored in the benthic layers (Hiddink et al., 2023; Ovando et al., 2023; Parker et al., 2018; Sala et al., 2021).

Global fishery records from 1990 to 2010 show that the median fuel use intensity was 639 L per ton catch (Parker and Tyedmers, 2014) with large differences between fishing methods, and continues to be the primary source for GHG emissions. Even within demersal trawlers, it fluctuates depending on the target species (Ziegler et al., 2018). As demersal species live on varying ocean depth and fishing grounds (Ingólfsson et al., 2007; Olsen et al., 2010), energy consumption varies with different stock densities, where a higher density leads to a higher catch rate and more fuel efficient fishery (Ziegler et al., 2018). According to the EU parliament, the fisheries sector is facing challenges in the accelerating energy crisis due to its high dependency on a stable supply of fossil fuels at a low price, highlighting the need for reducing fuel use intensity and shifting to alternative, low-carbon fuels (European Parliamentary Research Services, 2023).

Decarbonization of the EU fishing fleets is therefore a priority, but there are however challenges to overcome before a large-scale energy transition in the fishing sector, due to e.g. high cost, lack of infrastructure and supply of alternative fuel, as well as practical and technical obstacles (European Parliamentary Research Services, 2023). Along with shifting to alternative fuels, energy transition consists of energy efficiency measures, that should be implemented before to minimize the volumes needed (European Commission, 2022; European Parliamentary Research Services, 2023).

To increase energy efficiency in fishing, managing stocks sustainably and using the most energy efficient fishing methods are of importance (Kristofersson et al., 2021). In addition, fishing technologies are increasingly becoming more energy efficient, reducing environmental impacts per unit caught, improving handling, and enhancing product quality. The optimization of the performance in the capture phase might influence profitability as well as impacts on climate, seabed habitats and biota (McConnaughey et al., 2020; Pusceddu et al., 2014).

Previous studies have focused on the general environmental impacts of current fisheries, and none have specifically examined the impact of fleet renewal on the GHG emissions. This research fills that gap by analyzing the renewal of the Icelandic bottom trawl fleet and its effect on fuel-related GHG emissions. The total number of trawlers decreased by 50%, from 84 vessels to 42 vessels from 2000 to 2022, and newer vessels have replaced older and often outdated trawlers (Statistics Iceland, 2023). In this study, with the reference year 2022, 14% of the total Icelandic demersal trawler fleet, in total 6 trawlers, was included. The reduction of trawlers is linked to several factors, including consolidation of fishing rights (quotas), increased prioritization of product quality, good working conditions and fuel efficiency, and labor agreements where the crew takes part when investing in new vessels (Agnarsson et al., 2016; Viðarsson and Thordarson, 2020). Although the new trawlers are supposedly better equipped and more efficient, the environmental aspects of the renewal have yet to be investigated.

2. Materials and methods

The Icelandic fishing fleet has gone through substantial renewal and reconstruction in recent years. The current study analyzed the effect of vessel renewal, fleet reconstruction, on the fuel use intensity (l/kg) and GHG emissions of Icelandic demersal trawl fisheries, based on the Life Cycle Assessment (LCA) methodology. This offers valuable insights into the potential environmental benefits of modernizing fishing fleets.

This study followed the International Standard Organizations (ISO) 14040 (ISO, 2006a) and 14044 (ISO, 2006b; Hauschild et al., 2018) with focus on climate change impacts. It also complied with ISO 22948 for GHG calculations, expressing GHG emissions as kg CO_2 equivalents. This is a common practice in LCA, in a step called impact assessment, to convert amounts of other greenhouse gases to the equivalent amount of carbon dioxide, to aggregate greenhouse gases based on their global-warming potential (GWP) (Eurostat, 2024). Results of other impact categories assessed beyond GHG emissions are presented in Table X1 in *Appendix*. Data was gathered first-hand from fisheries companies in Iceland which participated in the research project "The effects of the renewal of the Icelandic fishing fleet on the carbon footprint of products" funded by The Icelandic Food Innovation Fund 2020–2023.

Due to large uncertainty and inconsistency in available data on this benthic carbon emissions due to trawling, and because the focus of this study is on assessing the GHG emissions of old and new renewed vessels, this study does not engage in incorporating potential carbon emissions due to benthic layer emissions.

2.1. Goal and scope

This study aimed to.

1) provide an up-to-date estimation of the GHG emissions of Icelandic demersal trawled fish,
2) evaluate the importance of fleet renewal and onboard processing on fisheries GHG emissions in relation to other factors

The functional unit assessed was "1 kg of demersally trawled fish at landing".

The focus of the study was on global warming potential, referred to as GHG emissions. The functional unit was chosen to cover potential differences in impacts based on catch composition and to investigate if the GHG emissions varied between the old trawlers and the renewed trawlers studied. The allocation method chosen for the base case was mass allocation. To demonstrate sensitivity towards choosing the allocation method when comparing the edible part of the different species, economic allocation was applied in a *scenario* as the fish species differ in price and ratio of the fish utilized for human consumption (edible part ratio; Table 3).

2.2. Data collection and system boundary

Data was collected first-hand from eleven trawlers owned by four major seafood companies in Iceland (Table 1) to represent cross-section of the Icelandic fleet, with respect to age, size, catch composition and operation. Fuel consumption (kg oil) was collected first-hand, where catch composition data was obtained both first-hand and from the open official catch-registry of the Directorate of Fisheries database (Fiskistofa, 2023). Challenges in obtaining fuel consumption and other data limited the study to eleven trawling vessels.

The earliest data was from 2012 and the latest from 2022. All data was aggregated and used as an annual average for the years provided by the companies. Hence, not all trawlers included the same reference years (Table 1), although some years did overlap between the trawlers. However, resource use has been shown to vary both within each year and between years (Ziegler et al., 2018).

Trawlers have been renewed during different time periods ($^{a\text{-}d}$ in Table 1). Trawler 2 replaced Trawler 1 in 2018, a 46-year younger vessel that was built to ensure better quality of the catches, better working conditions, and lower fuel consumption. Similar reasons led to the replacement of Trawler 3 by Trawler 4, and for Trawler 10 by Trawler 11. Trawler 8 replaced two older vessels, Trawler 6 and Trawler 7, where Trawler 5 and Trawler 9 are still in operation although being older vessels, thereby providing a benchmark for the newer vessels. Fuel

Table 1
Information about the trawlers studied and years data was collected for the current study. Trawlers are numbered, where subscription indicates the same trawler. Old vessels are indicated with blue color and new vessels with green color. Colored numbers indicate fuel intensity (liters oil per kg catch).

Trawler	Owner of the vessel	Building year	Length (m)	Width (m)	GT	Hp	Fuel intensity (l/kg) during the reference years for the trawlers										
							2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
1[a]	A	1972	53.7	9.5	809	2300	0.17										
2[a]	A	2018	51.3	13	1222	2407									0.17	0.18	
3[b]	B	1977	51.8	10.8	745	2200	0.35	0.30	0.23	0.28	0.29	0.28					
4[b]	B	2017	62.6	13.5	2081	2172							0.23	0.21	0.25	0.26	0.25
5	B	1987	56.5	12.6	1470	2991				0.22	0.23	0.23	0.23	0.25	0.29	0.30	0.29
6[c]	C	1972	55.8	9.5	809	2300			0.53	0.43							
7[c]	C	2000	37	10.4	600	1436				0.35	0.34						
8[c]	C	2018	51.3	13	1222	2407								0.24	0.28		
9	C	1991	29	7.9	356	1000									0.24		
10[d]	D	2007	29	10.4	486	699							0.17				
11[d]	D	2019	29	12.3	611	788									0.19	0.19	

a-d indicate replacement of trawlers, before and after changes

intensity (l oil/kg catch) at each reference year for each of the trawlers can be seen in Table 1.

Annual data regarding steaming and catching for Trawler 4 and Trawler 5 was provided first-hand where liters of oil were measured both during steaming and during catching, to investigate if trend of longer catching distance appeared with later years. Furthermore, the impact of changing Trawler 5 from a freezer trawler to cooling trawler was investigated.

The system boundaries included datasets of fuel consumption, catching ground, catch composition and the descriptions of the trawlers studied, of the eleven different bottom-trawlers (Fig. 1). The construction of the vessel itself, use of coolants, anti-fouling, cleaning agents and other resources were not within the system boundaries as they have shown to have minimal influence on the results except for coolants. Small fisheries can have up to 40% increase in GHG emissions due leaks, repairs and services in onboard cooling systems (Winther et al., 2009; Ziegler et al., 2013, 2018). However, as sufficient data was not available for coolants in the current study, it remained outside the system boundaries.

2.3. *Life cycle impact assessment (LCIA)*

Calculations were performed using SimaPro version 9.1.0.8 software (PReConsultants, Amersfoort, Netherlands) in conjunction with the ecoinvent 3.8 Life Cycle Inventory Database (Wernet et al., 2016).

The environmental impact of focus in this study was global warming potential (GWP100a) although all the impact categories are presented in Table X1 in *Appendix*. The average fuel consumption yearly during bottom trawl fishing (Fig. 1) was modelled for each trawler and year in the software. The impact assessment method used in the current study was CML-IA baseline V3.08/EU25 and was chosen to be able to compare with Smarason et al. (2014), which already compared long-liners to trawlers with the Icelandic fishery. However, the fleet renewal impact had yet to be investigated as well as the general GHG emission estimate for Icelandic trawling updated.

2.4. *Sensitivity analysis*

A sensitivity scenario was identified to evaluate the sensitivity of the results (Table 2).

The allocation method chosen as the *base-case* was dependent on the mass of the catch (mass allocation), but as the different species vary both in value and utilization ratio, a *scenario* describing economic allocation was added when comparing the edible part (eatable part) of the different species studied (Table 3). Therefore, economic allocation *scenario* was assessed, as both value of the fillets and the processing residues vary across the species studied, affecting the economically based allocation (*scenario*) compared to the mass allocation (*base-case*) (Svanes et al., 2011). Hence, the *scenario* showed if the GHG emissions were allocated based on monetary value (The Icelandic currency, ISK) as the fish is often caught due to the relatively high price of the fillet. Further details

Table 2
Sensitivity scenario of fishing 1 kg of demersal fish using bottom trawling.

Sensitivity scenario	Sensitivity description
Allocation method	• Results could vary as the species vary in edible part and value

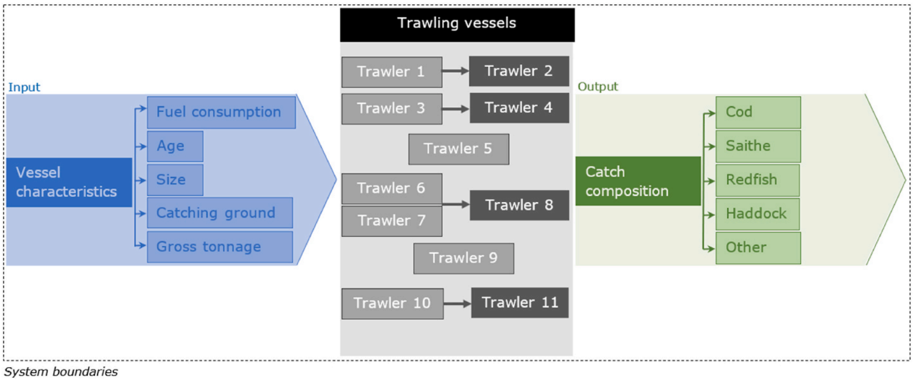

Fig. 1. System boundaries of the Life Cycle Assessment of producing 1 kg of demersally trawled fish at landing. The trawling vessels are described in Table 1.

Table 3

Ratios of streams from target species where values are edible except values in brackets, without further food processing. The total value both in base case and scenario are expressed in kg/kg and ISK/kg and collected from Statistics Iceland (2023).

	Fillet	Head and backbone	Liver and roe	Skin and cut-offs	Total mass for fillets only (*Base-case*) (kg/kg)	Total value for fillets only (*Scenario*) (ISK/kg)
Cod	39%	41%	14%	(6%)	39%	90%
Haddock	36%	42%	(14%)	(7%)	36%	92%
Saithe	38%	40%	(14%)	(8%)	38%	88%
Redfish	35%	(65%)			35%	79%

regarding prices of the different parts of each fish species are listed in Table X2 in *Appendix*.

2.5. Statistical analysis

Statistical and regression analyses were conducted utilizing Microsoft Office 365's Excel software (Microsoft, Redmond, WA, USA). Results were presented as mean values ± standard deviation (SD), with a significance threshold of $p < 0.05$ to ascertain statistical significance.

Multivariable linear regression model was developed to assess the outcomes for the various trawlers, and to identify the most influential contributing variables (Montgomery and Runger, 2014). Prior to developing the model, the authors selected the most relevant explanatory variables to analyze their impact on the trawlers GHG emissions. The model was fitted with the response variable GHG data, evaluated by R^2 metrics and the explanatory variable parameters significance tested with p-values. The resulting model is described with the following equation:

$$GHG = b_0 + b_1 CATCH + b_2 AGE + b_3 SIZE + b_4 GT + b_5 ZONE + e$$

where GHG emissions is the response variable, and catch, age, size (length/width), GT (gross tonnage), and zone (effort due to fishing zone, ranked from 1 to 5) are the selected explanatory variables, and b the model parameters.

3. Results and discussion

3.1. Estimation of the GHG emissions of Icelandic demersal trawled fish

Each fishing vessel displays unique operational patterns and catch compositions and no clear trend noticed in fuel efficiency for newer vessels compared to the old vessels (Fig. 2). Specifically, Trawler 2 and Trawler 11 show a slightly higher fuel use intensity than the vessels they replace, while Trawlers 4 and 8 have a lower fuel use intensity. The GHG emissions were demonstrated along with the kg CO_2-eq and fuel intensity (l/kg) of both old and renewed trawlers in Fig. 2.

The results show varying values from 0.5 to 1.0 kg CO_2-eq per kilo unprocessed catch, depending on the trawler, years and catch composition. Previously reported GHG emissions from 2014 were 1.0 kg CO_2-eq per 1 kg demersal fish landed (Guttormsdóttir, 2009; Parker et al., 2018). This variation could explain a trend of lower GHG emissions with target species such as cod, saithe and haddock, and higher GHG emissions for redfish (Fig. 2). The reason for a higher GHG emissions in vessels with redfish as target species could be due to redfish being caught generally at 500–600 m depth (Sigurdsson et al., 2006), where cod, saithe and haddock are generally caught at <200 m depth although cod can be found down to 500 m depth (FAO, 1990; Marine & Freshwater Research Institute, 2023). Furthermore, according to the Marine and Freshwater Research Institute, redfish are generally found in lower densities compared to the other fish species, increasing the catch-per-unit-effort (CPUE) (Hornborg et al., 2018; Ziegler et al., 2018), partially explaining the higher GHG emissions from redfish. However, changing the fuel type for the vessels could significantly lower the GHG emissions as shown with different energy source scenarios when processing fishmeal and fish oil (Hilmarsdóttir et al., 2022)

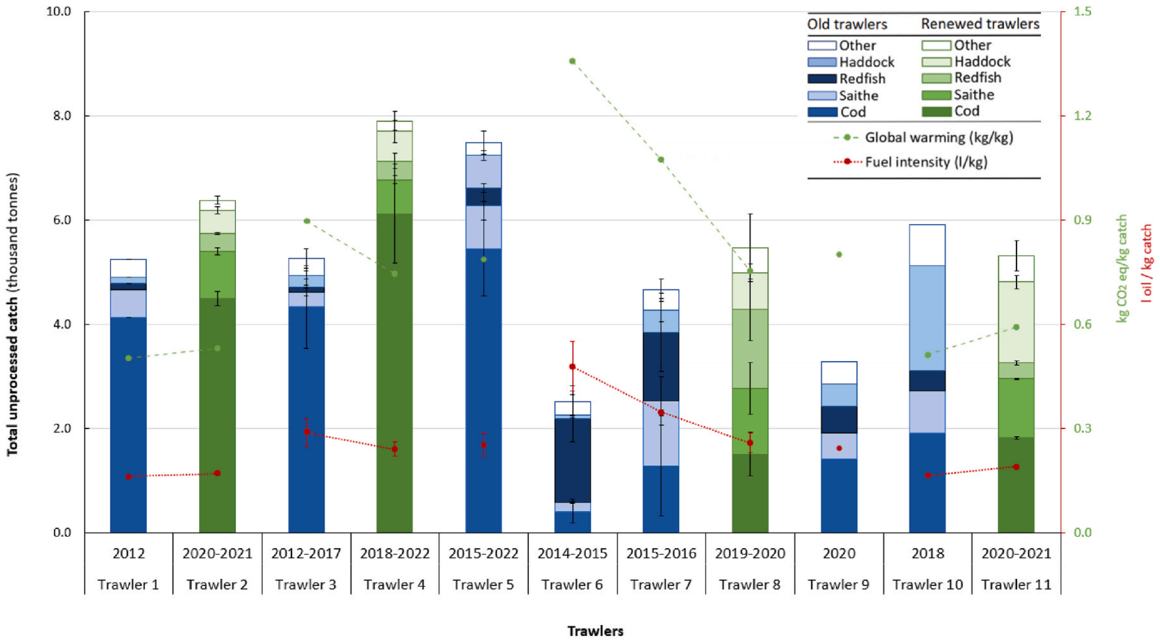

Fig. 2. Catch composition of each trawler in reference years are displayed in the figure bars. Different colors in bars present a different species including old or renewed trawler (see figure legend). The global warming potential (green dashed colored line) of unprocessed catch for each trawler and the catch composition along with fuel intensity (red dotted colored line). Global warming potential and fuel intensity are expressed on the right y-axis and total unprocessed catch on the left y-axis. Standard deviations are expressed as error bars when more than one reference year is in the dataset. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.2. Evaluating GHG emissions on the edible part of the catch

To evaluate GHG emissions on the edible part of the catch, mass – and economic allocation was estimated, as the target species varied both in value and ratio utilized for human consumption. As the mass allocation (base-case) measured the mass of each stream, such as cod fillets being 39% of the cod (kg/kg; Table 3), the economic allocation of cod fillet was 90% of the cod's value (ISK/kg; Table 3). Along with varying fillet prices for the species studied, valorization of the side-streams varies, affecting the GHGs. Further details regarding prices for each part of the fishes are shown in Table X3 in *Appendix*.

The GHG emissions from the unprocessed catch landed was allocated to the edible part of each fish species, including kg CO_2-eq per kg protein of the edible parts calculated from ISGEM database (Matis, 2023) (Table 4). Furthermore, in the current study, edible parts of the fish do not include feed or bait, only parts that are edible and sold directly for human consumption (see Table 5).

Currently, redfish is only caught for its fillets, although the side-streams are processed into fishmeal- and fish oil, and/or used as bait. The GHG emissions of redfish are estimated at 2.7 kg CO_2-eq per kg edible product and around 15.1 kg CO_2-eq per kg protein, estimated with mass allocation (Table 4). For the other species, the emissions varied as more than the fillet was considered edible, where cod, saithe and haddock ranged from 3.8 to 5.9 kg CO_2-eq per kg protein if the GHG emissions were allocated on edible part of the fish. The reason for a higher emissions of redfish protein could be due to higher emissions of the unprocessed redfish catch at landing, alongside the low utilization ratio as the fillet is currently the only part being utilized for human consumption.

3.2.1. Comparison between mass – and economic allocation

Previous studies calculated with economic allocation (kg 2.7 CO_2-eq with mass allocation) have reported 1.0–1.7 kg CO_2-eq per kg demersal fish landed (Parker et al., 2018), and 2.4 kg CO_2-eq per kg cod (Ziegler and Hansson, 2003). These values are relatively higher value than presented in the current study for the edible part of cod, which was 0.7 and 0.8 kg CO_2-eq per edible part of the cod for the *base-case*, and *scenario*, respectively. However, if the emissions were allocated solely to the fillet, emissions would range from 1.4 to 2.7 kg CO_2-eq per kg of demersal fish fillet, which would be closer to previously reported values from Parker et al. (2018) and Ziegler and Hansson (2003). Hence, one important explanation for the relatively low emissions resulting for Icelandic seafood from demersal trawling is the very high rate of utilization.

When comparing the GHG emissions between mass- (*base-case*) and economic allocation (*scenario*)(Fig. 3), the ratio has shifted. For cod and haddock, economic allocation *scenario* showed higher percentage of the GHG emissions being allocated on the edible part, possibly due to higher utilization rate or those fish species compared to redfish and saithe. Furthermore, for redfish being the target species, Trawlers 7–9 show that with mass allocation, the GHG emissions for redfish are <10% higher if allocated by mass compared to value (*scenario*), and <6% for saithe. The reason might be both due to the ratio of side-streams being valorized, and the price for each of the side-streams, as edible parts of saithe and redfish are nearly half of the value for edible parts of cod and haddock (Fiskistofa, 2023; Statistics Iceland, 2023). Therefore, an opportunity to utilize a higher ratio of redfish and saithe could result with a lower GHG emissions allocated to the fillet, distributing the emissions to other side-streams, and possibly increasing the value of the fish species.

Table 4
GHG emissions allocated on unprocessed catch landed compared to allocation on edible fish parts and fillet. Values represent the base-case which is with mass allocation, where economic allocation scenario in brackets.

	Cod	Haddock	Saithe	Redfish
GHG emissions (kg CO_2-eq/kg unprocessed catch)	0.7 (0.8)	0.5 (1.0)	0.8 (1.0)	1.0 (0.8)
Edible product	87%	78%	78%	35%
Allocating only to edible parts[a]	0.8 (0.9)	0.7 (1.2)	1.1 (1.2)	2.7 (2.3)
Allocating all to the fillet[a]	1.8 (2.1)	1.4 (2.7)	2.2 (2.5)	2.7 (2.3)
kg CO_2-eq per kg protein edible parts [b]	4.5 (5.2)	3.8 (7.3)	5.9 (6.9)	15.1 (12.5)

[a] numbers from the regression model.

[b] calculated from the ISGEM database (Matis, 2023).

Table 5
Values based on the regression analysis, expressing kg CO_2eq/kg catch and average for each fish species depending on catch volumes.

Fish species kg CO_2-eq/kg catch	All the trawlers Total catch	Trawlers by target species >1000 tons catch	Comparison with Ziegler et al., (2022)
Cod	0.70	0.72	0.68
Haddock	0.51	0.55	0.79
Saithe	0.82	0.83	0.75
Redfish	0.95	1.08	–

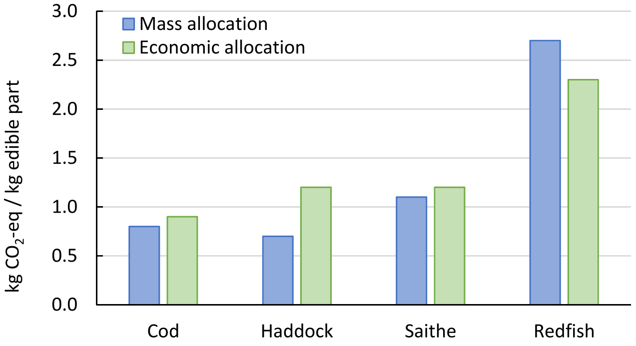

Fig. 3. Average GHG emissions for the edible part of each fish species compared between mass and economic allocation.

3.2.2. Utilization possibilities

Higher utilization ratios of the demersal species can lower emissions of the edible part, by valorizing higher ratio of the side-streams for human consumption. Cod utilization has increased over the years, and today even higher part of the cod is utilized, skin and guts, where the skin is sold and used for collagen production (Feel Iceland, 2023) and medical applications (Kerecis, 2023). However, as utilization of by-products is often part of the newer trawlers it can lead to increased energy intensity onboard the vessels and as long as fishing vessels operate on fossil fuels, onboard processing is more climate intensive than processing on land, if using non-fossil energy sources (Hilmarsdóttir et al., 2022). That can result in allocating impacts to higher ratio usage of side-streams which can lead to a higher GHG emissions of individual trawlers. As an example, use of refrigerants in onboard cooling systems have shown to be responsible for <30% of the total GHG emissions in landings (Ziegler et al., 2018), and results from our study might therefore be underestimated for some fish species. However, that data was not possible to collect for the fishing vessels under study here, and therefore falls outside the system boundaries. The results from Ziegler et al. (2018) demonstrate the valorizing side-streams are not "free" of environmental impacts as it often claimed, e.g. requires use of additional energy for processing and chemicals. Hence, applying LCA remains critically important when exploring valorization options and changes within production processes.

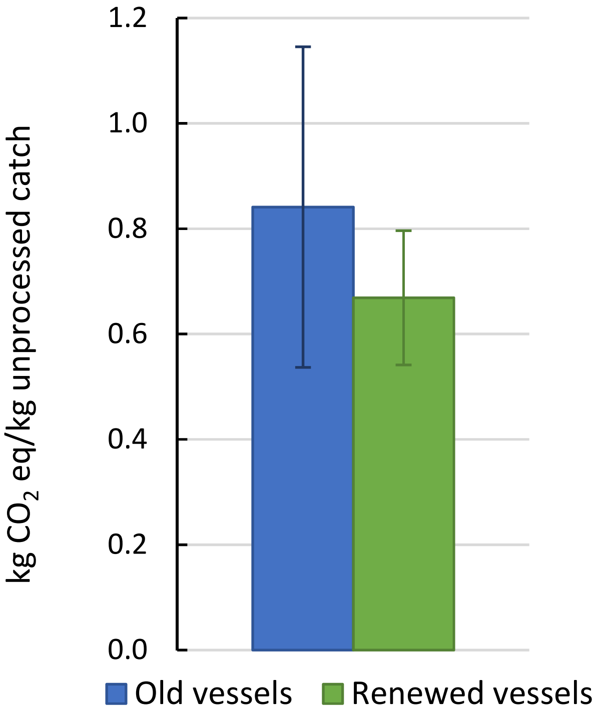

Fig. 4. Average GHG emissions per kilo unprocessed catch in old (blue color) and renewed vessels (green color) during the reference years. Error bars represent standard deviation. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.3. Evaluating the importance of fleet renewal, catching and steaming, onboard processing on fisheries GHG emissions

The utilization of by-products was more impactful in reducing GHG emissions compared to the vessel renewal (Fig. 3). The eleven trawlers were categorized as old (blue color; Fig. 4) and renewed vessels (green color; Fig. 4) and average emissions estimated per kilo catch. The average CO_2 emissions per unit of catch have been reported to reduce by approximately 40% in Iceland's demersal fisheries, between 1997 and 2018 (Kristofersson et al., 2021). However, in the current study, this reduction was not shown between old and new vessels indicating that fleet renewal is not the primary factor reducing GHG emissions. The fuel intensity (l/kg) was slightly higher for old vessels (0.28 ± 0.11) compared to renewed vessels (0.22 ± 0.0), which explains the small impact of the fleet renewal. Fuel intensity was further investigated in relation to steaming, catching and onboard processing.

3.3.1. Fuel intensity compared with steaming, catching, and onboard processing

Fuel intensity remained similar in the current study as previously reported (0.2–0.5 l) (Ziegler et al., 2022), although many factors can affect fuel consumption during fishing (catching and trawling) (Hilmarsdóttir et al., 2022). Two trawlers (*Trawler 4* and *Trawler 5*) were further compared to investigate if fuel intensity would vary between *steaming* and *catching* phases of the trawler. Additionally, onboard processing was investigated in *Trawler 5*, as it used to have onboard processing (freezer trawler) from 2012 to 2014 but was converted to a fresh fish trawler in 2015.

Both trawlers showed increased GHG emissions from 2018 to 2021. This increase could be due to longer trawling distances, less efficient engines, or larger quantities of cooling media for optimal chilling (Fig. 5).

On average, GHG emission originated 60% from catching (58% for old and 63% for the newer trawlers) and 40% from steaming in a chilled/superchilled fish trawler. Therefore, an overall estimation of.

Around a 24% reduction of the GHG emissions during catching was noticed when *Trawler 5* was changed from a freezing to cooling their product (from 2012 to 2014, and 2015–2022, respectively). Changing the trawler from freezing trawler to a fresh fish trawler not only resulted in reduction of GHGs, but also increased the value of the catch, as chilled/superchilled fish has a higher price than frozen fish (Flick, 2009), minimizing the trade-off for this change. Furthermore, newer trawlers could possibly process and cool the catch quicker along with better general working conditions for the crew depending on vessel design. Moreover, emission standards and fishing zone access can vary depending on the vessel length, whereas the Norwegian Maritime Authority apply stricter regulations for vessels over 80 m (Norwegian Maritime Authority, 2012, 2023). Therefore, not only can handling onboard and other onboard processing affect the GHG emissions (Fig. 5b), but also future vessel design due to less strict length regulations (rather than regulating beam/width), which is an example where regulations can counteract technological improvement and could be a future concern. However, currently stock size is reported to have greater effect on fuel efficiency rather than vessel size (Byrne et al., 2021; Kristofersson et al., 2021; Ziegler and Hornborg, 2014).

To identify parameters impacting the GHG emissions and to evaluate the influence of key variables, a regression analysis was performed.

3.4. Trawler variables influencing GHG emissions - a regression analysis

All the selected explanatory variables in Eq.1influence the GHG emissions to some level and the regression analysis suggests that $R^2 =$

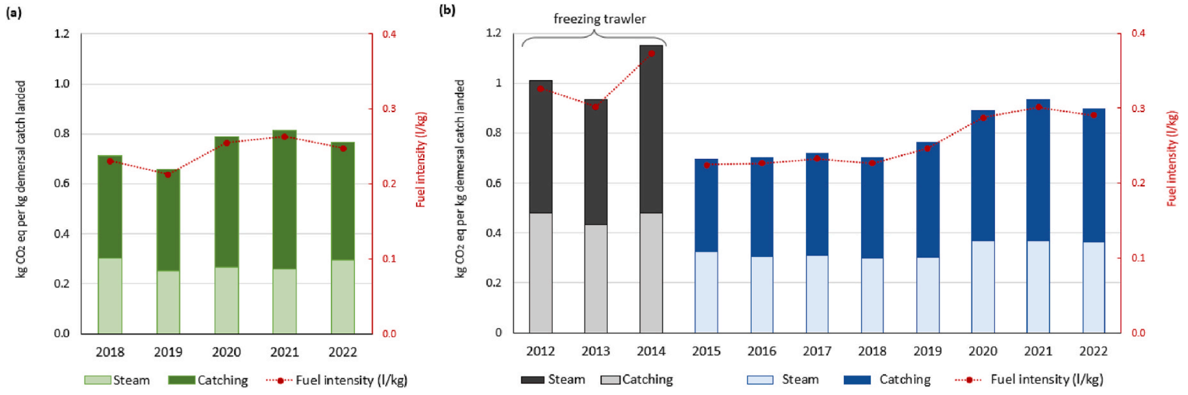

Fig. 5. GHG emissions (kg CO_2-eq) for Trawler 4 (a) and Trawler 5 (b), of 1 kg demersal fish landed, by trawling during various years. Emissions were divided between steaming and catching during trawling and compared with fuel intensity (l/kg) of the second x-axis marked in red. Trawler 4 has been renewed (green color) but not Trawler 5 (blue color). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

94.3% of the variation in the GHG emissions can be explained by the explanatory variables *catch* ($p = 0.039$), *age* ($p = 0.027$), *size* ($p = 0.032$), *GT* ($p = 0.065$), and *zone* ($p = 0.002$). The explanatory variables *catch, age, size* and *zone* were found to have most effects, $p < 0.05$ in the model, while the explanatory variable *GT has* a higher p value of 0.065. These results indicate that the weight of the trawlers (gross tons) influences the GHG emissions less than the catch, trawler age and fishing zone. Trawler size and shape influenced the GHG emissions. Icelandic regulations limit trawler length to 30 m, leading to wider designs that increase drag and fuel use. These regulations also limit engine size, potentially reducing fuel efficiency.

Fig. 6 shows graphs locating the trawlers investigated in terms of total GHG emissions and total catch for the reference years. The graphs are shown for different fish species (cod, saithe, haddock and redfish) and the slope of a best-fit regression line can represent the kg CO_2-eq/kg catch ratio. The comparison does not show a clear trend for GHG emissions for newer vs older trawlers during the reference period. Comparison between the fish species indicated that a kg of redfish gave an average of 0.95 kg CO_2-eq, cod 0.70 kg CO_2-eq, saithe 0.82 kg CO_2-eq, and haddock the lowest or 0.51 kg CO_2-eq, if GW was divided for all the unprocessed catch per each trawler. For comparison results from (Ziegler et al., 2022, average values for the period 2007–2017) showed greenhouse gas emissions in kg CO_2-eq/kg catch at landing for cod of 0.68, for saithe 0.75 and haddock 0.79. When comparing the total catch of all the trawlers, previously published data from Ziegler et al. (2022) showed less than 3% increase in GHG emissions for cod, 55% lower for haddock, and 9% higher for saithe. Values calculated with the total catch was similar to more refined data with only the target species (over >1000 tons/year).

As Fig. 6 shows there are trawlers with low catch quantity for each of the studied species, this is most apparent for redfish where there are only three trawlers (T6, T7 and T8) that are targeting redfish to any extent during the reference period. For cod, however, only one trawler (T6) catches less than 1000 tons/year and for saithe and haddock the catches are more evenly distributed between trawlers.

The regression model showed that catch, age and fishing zone account for approximately 94% of the GHG emissions from trawlers, with CO_2 emissions varying across fish species. As the fishing industry continues to evolve, regression models could help identify which variables to prioritize for reducing GHG emissions.

4. Conclusions

The study showed that.

- GHG emissions of unprocessed catch varied from 0.5 to 1.0 kg CO_2-eq per kilo, depending on the trawler, years and catch composition
- GHG emissions for cod, haddock, saithe and redfish varied from 0.7 to 2.7 kg CO_2-eq per kilo edible part, depending on the species and valorization ratio of each species.
- Onboard processing at sea and certain types of vessel regulations can lead to increased fuel usage. Evaluation of the GHG emissions should consider the trawler's target catch species along with influencing factors, such as the trawler age and shape

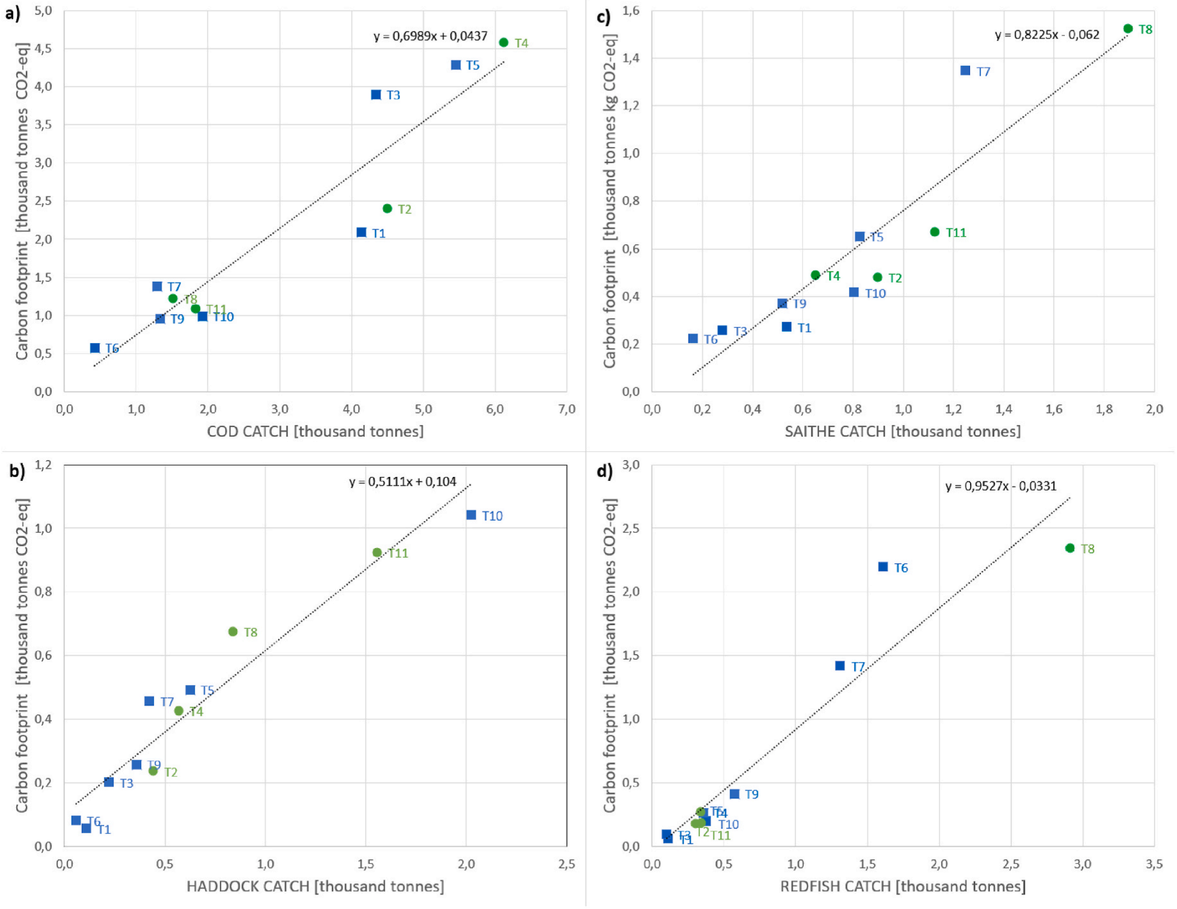

Fig. 6. Comparison between the different trawlers for total GHG emissions and the total amount caught in the reference years. The relation is presented in four graphs for different fish species cod (a), haddock (b), saithe (c), and redfish (d). Old vessels are indicated with blue color boxes and new vessels with green color dots. The trawlers' information can be seen in Table 1 and the differentiation between the reference years in Fig. 2. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

- The GHG emissions of unprocessed catch did now show significant difference after vessel renewal
- Of the variables analyzed the weight of the vessels influenced the GHG emissions less than the catch, trawler age and fishing zone. The regression analysis however did not show a clear trend for older vs newer trawlers in terms of GHG emissions
- Slight increase in fuel intensity from 2018, both during steaming, and catching
- The utilization of side-streams was more impactful in reducing GHG emissions compared to the vessel renewal. However, valorizing side-streams can increase emissions and hence, LCA methodology is highly recommended to explore options and estimate the effects of the changed process beforehand

Recommendations for the industry would be to investigate onboard processing steps for energy required additionally for the vessels, utilize the by-products at a higher rate for most species. Furthermore, following points are suggestions for future research and actions that aim to enhance the sustainability of bottom trawling practices by leveraging technology, policy and comprehensive data analysis.

- **Enhanced Data Collection** would include implementation of real-time monitoring systems for fuel consumption and emissions to improve the accuracy of GHG impact models which could be linked to different species caught at each time for more exact calculations of impacts for each caught species
- **Low-Carbon Technologies** would reduce fossil fuel reliance and emissions
- **Optimized Fishing Practices** would reduce bycatch and therefore environmental impacts by adopting fuel-efficient and selective trawling methods
- **Sustainable Fishing Policies** would require incentives and regulations for energy-efficient vessels and low-emission technologies as well as sustainable utilization of fish stocks, which build on thorough environmental assessments based on detailed validated data to reduce risk of implementing less sustainable fishing policies
- **Comprehensive Life Cycle Assessments** would identify areas for reducing environmental impacts if all stages of the fishing process were included

CRediT authorship contribution statement

Guðrún Svana Hilmarsdóttir: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Jónas R. Viðarsson:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Birgir Örn Smárason:** Writing – review & editing, Visualization, Validation, Methodology, Conceptualization. **Sæmundur Elíasson:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Friederike Ziegler:** Writing – review & editing, Validation. **Ólafur Ögmundarson:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Conceptualization.

Declaration of Competing interest

Authors have no conflict of interest to declare.

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6. Appendix

Table X1

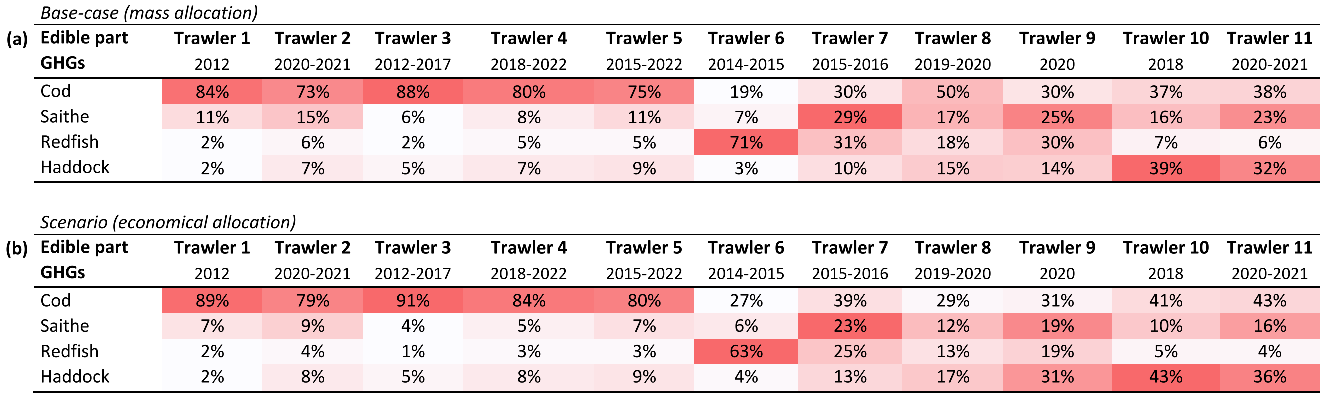
The environmental impacts of each trawler per one kg of unprocessed catch. as an average at years ranging from 2012 to 2022

Environmental impacts per kg unprocessed catch													
Impact category	**Unit**	**Total average**	**Trawler 1**	**Trawler 2**	**Trawler 3**	**Trawler 4**	**Trawler 5**	**Trawler 6**	**Trawler 7**	**Trawler 8**	**Trawler 9**	**Trawler 10**	**Trawler 11**
			2012	2020–2021	2012–2017	2018–2022	2015–2022	2014–2015	2015–2016	2019–2020	2020	2018	2020–2021
Abiotic depletion	kg Sb eq	1.3 E−07	8.7 E−08	9.2 E−08	1.5 E−07	1.3 E−07	1.4 E−07	2.3 E−07	1.9 E−07	1.4 E−07	1.3 E−07	8.9 E−08	1.0 E−07
Abiotic depletion (fossil fuels)	MJ	1.1 E+01	6.9 E+00	7.3 E+00	1.2 E+01	1.0 E+01	1.1 E+01	1.9 E+01	1.5 E+01	1.1 E+01	1.0 E+01	7.1 E+00	8.2 E+00
Global warming (GWP100a)	kg CO2 eq	7.8 E−01	5.0 E−01	5.3 E−01	9.0 E−01	7.5 E−01	7.9 E−01	1.4 E+00	1.1 E+00	8.0 E−01	7.5 E−01	5.1 E−01	5.9 E−01
Ozone layer depletion (ODP)	kg CFC-11 eq	1.4 E−07	8.9 E−08	9.4 E−08	1.6 E−07	1.3 E−07	1.4 E−07	2.4 E−07	1.9 E−07	1.4 E−07	1.3 E−07	9.0 E−08	1.0 E−07
Human toxicity	kg 1.4-DB eq	1.3 E−01	8.2 E−02	8.7 E−02	1.5 E−01	1.2 E−01	1.3 E−01	2.2 E−01	1.8 E−01	1.3 E−01	1.2 E−01	8.4 E−02	9.7 E−02
Fresh water aquatic ecotoxicity	kg 1.4-DB eq	1.9 E−02	1.2 E−02	1.3 E−02	2.2 E−02	1.8 E−02	1.9 E−02	3.3 E−02	2.6 E−02	2.0 E−02	1.9 E−02	1.3 E−02	1.5 E−02
Marine aquatic ecotoxicity	kg 1.4-DB eq	5.2 E+01	3.4 E+01	3.6 E+01	6.0 E+01	5.0 E+01	5.3 E+01	9.1 E+01	7.2 E+01	5.4 E+01	5.1 E+01	3.4 E+01	4.0 E+01
Terrestrial ecotoxicity	kg 1.4-DB eq	4.0 E−04	2.6 E−04	2.7 E−04	4.6 E−04	3.8 E−04	4.0 E−04	6.9 E−04	5.5 E−04	4.1 E−04	3.9 E−04	2.6 E−04	3.0 E−04
Photochemical oxidation	kg C2H4 eq	3.9 E−04	2.5 E−04	2.7 E−04	4.5 E−04	3.8 E−04	4.0 E−04	6.9 E−04	5.4 E−04	4.1 E−04	3.8 E−04	2.6 E−04	3.0 E−04
Acidification	kg SO2 eq	1.7 E−02	1.1 E−02	1.2 E−02	2.0 E−02	1.6 E−02	1.7 E−02	3.0 E−02	2.4 E−02	1.8 E−02	1.7 E−02	1.1 E−02	1.3 E−02
Eutrophication	kg PO4 eq	2.3 E−03	1.5 E−03	1.6 E−03	2.7 E−03	2.2 E−03	2.3 E−03	4.0 E−03	3.2 E−03	2.4 E−03	2.2 E−03	1.5 E−03	1.8 E−03

Table X2
The value (ISK/kg) of each part of the target fish species, used in economical allocation (scenario)

ISK/kg	Cod	Haddock	Saithe	Redfish
Fillet	1684	1809	1014	1246
Head	109	102	90	178
Backbone	71			
Skin	135	130	130	
Liver and roe	165	318	282	
Cut-offs	450			

Table X3
Base-case (a) and scenario (b) for the edible part of different fish species. as a percentage of the total catch during the reference period for different trawlers. Darker red color indicates higher GHG emissions compared between the trawlers for the same fish species



Base-case (mass allocation)

(a)

Edible part GHGs	Trawler 1 2012	Trawler 2 2020-2021	Trawler 3 2012-2017	Trawler 4 2018-2022	Trawler 5 2015-2022	Trawler 6 2014-2015	Trawler 7 2015-2016	Trawler 8 2019-2020	Trawler 9 2020	Trawler 10 2018	Trawler 11 2020-2021
Cod	84%	73%	88%	80%	75%	19%	30%	50%	30%	37%	38%
Saithe	11%	15%	6%	8%	11%	7%	29%	17%	25%	16%	23%
Redfish	2%	6%	2%	5%	5%	71%	31%	18%	30%	7%	6%
Haddock	2%	7%	5%	7%	9%	3%	10%	15%	14%	39%	32%

Scenario (economical allocation)

(b)

Edible part GHGs	Trawler 1 2012	Trawler 2 2020-2021	Trawler 3 2012-2017	Trawler 4 2018-2022	Trawler 5 2015-2022	Trawler 6 2014-2015	Trawler 7 2015-2016	Trawler 8 2019-2020	Trawler 9 2020	Trawler 10 2018	Trawler 11 2020-2021
Cod	89%	79%	91%	84%	80%	27%	39%	29%	31%	41%	43%
Saithe	7%	9%	4%	5%	7%	6%	23%	12%	19%	10%	16%
Redfish	2%	4%	1%	3%	3%	63%	25%	13%	19%	5%	4%
Haddock	2%	8%	5%	8%	9%	4%	13%	17%	31%	43%	36%

Data availability

Data will be made available on request.

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