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Greenhouse gas emissions of seafood from Danish capture fisheries in the Skagerrak, Kattegat, and western Baltic

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Abstract

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Interest in finding sustainable diets is increasing where more attention has been paid to the role of seafoods in recent years. Danish fisheries' producer organisations are interested in better understanding the carbon footprint and nutritional content of different species caught in Danish fisheries and how they compare to other types of animal-source food. The aim of this report is to place a selection of seafood products from Danish capture fisheries in a sustainable nutrition context. This is done by quantifying their greenhouse gas emissions, inferred from fishing effort, as well as nutritional content and relate findings to previous estimates of other common animal-source foods (farmed salmon, chicken, pork and beef). Furthermore, attempts to identify important drivers and improvement potentials are made. It is found that in terms of nutritional value, fatty fish (herring and farmed salmon) have a higher combined nutrient density than other foods included. Overall, herring and plaice caught in Danish fisheries in the Skagerrak, Kattegat and western Baltic are animal-source foods with lower greenhouse gas emissions than pork, beef, chicken, and farmed salmon. The same results are found for cod compared to pork and beef. Variability within and between gears, fishing areas and over time is however found, indicating improvement potentials. In the Skagerrak and Kattegat, shifting from demersal trawling to Danish seine/other gear types would lower fisheries greenhouse gas emissions considerably, while this potential is smaller in the western Baltic Sea. This partly reflects different targeting patterns, where cod is the main target species in the western Baltic Sea, while it is more a by-catch in crustacean fisheries in the other fishing areas. When results are compared with other fisheries targeting the same species, Danish plaice fisheries are associated with considerably lower fuel use relative to other fisheries for plaice. Results for Danish herring and cod vary depending on fishery, with some fisheries being less efficient than found elsewhere. The outcome for Danish fisheries is in part reflecting the different gears used but could also indicate different stock status, in particular for cod, and different methodological approaches. More detailed analysis, with collection of actual fuel use data for these fisheries instead of using modelled data, would be of interest to allow for further understanding of drivers as well as validation of results.

Key words: seafood, greenhouse gas emissions, fisheries, cod, plaice, herring

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Content

Preface

This work has been funded by the Danish Fiskeafgiftsfonden ("Projekt CO2 aftryk i Dansk Fiskeri"). Representatives of three Danish Producer Organisations (DFPO, DPPO, and FSK-PO) have been a part of the project planning and have provided comments on this report. For further details on what type of input and how that has been taken into account see Appendix 1.

Introduction

There is an increasing interest in what characterizes sustainable diets. To capture all different environmental aspects to consider in full is a challenging task, where Life Cycle Assessment (LCA) methodology has been increasingly utilized as a starting point. LCA is an ISO standardized systems analysis tool that aims to quantify a broad set of emissions and resource use associated to a product throughout its life cycle – from production to end-of-life (ISO 2006a,b). LCA studies shall, according to the standard, cover all relevant types of environmental impacts that need to be considered to fulfil the goal of the study. However, some of these impacts are more readily quantified in relation to a product supply chain (e.g., emissions that contribute to climate change, greenhouse gases GHGs) while others (e.g., impacts on biodiversity) are more difficult to assign quantitatively to a product, and methods are still under development. A so-called carbon footprint is an LCA study that is limited to only studying the combined greenhouse gas emissions of a product. Carbon footprints are often applied instead of a broader LCA due to a combination of the climate crisis and the availability of robust methods for estimation of this global impact, and a lack of such methods to cover more site-specific environmental aspects such as biodiversity. While the carbon footprint in some cases can serve as an indicator of broader impact (Ziegler et al. 2016a), in particular in fisheries, it is crucial to be aware of potential trade-offs can be hidden when only one type of impact is assessed – especially since the systems perspective on environmental impacts that is taken in LCA intends to avoid shifting burdens between different impacts.

Comparisons between LCAs with common metrics such as greenhouse gas emissions of different food systems are also complicated. It is important to be aware of that each study is designed to fulfil its specific goals, which differ between studies and have strong influence on outcomes. Comparisons of values across different LCAs are therefore not straight-forward and it is critical that methodological choices and available data is harmonized across studies that are to be compared to the extent possible. As an example, production systems on land are more complex in their emission modelling than capture fisheries. Fed animal production systems on land or in water involve complex feed sourcing patterns, which are highly variable over time depending on factors like supply and price. They are also more complex in the sense that, on top of energy requirements, they are associated with biogenic emissions (such as methane) and there are different approaches to model impacts from land use changes, the latter strongly influenced by assumptions related to deforestation (Ziegler et al. 2022). Modelling effects from land use change is also an area under rapid methodological development and for which current methods differ widely and complicates comparison across studies (e.g De Rosa et al. 2016).

The role of seafoods in sustainable diets has received increased attention in recent years, seen for example in the number of scientific publications over time. LCA has been applied to a range of seafood production systems from both capture fisheries and aquaculture since the early 2000s (recent global assessment based on their findings are found in Gephart et al. 2021). LCAs of seafood from capture fisheries have repeatedly concluded that it is in general the fishing phase in the product's life cycle that contributes most to the total greenhouse gas emissions (Avadí & Fréon 2013; Ziegler et al. 2016a). This is driven by fuel use by fishing vessels during the fishing trip; this is also a driver of most other impact categories in LCAs such as acidification, eutrophication, etc.. Exceptions when transport matters more include if airfreight occurs in the supply chain – and transport mode matters at least equally as distance (e.g., Ziegler et al. 2021). In turn, the fuel use intensity (litre per landing volume) during fishing varies with at least three orders of magnitude depending on fishery – from ~10 to 10 000 litres per ton in available fuel data records (Parker & Tyedmers 2015). Drivers behind this variability are strongly related to differences in catch per unit effort. This is influenced both by inherent differences in behaviour and catchability between species (e.g., shoaling or not), but also from various management-related decisions such as use of different gears in a fishery (e.g., Thrane 2004; Ziegler & Valentinsson 2008; Driscoll & Tyedmers 2010), fleet structure (Ziegler et al. 2016b) or stock status (Ziegler & Hornborg 2014; Byrne et al. 2021).

Another aspect to consider when comparing across foods is that greenhouse gas emissions per mass unit, the metric most commonly used, does not account for each food item having its characteristic nutritional properties (Golden et al. 2021), both in terms of content and how bioavailable these nutrients are. Seafood is both nutrient-dense and nutrients are found in highly bioavailable forms. The so called “meat effect” also applies to animal-source seafood, where eating these products increases the bioavailability of nutrients from other parts of the meal, such as vegetables (Thilsted 2019). Combining high nutritional value with minimal environmental impacts is referred to as ‘sustainable nutrition’, and studies have for example combined greenhouse gas emissions (i.e., carbon footprint) with nutritional content (Hallström et al. 2019). When nutritional value and carbon footprint is combined, seafood is highly diverse but on general offers a better option for sustainable nutrition than land-based animal production.

In light of the recent interest in sustainable diets, and seafood in particular, Danish fisheries producer organisations are interested in estimating the carbon footprints and nutritional content of different seafoods originating in Danish fisheries and how seafood products compare to other food products. The objectives of this study are therefore to i) quantify the greenhouse gas emissions of the fishing phase of Atlantic cod *Gadus morhua*, European plaice *Pleuronectes platessa,* and Atlantic herring *Clupea harengus* caught in Danish fisheries in in the Skagerrak, Kattegat and western Baltic (ICES SDs 20-22); ii) compare these results with previous LCA findings on common animal-source foods for Danish consumers (pork, beef, chicken and farmed salmon); iii) incorporating the nutritional diversity between the foods assessed; and iv) identify potential drivers, variability and improvement potentials of current GHG emissions of Danish seafoods. The overall aim is to place a set of seafoods from Danish capture fisheries in a sustainable nutrition context.

Material and methods

Estimation of greenhouse gas emissions

Fuel use intensity records

The fuel use intensity (measured in litres fuel used per kg landed) of the Danish capture fisheries is based on estimates from a kW-model developed by Bastardie and colleagues (accepted). The model estimates fuel use of a vessel based on engine power and vessel speeds and applies this to a dataset on fishing effort and landings in Danish fisheries (based on information from official logbooks, sales slips, and Vessel Monitoring System [VMS] data) separated by fishing area, fishing gear type and mesh size used. Fuel use intensity is then estimated per fishing segment or 'métier' as they are called in the European Data Collection Framework (DCF; EC 2017) which represents a combination of gear type, target species assemblage and mesh size range. Vessels not equipped with VMS, i.e. vessels under 12 m, are treated separately using logbooks in combination with AIS (Automatic Identification System). The dataset covers all Danish landings of herring, 99% of cod landings and 97 % of plaice from the three areas during the years 2005-2019 (landings by the smaller vessels with unspecified gear was excluded). For further details see Bastardie and colleagues (accepted). The different fishing segments included in the analysis for the species are found in Table 1.

Table 1 Description of fishing segments included for the species studied.

No.	Fishing segment	Species
1	Demersal trawl (>=120 mm mesh), Skagerrak	cod, plaice
2	Demersal trawl (90-119 mm mesh), Skagerrak	cod, plaice
3	Danish seine (>=120 mm mesh), Skagerrak	cod, plaice
4	Danish seine (90-119 mm mesh), Skagerrak	cod, plaice
5	Demersal trawl (90-119 mm mesh), Kattegat	cod, plaice
6	Demersal trawl, larger vessels, Western Baltic	cod, plaice
7	Danish seine, Western Baltic	cod, plaice
8	Gillnets, smaller vessels	cod, plaice
9	Demersal trawl, smaller vessels	cod, plaice
10	Handline, smaller vessels	cod
11	Pelagic trawl (32-69 mm mesh), Skagerrak	herring
12	Pelagic trawl (32-69 mm mesh), Kattegat	herring

The fuel use intensities estimated here were compared with other available LCA-related records for the targeted species. Data underpinning the recent Blue Food Assessment

(Gephart et al. 2021) were used for general comparison of all records available for the species. This represents a set of records extracted from the FEUD data base (Parker & Tyedmers 2015) during fall 2020 and covers 164 records for Atlantic cod, 70 records for Atlantic herring and 33 records for European plaice separated by gear type. An average of all gear types was used as a benchmark. The fuel use intensities from this study were also compared with previous studies on Danish fisheries for cod, herring and plaice (values allocated by mass in table 1 in Thrane 2004). The previous Danish study represents statistical data from 330 vessels that represents a sample of the 1 528 Danish vessels (or 99% of total Danish catches by value in the early 2000s) based on data from the Danish Research Institute of Food Economics.

Quantification of greenhouse gas emissions (GHGs)

The basis for comparison in LCAs is called the functional unit (FU) and should reflect the main purpose of the production system and goal of the study. However, different activities often result in more than one product, for example in fish processing where the output is both fish fillets and side streams consisting of e.g., heads, bones, etc. When quantifying emissions per FU, and avoiding allocation is not possible, a choice of allocation method must be done for distributing the environmental burdens between different products. This is most often done based on mass or economic value. Allocation by mass implies that the main product and side streams that are utilized are treated the same in terms share of environmental impacts. If using allocation by economic value, a larger share of environmental impact is attributed to the volume with higher economic value, e.g. for seafood, utilized side streams are attributed lower environmental burden compared to the fillet based on their lower relative economic value. This choice, in combination with choice of FU, can have a strong influence on the outcome of the assessment. Results of studies using different approaches cannot therefore not be directly compared.

In this study, the FU is defined as *1 kg edible seafood at the point of landing* based on species-specific conversion factors for edible yield from liveweight (emissions from the processing step are not included). This FU was chosen to be able to compare across species. Allocation is based on mass, with an assumption that non-edible side streams are not further utilized (i.e., all environmental burden is attributed to the edible part). It is thus important to be aware of that this represents a worst-case scenario, and that utilization of side streams would decrease the product's greenhouse gas emissions. Side streams in the fish processing industry are often used as feed or biogas, but since the degree of utilization was not known for the studied products, it was not considered.

The selection of Danish seafoods were decided in dialogue with the three main producer organizations in Denmark (the Danish Fishermen Producer Organization [DFPO], the Danish Pelagic Producer Organization [DPPO], and the Coastal Fisheries Producer Organization [FSK-PO]) and covered Atlantic cod *Gadus morhua*, European plaice *Pleuronectes platessa* and Atlantic herring *Clupea harengus* caught with different gears in the Skagerrak, Kattegat and western Baltic (ICES SDs 20-22). Fuel use estimates for the different species are based on landings of all species in a certain fishery (Bastardie et al. accepted) and the fuel use intensity of each fishery is combined into a weighted average for each species, based on the contribution of each fishery to total landings of each species during 2017-2019. This value was converted into greenhouse gas emissions following an approach developed by Parker and colleagues (2018). In short, this includes multiplying the volume of diesel fuel used per tonne landed with emission factors from combustion (assumed to be diesel "MK 1"; 2.54 kg CO_2e/l[1]) and production of diesel (based on data from the LCA database Ecoinvent v 3.7.1, process "Diesel {Europe without Switzerland}| market for | Cut-off, S, following IPCC 2013; 0.49 kg CO_2e/kg diesel). In lack of specific and detailed data, a fixed percentage of additional emissions related to non-fuel activities on the fishing vessel, such as production of gear, vessel and ice and production and emissions of refrigerants is then applied, based on findings in earlier LCAs. Parker and colleagues (2018) used a general addition of 25% for all fishing types based on the finding that fuel typically constituted 60-90% of fishing emissions. Follow-up work by Ziegler and colleagues (2021) derived at a proportion represented by fuel production and combustion for different fisheries. In this study we added non-fuel emissions from the latter reference to be able to differentiate between demersal gears (adding 17%) and pelagic fisheries (adding 23%).

Nutritional content

Nutrient content for the fish species was taken from the FAO database uFiSh 1.0[2], except for plaice for which data was lacking. Data for plaice and terrestrial animals was taken from the Swedish Food Composition Database of the Swedish Food Agency (version 2021-05-03[3]). A method for aggregating nutrients to a nutrient density score (NDS) developed by Bianchi and colleagues (in prep) was applied. In this method, the content of 23 nutrients (of which two, saturated fat and sodium, were classified as undesirable) in 100 g of raw fillet is related to the RDI[4] (recommended daily intake) for each nutrient, resulting in a ratio which is then summed up for all nutrients. For the undesirable nutrients, content was instead related to the MRI (maximum recommended intake) and to obtain a final score, the ratios of the undesirable nutrients are subtracted from the sum of ratios of the desirable nutrients, resulting in a lower score. The ratio is set to not exceed 1, i.e., the nutrient content is "capped" at the RDI, meaning that when the RDI is reached for a nutrient, a higher content will not further increase the NDS.

The nutrient density score (NDS) as well as single RDI values for selected nutrients for which animal products are important sources (Zn, Fe, Se, I, Vit D, Vit B12, PUFAs) is used as a reference for consideration of the nutritional differences between the different studied seafood species and alternative animal-source foods.

Comparison with other products

For comparison with terrestrial-sourced animal foods, it was decided to use data representative for Danish consumption and production of these alternatives. Two data sources were evaluated for this purpose, Leip and colleagues (2010) and Moberg and colleagues (2019). The study by Leip and colleagues (2010) was seen as favorable for our purpose since it is a broad and systematic assessment of animal production in all EU

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[1] https://drivkraftsverige.se/uppslagsverk/fakta/berakningsfaktorer/energiinnehall-densitet-och-koldioxidemission/
[2] Food and Agriculture Organization of the United Nations (2016) FAO/INFOODS Global Food Composition Database for Fish and Shellfish, version 1.0 - uFiSh1.0 Rome, Italy
[3] https://www7.slv.se/SokNaringsinnehall/
[4] as defined by Codex Alimentarius (FAO & WHO 2017), and for omega-3 fatty acids by FAO (2010)

member states, and methods and data were transparent, which allows understanding results and adjusting methodological choices for a fair comparison. There is also a public database in Denmark ("Den store klimadatabase") that comprises estimates of greenhouse gas emissions for a multitude of food products (including meat and seafood)[5]. For our purpose, which was to analyze the greenhouse gas emissions of different Danish fisheries and their seafood products and relate them to alternative animal-source foods, this Danish public database could not be used for methodological reasons (explained in detail in Appendix 2).

Norway is the country producing most salmon in the world and salmon consumed in Denmark almost exclusively originates in Norwegian open sea culture. Data was therefore retrieved from the most recent study of salmon farmed in Norway (Winther et al. 2020; Ziegler et al. 2021). For the best available and methodologically harmonized comparisons, data for pork and chicken produced in Denmark and European "average" production of beef (as no LCA data was available for Danish production) was used (Leip et al. 2010). Estimates used in this study include biogenic and fossil-fuel based greenhouse gas emissions derived from agriculture and salmon grow-out (feed, livestock and salmon farming) and by-products assumed to be not further utilized. Greenhouse gas emissions from Land Use Change were intentionally excluded, as it was not possible to harmonize methods for their assessment across the studies (Leip et al. 2010 and Winther et al. 2020). The same approach was taken for comparison between seafood and terrestrial animal-source foods in Winther et al. (2020) and it means that emissions are underestimated for foods that depend on feed inputs causing this type of emissions (e.g. chicken and salmon). Indicative contributions from Land Use Change are around 30% of farmgate emissions of liveweight salmon (Winther et al. 2020), around 30% also for Danish pork and about 40-50% of emissions of Danish chicken respectively (Leip et al. 2010). Note that different methods are used to quantify these emissions in the two studies, leaving the absolute results incomparable. The different approaches taken to account for these emissions and resulting estimates are associated with a high degree of uncertainty in LCA modeling (e.g., assumptions on degree of deforestation to grow soy caused by the product, time period to use). Including these estimates increases the greenhouse gas emissions for animals that are fed feed components originating in countries with expanding agricultural land, e.g. soy from Brazil is important, but is also associated to considerable uncertainty. Attention has also recently been brought to potential effect on greenhouse gas emissions from ocean-based food production through disturbance of the seafloor from using demersal trawls (Sala et al. 2021). These recent estimates are associated with even larger uncertainties and are being further scrutinized; it is currently unclear how they would affect the greenhouse gas emission modeling of seafood from capture fisheries. To this end, accounting for biogenic greenhouse gas emissions from land use change and benthic disturbance was not feasible given current availability of methods and data.

Edible yields for land-based animals were based on Clune and colleagues (2017) in the form of carcass to edible (comparative unit is raw boneless meat). For Norwegian salmon, official data from the Norwegian Directorate of Fisheries (Winther et al. 2020) was used and for the Danish products from fisheries (live weight to edible) we used data from EUMOFA (Table 2). As mentioned, no use of side streams from processing was

[5] https://concito.dk/projekter/store-klimadatabase

assumed for all products in the comparison, i.e. all production-related pressures were allocated to the edible meat.

Table 2 Conversion factors used for edible yield from live-weight (fish) or carcass weight (terrestrial) for the different products studied.

Product	Conversion factor to edible
Beef	0.70
Pork	0.59
Chicken	0.77
Salmon	0.45
Herring	0.52
Cod	0.33
Plaice	0.37

Identification of drivers, variability and improvement potentials

For the studied Danish seafoods, different fleets and gear types, in different areas are involved. The exploited stocks of the different areas have different stock development over time that may affect catch per unit effort. The underpinning data was therefore further analyzed: between different fisheries (based on gear type, fleet, and fishing area), correlations between stock status and fuel use intensities, and comparison to other available records on fuel use intensities for the targeted species, with the objective to further the understanding of results and identify improvement potentials.

The fuel use intensity was analyzed per kg live weight (LW). The latest three-year average (2017-2019) was used for studying differences between fleet segments and areas for fisheries landing cod and plaice. The use of a short time-period was assumed to lessen influence of changes in fleet structure, management regulations and stock status over time. Data on herring fisheries only covered one gear (pelagic trawl) and two areas (Kattegat and Skagerrak) during 2017-2019.

For correlation between fuel use intensity and stock status, annual average values for fuel use intensity of fisheries landing cod with different gears and fleets, separated by fishing area, was used (covering years 2005-2019). Available estimates for spawning stock biomass (SSB) were retrieved from stock advice provided by the International Council for the Exploration of the Sea (ICES)[6] for the same period. Cod in the Kattegat was not included since only relative SSB was available, and landings of cod from the period has mainly been as bycatch due to poor stock status.

[6] www.ices.dk (retrieved during November 2021)

Results

Greenhouse gas emissions

The weighted average of greenhouse gas emissions of the studied Danish seafoods was highest for cod and lowest for herring (Figure 1). The difference in emissions reflects a combination of differences in catch efficiency (herring most efficient), edible yield (herring highest) and the contribution of different gear types (affecting the difference between cod and plaice that are caught in the same fleet segments).

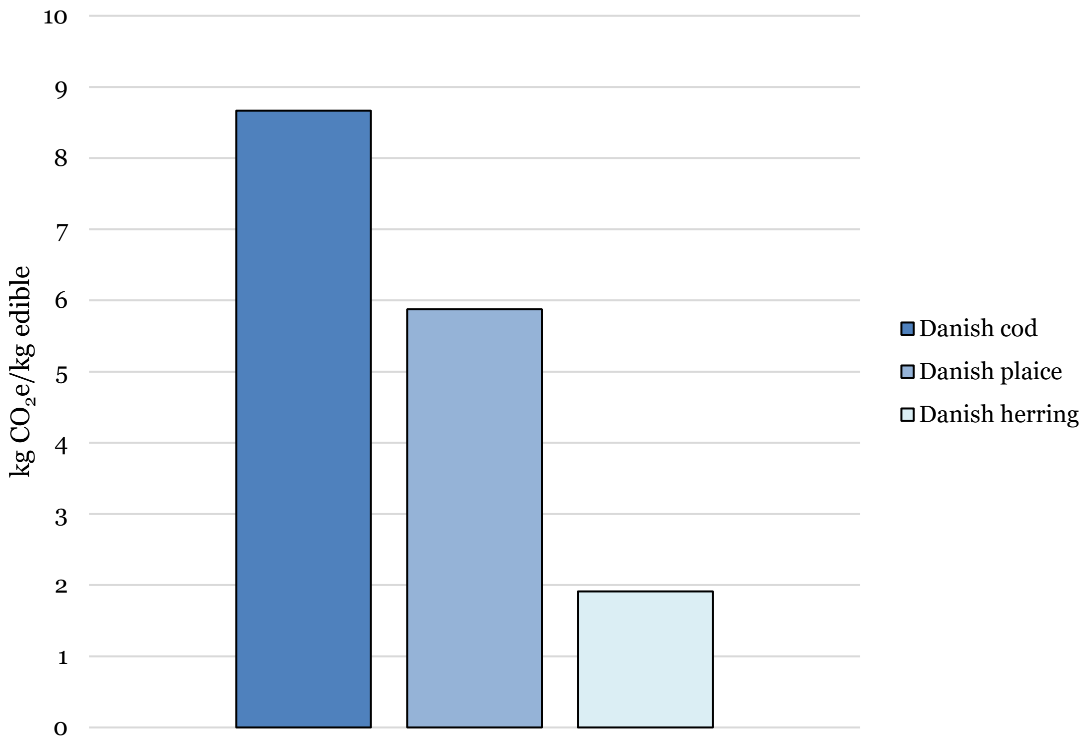

Figure 1 Weighted average (based on contribution to landing volume) of greenhouse gas emissions at the point of landing per kg edible cod, plaice and herring caught in Danish fisheries in the Skagerrak, Kattegat and western Baltic (ICES SD 20-22). Note that all impacts are placed on the edible portion under the assumption that by-products are not further utilized. This assumption was made in lack of data and leads to higher values compared to seafood where by-products are utilized.

When comparing with other animal-source foods, the weighted average of herring and plaice from Danish capture fisheries studied perform better in terms of greenhouse gas emissions (Figure 2). For Danish cod, the weighted average was lower than pork and beef, but higher than chicken and farmed salmon. Herring represents the product with the lowest greenhouse gas emissions amongst all products.

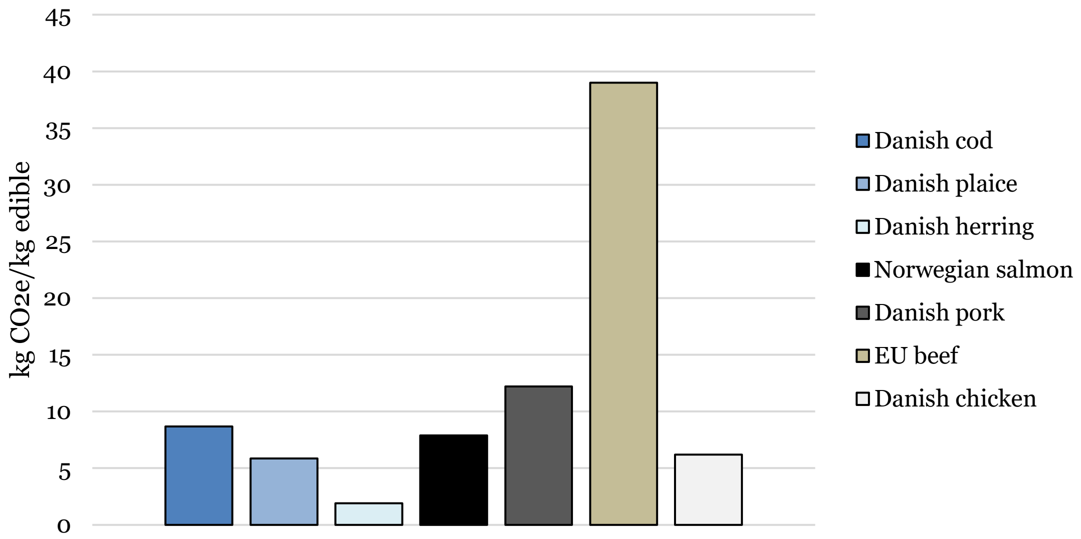

Figure 2 Weighted averages of greenhouse gas emissions of seafoods from Danish fisheries compared to Norwegian farmed salmon (Winther et al. 2020; Ziegler et al. 2021) and terrestrial animal-based foods (Leip et al. 2010). For all foods, it is assumed that by-products are not further utilized, and all impacts are placed on the edible part.

Nutrition

The terrestrial and aquatic animal foods compared differ regarding their nutritional content. Each product contains varying amounts of the nutrients of interest (Figure 3). Fatty fish is rich in fatty acids and vitamin B12, while cod is extremely rich in iodine, and beef in iron and zinc (Figure 3). The content of vitamin B12 in 100 g of farmed salmon and herring exceeds RDI, and the same is true for iodine content in cod.

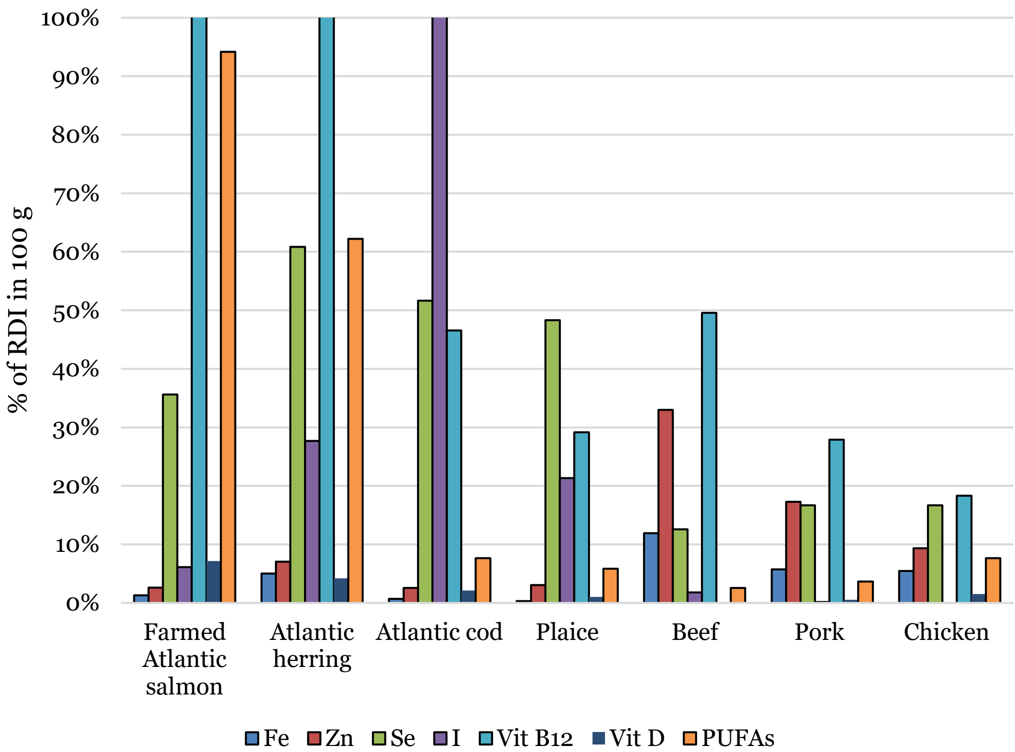

Figure 3 Content of iron (Fe), zinc (Zn), selenium (Se), iodine (I) vitamins B12 and D (Vit B12 and Vit D), and polyunsaturated fatty acids (PUFAs) in 100 g of the studied products relative to Recommended Daily Intake (RDI) of each nutrient. Note that the content of iodine in cod and vitamin B12 in 100 g of salmon and herring exceeds the RDI (here capped at 100%).

When nutrient density is calculated based on these nutrients combined with 17 other nutrients, the differences between products even out and the main differences found are between fatty fish (salmon and herring), which have a higher nutrient density than all other foods analyzed (Figure 4). The capping also leads to more even results across foods as it takes out very high ratios for certain nutrients. When greenhouse gas emissions are related to the nutrient density instead of kg edible, the relative performance of the products is at large unchanged (c.f. Figure 2), except for salmon whose high nutrient density results in outperforming both plaice and chicken. Herring is still associated with the lowest emissions.

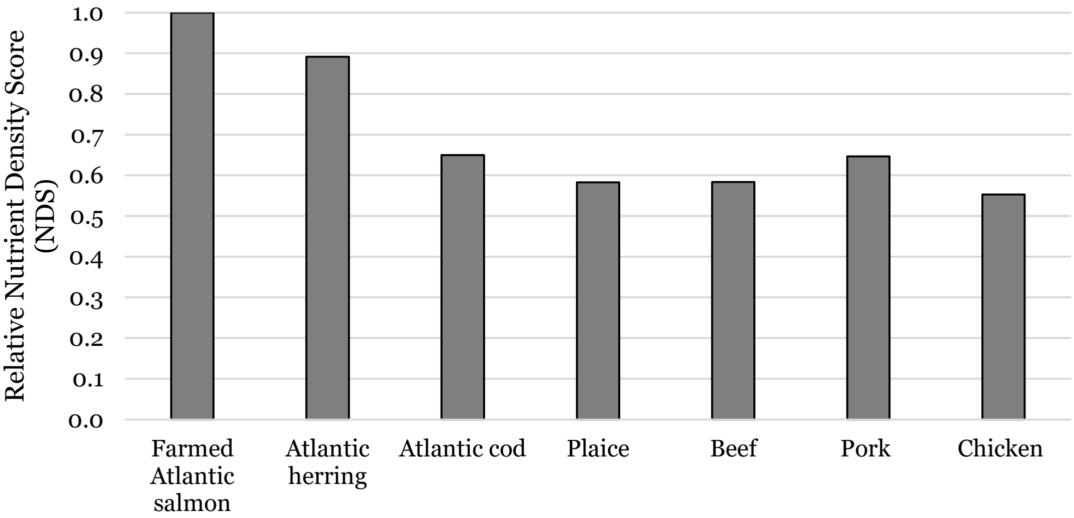

Figure 4 Relative Nutrient Density Score where products are related to the product with highest score (salmon = 1).

Drivers and variability

Plaice was mainly targeted with Danish seine in the Skagerrak whereas cod was to a larger extent landed from demersal trawl fisheries (Figure 5). Demersal trawl fisheries contributed to 83% of total cod landings and to 55% of plaice landings. Plaice was to a larger extent than cod targeted with Danish seine (42% and 13% of total landings, respectively). Smaller vessel sizes contributed to 7% of the landing volume of cod and 6% for plaice.

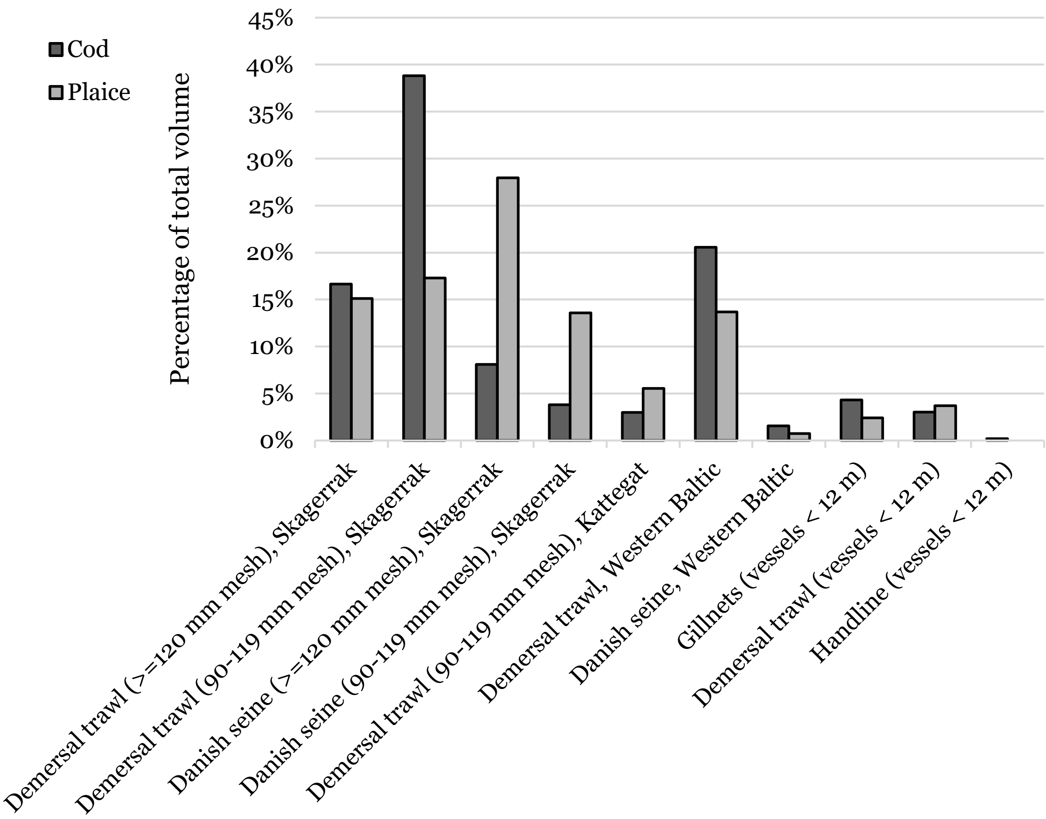

Figure 5 Share of landings of cod and plaice by different gears and in different areas.

The fuel use intensity was overall lower for Danish seine fisheries compared to demersal trawling for all fishing areas, and the fuel use intensity of demersal trawls was also more variable than Danish seines between areas and fleets (Figure 6). The substantial difference in fuel use intensity for demersal trawls between areas – considerably less fuel use intensive in the Western Baltic – is likely an effect of different target species; Norway lobster (*Nephrops norvegicus*) is targeted in all demersal trawl fisheries except for the western Baltic. Fishing operations targeting crustaceans of high economic value allow for high fuel use intensity. Fisheries with smaller vessels (<12 m) fish in all areas and are not analyzed by fishing area; this fleet segment has an intermediate fuel use intensity compared to larger vessels, the latter being more variable between fishing areas. Use of gillnets results in a lower fuel use intensity compared to demersal trawling and are similar to Danish seine fisheries. Handlines have a lower fuel use intensity than most demersal trawl fisheries, but higher than Danish seine and gillnets. Overall, a larger share of plaice landings comes from more fuel-efficient segments than trawled cod (Figure 6). Combining all fisheries into a weighted average based on landing volume (Figure 1), therefore results in an overall lower fuel use per kg for plaice than cod landed in Danish fisheries.

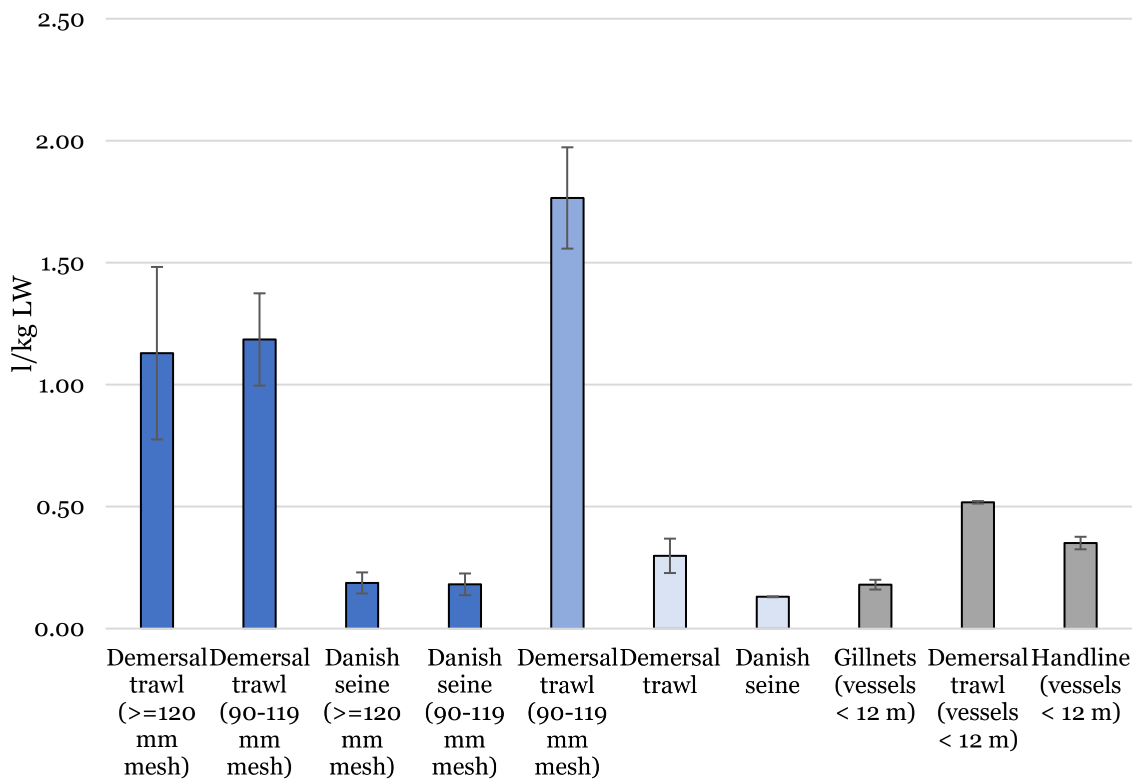

Figure 6 Fuel use intensity (average 2017-2019 with standard deviation) for different gears in the Skagerrak (darkest blue), Kattegat (medium blue), Western Baltic (light blue) and all areas by vessels < 12 m (grey).

Herring is exclusively fished with pelagic trawls. The fishery in the Kattegat (0.08 l/kg LW) was considerably more fuel efficient compared to the Skagerrak fishery (0.46 l/kg LW). The Kattegat fishery data showed the same low value for the whole time period (2005-2019) whereas the Skagerrak fishery had the same fuel efficiency at start but showed a substantial increase in recent years (from 0.15 to 0.73 l/kg LW). The potential reason for this increase is unclear, the only known change in the fishery that has taken place in recent years is change in fishing pattern to avoid bycatch of saithe *Pollachius virens* (Claus Reedtz Sparrevohn, scientific advisor Danish Pelagic Producer Organization, Pers. Comm.)

When the vessel size, gear- and area specific values for the different Danish seafoods are compared in terms of GHG emissions separately with the other products (farmed salmon, pork and beef), it is shown that they generally perform better with the exception of most seafood fished with demersal trawls (Figure 7). However, demersal trawl fisheries in the western Baltic and with vessels smaller than 12 meters are also associated with lower GHG emissions than the compared products.

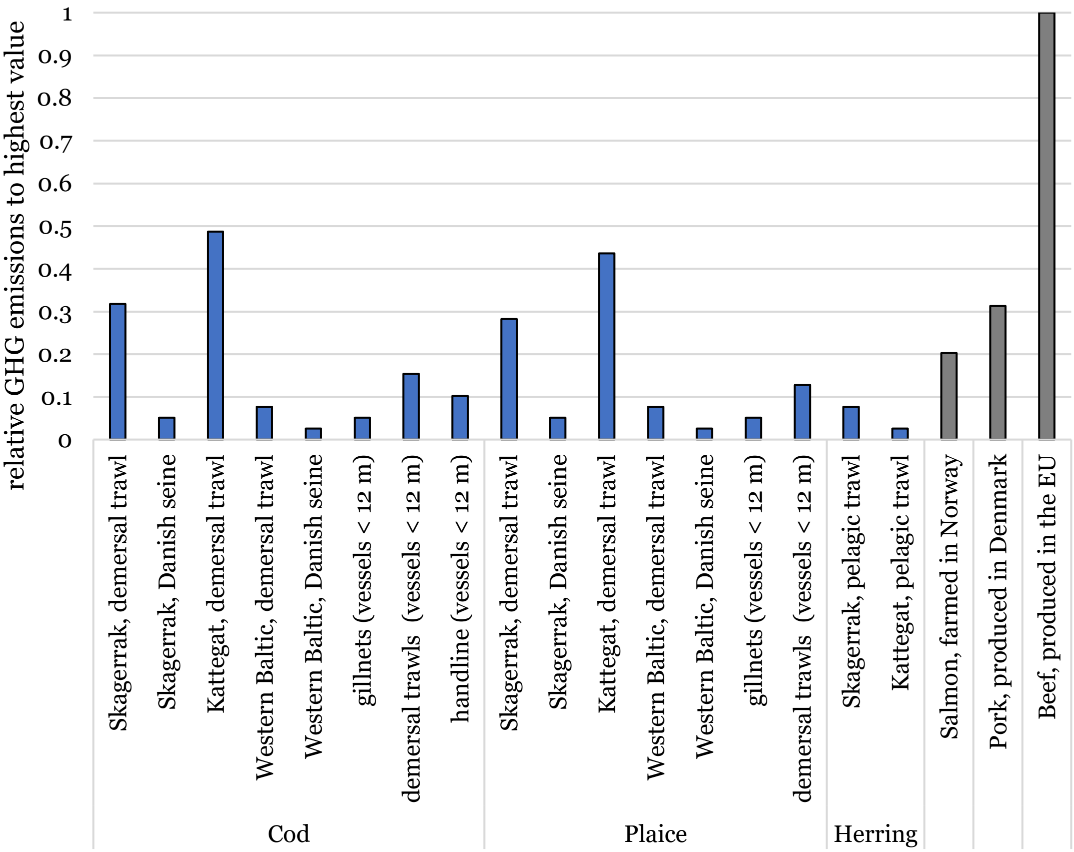

Figure 7 Greenhouse gas emissions relative to the highest value (beef = 1) for the studied products separated by gear type, fishing area and vessel size

Compared to other available records on fuel use intensity in global fisheries Danish fisheries exhibit variable performance (Figure 8). For plaice, all fisheries have lower fuel use intensity than average value for the species. For cod, some of the demersal trawl fisheries had a higher fuel use intensity than average, but most fisheries had lower than average values for fuel use intensity. For herring, Kattegat fisheries had lower and Skagerrak fisheries higher fuel use intensities than the average for herring.

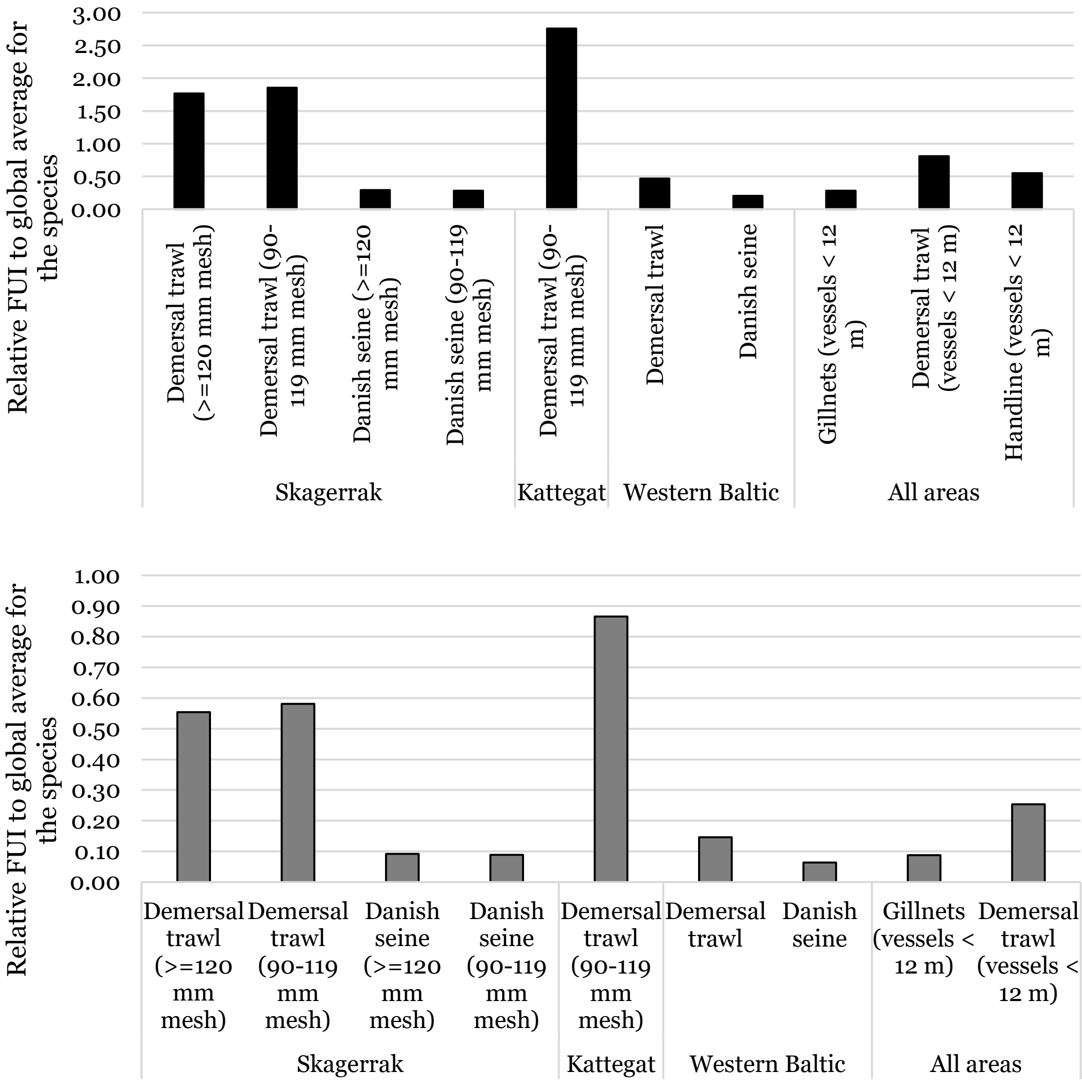

Figure 8 Relative fuel use intensity (FUI) of Danish cod (top panel) and Danish plaice (bottom panel) expressed as relative to average values (=1) for the species in available data used in Gephart et al. (2021) based on data from FEUD (Parker & Tyedmers 2015).

The effort-based model provided higher values for the species than a previous analysis of Danish fisheries that used statistical data on energy consumption and catches in volume and value (Figure 9). However, besides different modeling approaches, there is also a temporal component to consider as the data in Thrane (2004) represents fuel use in year 2000.

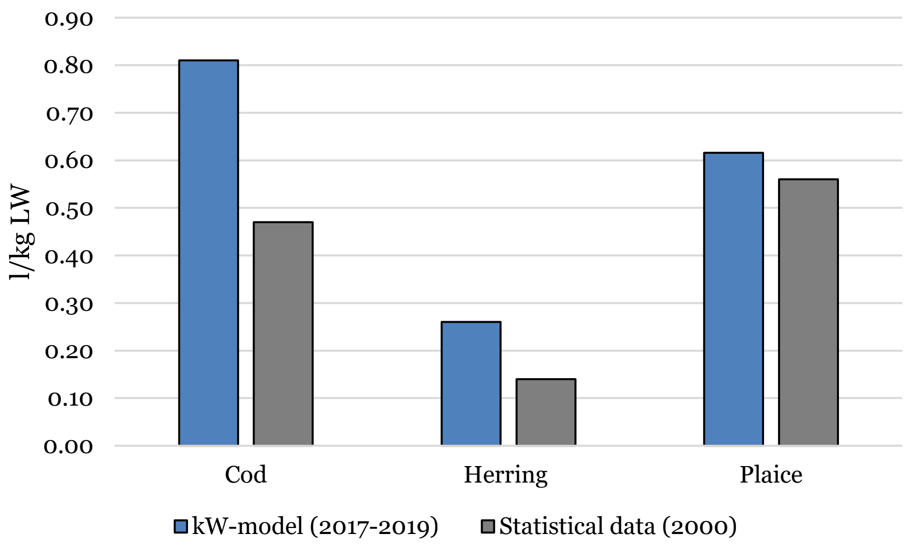

Figure 9 Data on fuel use intensity from this study (effort-based model) compared to older estimate (mass allocated based on catch composition from statistical data; Thrane 2004).

When looking at development over time and potential influence of stock status, the fuel use intensity for the larger vessels has overall decreased for cod in the Skagerrak between 2005-2019, but not in the western Baltic (Figure 10). However, it is important to point out that it is a mixed fishery in the Skagerrak that target a wide mix of species other than cod. Overall landings have increased for the fisheries studied in the Skagerrak during the same period (16% from 2005 to 2019), while cod has not increased to the same extent (10% respectively). Furthermore, the Skagerrak fishery has seen an increase in fuel use intensity since year 2015. To this end, the trend in fuel use intensity seen can thus not be isolated to the cod stock status and is not further analyzed.

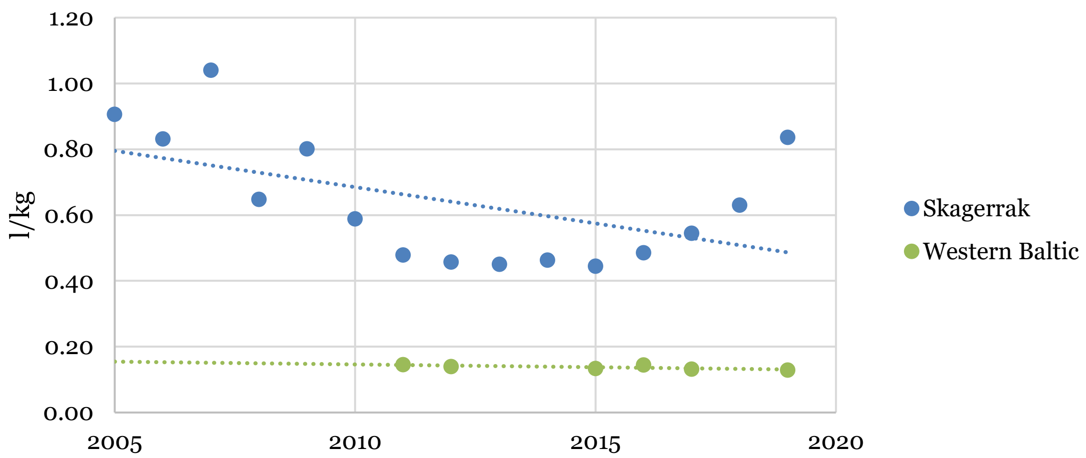

Figure 10 Fuel use intensity for fisheries with larger vessels landing cod with demersal trawl or Danish seine in Skagerrak (average for fisheries no. 1-4 in Table 1) and Western Baltic (fishery no. 6 in Table 1) during 2005-2019 per fishing area.

Overall, the SSB for the cod stock in the western Baltic is smaller and has a more restricted spatial distribution compared to the cod stock fished in the Skagerrak (area 27.47d20, i.e., North Sea, eastern English Channel, Skagerrak) – on average estimated at ~ 17 700 compared to 68 000 tons respectively. When compared, fisheries in the western Baltic are more fuel efficient than Skagerrak cod fisheries. If this is an effect of the targeting pattern (e.g. main targeted species in different mixed fishery, fleets) or stock status cannot be determined in this study but requires further investigations at higher level of detail of data. The fishery for cod in the western Baltic is, however, closer to a fishery targeting primarily cod. The fuel use intensity over time for this fishery relative to cod stock status shows no trend suggesting that higher SSB correlates with lower fuel use intensity (Figure 11).

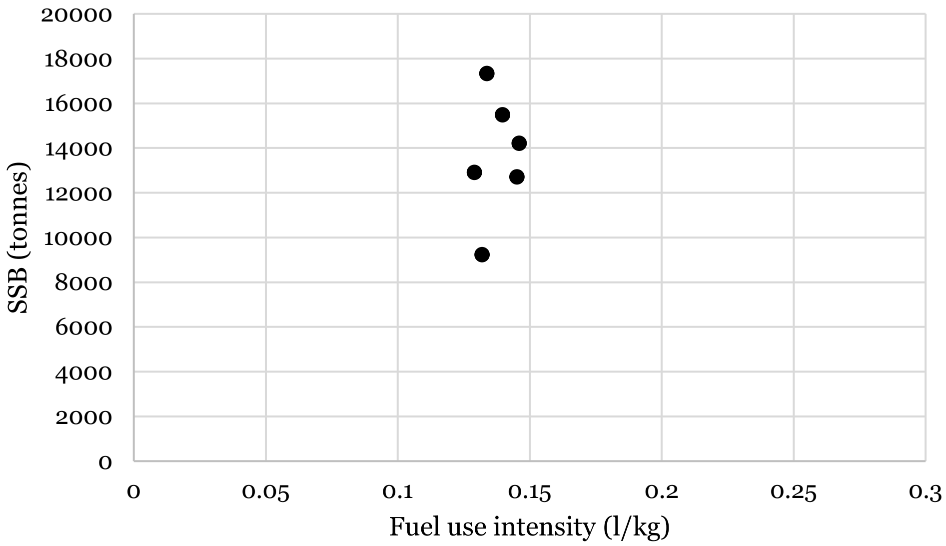

Figure 11 Spawning stock biomass (SSB) estimates for cod versus fuel use intensity for the demersal trawl fishery landing cod (vessels >12 m in length) in the western Baltic.

Discussion

Greenhouse gas emissions of Danish seafoods

This study has shown that in relative terms, herring is associated with the lowest greenhouse gas emissions and cod the highest of the Danish seafood analyzed here. The absolute values found can be compared to a recent analysis of Norwegian fisheries (data from Winther et al. 2020 and Ziegler et al. 2021, recalculated for a standardized comparison). An average Norwegian cod in 2017 was associated with considerably lower emissions than the average value for Danish cod (2.02 kg CO_2e/kg edible compared to 8.67 kg CO_2e/kg edible). This difference may in part be caused by different gear use. Norwegian cod was mainly caught by the coastal fleet using gears like gillnets, long-lines and handlines (51%), followed by demersal trawlers (35%) plus some by ocean-going long-liners (9%) and coastal seines (5%) (Winther et al. 2020). In this study, it is the fuel use intensity of the Danish demersal trawl fisheries that drives the higher emissions of a weighted average of Danish cod; however, when fished with Danish seine or gillnets, Danish cod has the same or lower emissions than the average value for Norwegian cod. For herring, Norwegian fisheries are also associated with lower emissions than Danish fisheries, on average 0.59 kg CO_2e/kg edible compared to 1.91 kg CO_2e/kg edible, respectively. However, the higher value for Danish fisheries is driven by the increased fuel use intensity in recent years in the Skagerrak; fisheries in the Kattegat have the same value as average Norwegian fisheries for herring. Plaice was not included in the Norwegian study.

To place outcomes of this study into a global context, the category 'Flounders, halibuts, soles' in the recent Blue Food Assessment (Gephart et al. 2021, using data from Parker and Tyedmers 2015) was identified to be in the highest range in terms of greenhouse gas emissions of seafood from capture fisheries. Findings of this study show that, Danish plaice is associated to lower fuel use intensity and thus greenhouse gas emissions for all gears compared to available records for the species, in particular for Danish seine fisheries. For Danish cod, belonging to the category 'Cods, hakes, haddocks', fisheries with demersal trawls may be almost threefold in fuel use intensity compared to average value for the species, whereas Danish seines and gillnets are associated with considerably lower fuel use intensity and associated emissions. Danish herring, belonging to the category 'Herring, sardines, anchovies', showed large variability between the Kattegat and Skagerrak fishing ground which would be interesting to follow up upon for better understanding of potential drivers.

The products compared showed high variability in nutrient content. The differences in content of individual nutrients are partly masked when aggregating to a combined nutrient index. When combined, fatty fish (salmon and herring) stand out with the highest nutrient density, while all other products have lower and relatively similar values. However, since the content of individual nutrients is highly different, seafood consumption choices could also involve focus on individual nutrient requirements. This could as an example involve recommendations for vegetarians that eat fish and/or bivalves to eat herring or mussels/oysters (the latter not included in this study), since they are very high in content of iron and vitamin B12 (Öhrvik et al. 2012, Behaderovic & Ziegler 2020). As an example, only 18 gram of herring provides the RDI of vitamin B12 (corresponding to 0.11 kg CO_2e) which can be compared to the need to consume 202 gram of beef (2.46 CO_2e) or 545 gram of chicken (3.38 CO_2e) respectively. However, B12 deficiency is rare in Nordic countries (vegans primarily at risk). Iron deficiency can however be a problem in particular for women, and here it can be noted that iron content is considerably higher in beef than herring, but highest in mussels (Öhrvik et al. 2012, Behaderovic & Ziegler 2020). Other examples include high iodine content in cod, vitamin D in salmon, zinc in beef. People experiencing deficiencies in one of these nutrients can increase their intake by taking this diversity into account.

Variability, drivers and future work

Absolute values for carbon footprints found in different studies are highly influenced by a range of factors, one being the quality of underpinning data and assumptions made in the modelling. This analysis is based on fuel use intensity derived from an effort-based model and does not represent actual collected data on fuel use in the fisheries. Effort-based models have their limitations as they represent a theoretically calculated fuel use, based on time spent fishing, engine power and vessel speed patterns, and cannot consider important factors like fishing method, weather, skipper skills, vessel age and many other factors that might influence the fuel use intensity of a fishing vessel and its fishing activities. A recent example with such a model separated into large- and small-scale fisheries led to a highly skewed global estimate for fuel use in fisheries (Greer et al. 2019 a,b). In a reply by Ziegler and colleagues (2019), the potential and challenges of effort-based models are described. A conclusion was that when effort-based models have been verified with actual fuel use data, the effort-based models often show higher fuel use intensities than actual data.

Major differences in fuel use intensity were found for the studied Danish fisheries – and in the end greenhouse gas emissions given it is the main driver for these emissions in capture fisheries (Parker and Tyedmers 2015; Parker et al. 2018). Although not treated exactly the same in the effort-based modeling, this study found no support for small-scale fisheries (vessels under 12 m) being generally less fuel intensive (in l/kg) compared to larger vessels – it is rather the gear type and fishing area that matters. However, if a species can be fished with different gears in an area that is associated with major differences in fuel use intensity, this can indicate improvement potentials for future decision-making on how to reduce greenhouse gas emissions from capture fisheries (see e.g. Driscoll & Tyedmers 2010 and Farmery et al. 2014 for other examples). Quantifying fuel use intensity on a regular basis may also provide important benchmarks to follow up upon. So far, there are only a few country-based estimates on the development of fuel use efficiencies or greenhouse gas emissions over time, including Iceland (Byrne et al. 2021), Australia (Parker et al. 2014) and Norway (Ziegler et al. 2021; Jafarzadeh et al. 2016; Schau et al. 2009). These studies have in general concluded that reduction of overcapacity and improved stock status is important to reduce fuel use intensity. This has previously been seen in the Danish fishery for Northern shrimp *Pandalus borealis*, where fleet size reduction from introduction of tradeable quotas has made the Danish fishery less fuel intensive per kg compared to Swedish and Norwegian fisheries in the same area and on the same stock (Ziegler et al. 2016b).

It is difficult to fully isolate the different factors that influence the outcome of this study, but no effect from stock status development can be detected at this level of detail of data and time span. Cod is caught in mixed fisheries in the Skagerrak and Kattegat, and within the short time period studied, cod abundance in all years in all the areas is at a historically low level. Furthermore, cod is caught in mixed fisheries where other species contribute to catch volumes and hence to their fuel use intensity. There are also considerable differences in fuel use intensity between different gears fishing catching cod. These factors complicate comparisons also with other areas where stock status may be better. As an example, the weighted average of the greenhouse gas emissions is higher for Danish cod compared to Norwegian cod. Cod spawning stock biomass is under B_{lim} in the western Baltic and a zero catch is advised by ICES for the Kattegat area since year 2002 – indicating very poor stock status – compared to the major cod fishery in Norway (Northeast Arctic) that has a spawning stock biomass above MSY $B_{trigger}$. Arguably, these differences should be reflected in the catch per unit effort of cod and hence the fuel use intensity when compared. However, to disentangle the effect of different factors requires more research, where it would be interesting to study to which extent fleet structure and gear use may mitigate fuel use intensity compared to stock status. For overall long-term sustainable resource utilization, a positive development in stock status is nevertheless essential.

Conclusion

This study has estimated greenhouse gas emissions of selected seafoods from Danish fisheries in the Kattegat, Skagerrak and Western Baltic based on a theoretical fuel use model applied to a comprehensive high-resolution data set of vessel effort (combined AIS, VMS, vessel-register, logbook and sales slip data). In general, the studied Danish seafoods perform favorable in terms of greenhouse gas emissions compared to pork and beef, and most also compared to chicken and farmed salmon. More detailed analysis is required for better understanding of the outcome, and ideally, collection of actual fuel use data for these fisheries should be initiated to allow for more precise estimations and verification of results. It would also be valuable cover the entire seafood supply chain – from fishery to consumer – and make sure data is available on the resource use and emissions of all the steps.

It is important to be aware of that the absolute values on greenhouse gas emissions for seafood products from capture fisheries can be highly variable between years, driven by for example stock status, catch composition and fleet structure (métiers engaged in the fishery). With all potential aspects influencing the outcome of a study and its comparability with other estimates, still, greenhouse gas emission reduction potentials seen in this report entail shifting effort to the least fuel use intense gears (more utilization of Danish seine and less demersal trawling), improved stock status and obtaining a higher edible yield through maximized utilization of landings – the higher proportion out of the live weight brought ashore that is utilized, the lower the fuel use intensity and greenhouse gas emissions per output.

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Appendix 1

Type	Input	Who	Effect on report
Analysis done	Suggestion to compare Skagerrak plaice caught with different gears; Sprat used for direct consumption versus for feed; Utilization of herring processing streams; and western Baltic cod from different fleets	All POs	The report considered fisheries for the species in all three areas (Skagerrak, Kattegat and western Baltic) with the exception of sprat (lack of fishery and data for the three most recent years for the areas). For herring, only the fishing phase was included, since the processing streams are utilized today, and it was decided to not include post-harvest activities in the project due to lack of available data.
	Choice of other food products to compare with (beef, pork, chicken and farmed salmon)	All POs	For the products chosen for comparison, the authors of the report decided which data and production system that was the most representative
	Focus modelling on the fishing phase since there is less possibility to change the market if improvement is sought for (also, rapid changes occur).	All POs	Modelled GHG emissions of the fishing phase including a generic value for non-fuel related emissions (such as gear production)
	Provide better understanding of the outcome of seafood in the CONCITO database	All POs	Detailed description of different LCA modelling approaches and how this affects LCA results such as those in the CONCITO database, written as an appendix to this report
First results	Suggestion to improve understanding of results in a dietary context	DFPO	Figures on nutritional content was amended to show % of total recommended intake instead of just content of individual nutrients
	Selective results presentation/dissemination	All POs	Each PO will disseminate results from the report individually and these will be

			communicated with the PO as sender
	Call for analysis of more fleet segments (<12m)	FSK-PO	This was an objective of the project that had been missed initially and consequently the smaller vessels using passive gears were included in the analysis
First draft report	Suggestion to throughout report further elaborate on results at a higher level of detail, not only with regard to species, vessel size and fishing areas (as already done), but also with regard to gear types	FSK-PO	The first draft report was focussed on cod, plaice and herring as species (i.e., GHG emissions were mainly expressed as weighted averages per species based on contribution to landing volume from all fleets landing the species). Since the data underpinning the analysis was available on higher resolution, GHG emissions were instead expressed at a higher level of detail (separating and comparing the estimates by gear types) in a new figure. Based on this, the abstract was updated accordingly.
	Call for improved transparency of stakeholder input to analysis and report	DPPO	Inclusion of appendix on stakeholder input for improved transparency

Appendix 2

Description of the "Big climate database version 1" by Concito

Consequential and attributional LCA

In Life Cycle Assessment (LCA) there are two different main schools of thought or principles to use in modelling. These two alternative approaches are called attributional and consequential. Attributional LCA (or A-LCA) is often described as "backward-looking" or "historic" LCA because it aims to describe the performance of current production by collecting production-related data for the most recent time-period for which data is available from the system under study. This is often data for a recent year or production cycle (aiming to use "average" or "typical" production data) and means that an A-LCA study is built on data on resource use, production and emissions for the specific production system studied. Consequential LCA (or C-LCA), on the other hand, is often described as "foreward-looking" LCA because it aims to model the future by making assumptions about what happens if demand for the production system under study grows. In a consequential LCA, data is used for the so called "marginal" system, i.e. the system that is expected to grow, based on a combination of factors such as price in relation to alternatives, supply and scalability of production.

A-LCA does not assume demand will grow for a product studied, in fact low A-LCA performance and lack of feasible improvement options may as well lead to reduced demand if a signal is sent regarding high impacts to consumers that are sensitive to this type of message. Furthermore, an A-LCA approach can certainly be used to model future scenarios building on knowledge about current performance combined with improvement potentials from technological or other innovation (but would in that case again aim to use "average and representative" data for that future production system rather than data for an assumed marginal system). As an example, if it is known that a new greenhouse heating technology is 10% more energy-efficient but still yielding the same harvests, then this can be implemented in a future scenario – without actually having been implemented in full commercial scale, which will inevitably be linked to uncertainties (data is theoretical or stemming from single experiments).

The Big climate database, with particular focus on seafood

The so called "Big climate database" (hereafter BC database) was published online in 2021 by Concito[7], and reports greenhouse gas emission data for a large range of food items taking a C-LCA approach. Since capture fisheries volume are limited and may not be able to increase with increased demand, this implies that for a capture fishery production system, e.g. producing herring, the database developers have identified an alternative production system that is likely to increase if demand for herring increases. The rationale given for this is that wild capture is limited and cannot satisfy a growing demand, especially if fish stocks are already fished to the limit of what they can produce. Instead, all wild-caught fish is modelled as farmed species in the BC database, predominantly as Tilapia and Atlantic salmon. So according to this thinking, increasing demand for herring, leads to increased production and consumption of salmon, and the latter system's greenhouse gas emissions is what is accounted for in the database. This

[7] https://concito.dk/projekter/store-klimadatabase

means that the greenhouse gas emissions presented for herring (or halibut or cod) has nothing to do with the actual resource efficiency of herring, halibut or cod fisheries. The results presented for these species rely entirely on assumptions about what happens on the seafood market if demand changes in a certain direction and production data for that system, not what the actual emissions of the specific product are today.

The very different approaches of C-LCA and A-LCA makes it impossible to compare results from studies using these different approaches. How could the efficiency of different fisheries (such as herring and cod with different gears) be compared using data for farmed fish? Hence, for that specific purpose, the C-LCA approach is not suitable. Also within one approach such as C-LCA, it can be questioned what can be said about the performance of herring vs halibut vs salmon if all are modelled using the same salmon data. Likewise, for all types of LCAs, modelling choices affects results to the extent that they are not comparable across different studies unless major methodological choices are aligned, such as system boundaries (what is included), background data sources, method for co-product allocation, impact assessment methods and land use change. There are also aspects such as representativity and temporal components that needs to be taken into account. For LCA results to be truly comparable across case studies and products, the same LCA methods (both overall approach and specific method choices) must be applied.

C-LCA introduces a loop of assumptions and data choices which propagates through the modelled system, choices that cannot be made objectively. If assumptions about future market development are made to model “marginal seafood” (i.e. the type of seafood expected to increase in the future based on price, scalability etc), similar assumptions are in theory needed for the choice of material and energy use in these supply chains. Marginal energy production is, at present, often fossil-based, at least initially if demand increases, until the production system has adjusted if the increased demand persists- or until anything else (regulations, technology, costs of alternative systems) has changed. In the production of fossil fuels or other supply materials used, assumptions are needed what the marginal material is at the time the study is undertaken. This latter, marginal energy/electricity issue may explain a feature that is difficult to comprehend in the BC database. ”Whitefish, raw”, tuna and smoked salmon are in the database all modelled as farmed Tilapia. In stark contrast to previous findings in seafood LCAs who identify production (i.e. fisheries or aquaculture) to be the step in the supply chain that gives rise to most emissions (see e.g., review by Vazquez Rowe et al. 2012, Bohnes et al. 2019) is that in the BC database, the main part of emissions are generated in post-harvest processing. This is even more surprising given that processing is located in Denmark (which has a relatively high proportion of non-fossil energy production).

Octopus is modelled as mussels in the BC database, likely only on the basis of both being part of the taxonomic group mollusks, and thereby octopus outperforms most other aquatic animals. In reality, increasing demand for octopus has sparked investment in octopus farming, an industry that is dependent of large quantities of whole fish to feed octopus in culture. Using taxonomic relationships as the basis for assigning substituting products proves to be a particularly poor choice for aquatic animals. Herring, modeled in the BC database as farmed Norwegian Atlantic salmon – while in reality constituting a major component of the feed for Norwegian salmon results in a theoretical scenario where Atlantic salmon are assumed to be fed Atlantic salmon. Another observation is that the salmon feed data in the BC database contain over 75% marine inputs and in addition to that livestock by-products, which does not resemble a feed that is fed to Norwegian salmon in Europe today. Livestock products are not used at all due to low consumer acceptance and marine inputs constitute about 25-30% of the feed (Winther et al. 2020).

The BC database may be easy to access but difficult to understand and interpret, in particular for laypeople without an in-depth knowledge of LCA methods and practice. Typos like writing "flash" instead of "flesh", "carbon hydrate" instead of "carbohydrate" etc do not make things easier. The modeling choices behind the BC database results in that seafood from capture fisheries get associated with agricultural impacts. Herring from capture fisheries has agriculture-related emissions and other wild-caught species (squid and deep-water shrimp) are responsible for indirect Land Use Change emissions caused by e.g. deforestation from feed production in countries with expanding agriculture. It is also difficult to make sense of the results presented in relation to each other, e.g. why canned tuna has much lower emissions than raw tuna (knowing that the canning process is energy intensive and has turned out to be a hotspot in several scientifically published LCAs, e.g. Almeida et al. 2015). It could of course be tuna from different fisheries or species with different fuel use intensities, but again, the data used has nothing to do with tuna (and the production data is the same between the two). Canned tuna in tomato sauce has twice the impact of canned tuna in water (but then who knows what a marginal tomato is?). In the BC database, there also exists some very old data (e.g. some data on energy use originates in publications published in 2003, with data being even older).

For all of these reasons, and as our purpose was to analyse the greenhouse gas emissions of Danish fisheries and their seafood products and relate them to alternative animal-source foods, the BC database could not be used and since the methods differ so much, it is not relevant to compare results presented in this report with those found in the BC database.

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