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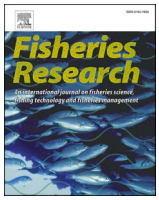

The environmental impacts of pelagic fish caught by Scottish vessels

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ABSTRACT

Food production is estimated to emit between 20–30 % of global anthropogenic carbon emissions. The need to achieve net zero emissions requires a transition to low carbon, sustainable food sources. Of the total greenhouse gas (GHG) emissions for food production, only 4 % are attributed to wild capture fisheries. However, within seafood GHG studies a wide range of estimates can be found across different species, fishing methods and regions. This study assesses the environmental impact of fish capture, including the carbon footprint (CF), by the Scottish pelagic fleet, a highly modernised fleet targeting herring, mackerel and blue whiting in the North Sea and Atlantic Ocean. A life cycle assessment (LCA) was undertaken to provide a standardised comparison of pelagic fish with other seafood studies. One kg of whole round fish caught by the Scottish pelagic trawl fleet had a CF of 0.452 kg CO_2 eq. Fuel burned during fishing operations was the largest contributing factor, accounting for approximately 96% of a CF. This figure was consistent with the expected results for a fishery for small pelagics, which are typically under 1 kg CO_2 eq. per kg of whole fish landed. When contrasted with other seafood LCAs, the results were found to be lower than most other seafood. Our results demonstrate that Scottish-caught pelagic fish are a low carbon food source that could contribute to minimising food-related GHG emissions.

1. Introduction

The direct effects of climate change are already apparent, e.g. crop failures due to adverse weather conditions (Lizumi and Ramankutty, 2015), increasing sea levels (Nicholls and Cazenave, 2010), species distribution shifts (Dulvy et al., 2008) and pollinator decline (Kerr et al., 2015). The need to limit the global temperature increase to 1.5 degrees C has become a worldwide imperative (IPCC, 2018). This has resulted in growing scientific and political pressure to reduce global greenhouse gas (GHG) emissions in an effort to mitigate the adverse effects and keep the net warming of the planet below 1.5 C° (UN, 2018). Consequently, there has been international co-ordination to meet this goal, as is evident from recent large-scale international pledges and agreements to mitigate emissions, such as the Paris Agreement (UNFCCC, 2015).

Food-related GHG emissions are responsible for approximately 20–30 % of all anthropogenic global GHG emissions, with 14.5 % attributed to livestock alone (Garnett et al., 2016). As a result, there is growing interest in identifying climate smart food production (Klytchnikova et al., 2015) and a desire to quantify and reduce GHG emissions related to agriculture, fishing and aquaculture (Audsley et al., 2009; Garnett, 2011; Smith et al., 2013). GHG emissions are estimated by life cycle assessment (LCA) (Avadí and Fréon, 2013; Garnett, 2014; Nijdam et al., 2012), whereby standardised techniques are used to estimate the climate-related and environmental impacts of a system or product, and to identify the main contributing factors. This standardised approach allows for greater comparability of the environmental impacts of different food products and helps to identify strategic options for food policy and for working towards the goal of net zero carbon emissions.

An important food source worldwide, seafood from both wild capture fisheries and aquaculture accounts for approximately 17 % of the global population's dietary animal protein intake (FAO, 2018). For over two fifths of the world's population this figure increases to 20 % of

Abbreviations: LCA, life cycle analysis; CF, carbon footprint; GWP, global warming potential; OD, ozone depletion potential; ADP, abiotic depletion of resources; ADPFF, abiotic depletion of fossil fuels; AP, Acidification potential; EP, Eutrophication potential; POMF, Photochemical oxidation formation; HT, Human toxicity potential; METP, marine ecotoxicity potential; TEPT, terrestrial ecotoxicity potential; FEPT, freshwater ecotoxicity potential.

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dietary animal protein intake (FAO, 2018). Improving fishing technology, such as the use of sonar to locate fish schools as well as improvements in fishing gear and engine design, has resulted in increasing quantities of seafood being harvested with decreasing effort and reduced danger to those involved. This expansion has not come without its own problems (e.g. the collapse of commercial fisheries, Myers et al., 1997), resulting in changes in the behaviour of apex predators (Estes et al., 1998), and extreme ecosystem shifts caused by the collapse of a food web (Pandolfi, 2005). As such, there are now safeguards in many countries to minimise the negative impacts of fishing and create sustainable and well managed fish stocks and stable marine environments (for example, national and international fishing quotas, no-take zones).

However, as the population continues to increase there is growing pressure on fisheries and all other food systems to continue to meet demand (Garcia and Rosenberg, 2010; Godfray et al., 2010). Given the projected population growth by 2050 and the commitment to meeting the UN sustainable development goals (UN, 2019), strategies for climate smart food systems need to be identified and developed. Climate smart food systems are those which meet the following criteria: they are either carbon neutral or relatively low in GHG emissions, they are resilient against climate change and extreme weather events and they have the ability to be sustainably increased to meet growing demand (World Bank Group, 2015).

The contribution of marine and freshwater food production systems to a nation's carbon footprint (CF) has been historically overlooked in global and national estimates. However, aquatic systems are now the focus of interest for many studies seeking to quantify the CF and other environmental impacts of various seafood products worldwide (Hilborn et al., 2018). A recent review by Parker et al. (2018) concluded that only 4 % of emissions from global food production can be attributed to fisheries. This is in sharp contrast to approximately 60 % of emissions from livestock (Garnett et al., 2016) though it should also be noted that considerably more terrestrial meat is eaten than fish worldwide. These comparisons highlight the importance of wild capture fisheries for contributing to climate smart food production. Considerable variation is observed between different fisheries, with fish species, fishing method, and region all known to have an effect on the CF of a particular species (Hilborn et al., 2018; Parker et al., 2018). Currently, there is a basic need for region-specific CF data for the most commercial fisheries.

LCA is the widely accepted methodology used to quantify the full environmental effects of seafood production from cradle (beginning of life cycle) to grave (disposal or recycling), or any subset within. Interest in LCA and carbon profiling in the seafood industry began in the late 1990s and early 2000s (e.g. Thrane, 2004; Ziegler et al., 2003). In the early years a lack of standardisation resulted in considerable variation in methodologies which made cross-comparison between studies difficult. Since then, the publication of the International Standard series 14000, e.g. 14,040 and 14044, (International Organisation for Standardisation, 2006a, b), specific guidelines (BSI, 2012), as well as general agreement within the scientific community has helped to Improve the issue of comparability. Two components of comparability are those of consistent system boundaries (the aspects of the product life cycle included in the assessment) and allocation (the term used for the partitioning of environmental impacts between products and co-products). Current approaches in LCA allow specific comparisons to be facilitated by using consistent system boundaries and offering guidelines towards details such as the issue of allocating emissions between co-products. There are two general types of LCA: attributional LCA (ALCA) and consequential LCA (CLCA). ALCAs are the most common and report a system's impacts at a given point in time, whereas CLCA explores possible changes in a system which may potentially alter impacts.

LCAs that have previously been undertaken for modern fisheries generally indicate that the capture process is the single most significant factor contributing to emissions over a product's entire lifespan (Avadí and Fréon, 2013; Hilborn et al., 2018), though its significance varies from fishery to fishery (Ziegler and Valentinsson, 2008). This variation is strongly related to the use of fuel during fishing (Hospido and Tyedmers, 2005; Parker et al., 2018) and general fishing efficiency (Ziegler and Valentinsson, 2008). Because of the importance of fuel economy on the GHG emission rate, influencing factors (such as the fishing method) can also have a large effect on a fishery's CF and other environmental impacts (Thrane, 2004; Tyedmers, 2000; Tyedmers et al., 2005; Vázquez-Rowe et al., 2010). Other studies have identified refrigeration leakage as also being of significance, particularly in the category of CF or Global Warming Potential (GWP) as it is often referred to in LCA papers (Vázquez-Rowe et al., 2010; Ziegler et al., 2011). The link between fuel usage and fishing efficiency also can be credited with the connection between environmental impacts and fishing method. Several studies have highlighted that efficiencies in catch rate vary across fisheries and gear types (Madin, 2015; Parker and Tyedmers, 2014). In some cases these can vary markedly even between geographically close regions (Iribarren et al., 2011; Ramos et al., 2011).

Small pelagic fisheries are generally considered to be one of the lowest impact fisheries, with purse seining often highlighted as being the most fuel efficient fishing method (Hilborn et al., 2018; Parker et al., 2018; Parker and Tyedmers, 2014). The pelagic mid-water trawl fishing method is more variable with some studies estimating it to be twice as high in terms of fuel burned per tonne of fish landed compared to purse seining (Parker and Tyedmers, 2014) although other studies having found it to be comparable (Jafarzadeh et al., 2016; Schau et al., 2009). Bottom trawling is found to be one of the most fuel intensive fishing methods (Schau et al., 2009; Winther et al., 2009), up to five times less efficient than purse seining in some instances. Crustacean fisheries are reported to have the highest GHG emissions documented to date (Parker et al., 2018).

Scottish vessels catch approximately 65 % of total fish caught in the UK (MMO, 2017). The largest and most valuable industry sector is the pelagic sector, making up 64 % of all Scottish landed fish, with a value of £202 million in 2018 (Scottish Government, 2019b). The Scottish pelagic fleet is comprised of modern, large, refrigerated seawater pelagic trawl vessels and purse seiners. These vessels target primarily Atlantic mackerel *(Scomber scombrus)*, Atlantic herring (Clupea harengus) and blue whiting (Micromesistius poutassou). These are landed at processing plants in Scotland, Norway, Denmark and Ireland and the products are sold worldwide almost exclusively for human consumption. Of the four major fisheries targeted by the Scottish pelagic fleet (North East Atlantic mackerel, North Sea herring, Atlanto-Scandian herring and North East Atlantic blue whiting) all but Atlantic mackerel currently have MSC certification (MSC, 2020a, b; MSC, 2020c, d), and are harvested at or below maximum sustainable yield (MSY) level as per ICES guidance (European Comission, 2019). The mackerel fishery, however, had its MSC status suspended in March 2019 (along with all other fisheries for the North East Atlantic mackerel stock), due to reputed overharvesting (Ramsden, 2019).

Despite the importance of Scottish pelagic fisheries to the UK and their role as a worldwide producer of pelagic fish, there is little region-specific data describing the contributions of Scottish-caught pelagic fish towards country-specific and global GHG emissions, or other climate related environmental impacts. Furthermore, given the government's commitment to reaching net zero carbon emissions (Scottish Government, 2019a) there is strong incentive for the industry to quantify the environmental impacts of Scottish caught pelagic fish and how it can contribute to achieving the goal of net zero carbon.

This study aims to quantify the environmental impacts of Scottish caught pelagic fish using ALCA. In order to do this it will: i) identify the main contributing factors causing the impacts; ii) estimate temporal and inter-vessel variability; and iii) determine how the environmental impacts compare to other seafood LCA studies.

2. Methods

The Scottish pelagic fleet is made up of 22 vessels, predominantly

pelagic trawl vessels ranging from 44 to 79.8 m in length. Three vessels use both the pelagic trawl and purse seining method to target different fisheries. Of the 22 fleet vessels, 50 % of the fleet participated in this study (n = 11). This sample contained vessels from two out of three home ports (72 % Shetland and 27 % Peterhead). As Fraserburgh vessels are geographically close to Peterhead and known to follow similar fishing patterns, this study sample can be considered representative of the entire Scottish pelagic fleet. The length of vessels sampled ranged from 61 to 78.9 m. This subset was considered to provide a reasonable representation of the size range of the fleet, although two vessels in the wider fleet were <61 m in length (56.2 and 44.9 m respectively). Both fishing methods (pelagic trawling and purse seining) were represented in the sample as well as a variety of vessel ages (ranging from 22 years to less than 6 months old), with this range also considered to be representative of the fleet. All vessels included in this study were anonymised by assigning an identifier for analysis and interpretation. Signed permission was gained from all vessel owners to allow for data access for the exclusive purposes of this study.

An ALCA approach was used in order to describe the CF and environmental impacts of Scottish pelagic fisheries. The focus was to understand the drivers behind the environmental impacts caused by the fishing stage and possible improvements. As such, the system boundary is from capture at sea to point of landing, including capital goods (summary in Fig. 1). Recycled content and end of life of capital goods were not included due to a lack of reliable data.

Primary data for vessel-specific details, capital goods and consumables were obtained from the skippers, bookkeepers and engineers for each vessel. This was carried out through in-person interviews and by telephone or email. Additionally, logs for fuel purchase, number of fishing trips per year and landings were obtained and, where necessary, third-party companies were contacted to provide further details (with permission of the vessel owners).

The following data were obtained for each vessel: capital goods (vessel age, length, weight, age at resale, any significant works undertaken, approximate lifespan); fishing gear details (weight and components of all nets currently in use, and their approximate lifespan); consumable details (average engine oil used in one year); antifouling details (frequency of treatment); total catch broken down by date and species per year; total fuel used broken down by periods and year; any significant non-fishing activities undertaken in the time period. Information on cleaning products was initially collected, although it was later removed from the analysis because the contribution was found to have no discernible impact on the end results and data could not be consistently obtained for all vessels. Refrigeration type was also confirmed by the vessel owners with all ships included in study utilising the study found to utilise the ammonia method. Leakage rate was assumed based on methodology used in Winther et al. (2009) and also by Seafish (2014) in their online GHG emissions profiling tool (http://profilerv2.seafish.org/index.php). Where primary data were not available, secondary data were obtained using the Ecoinvent 3.3 and European Life Cycle Database (ELCD) 3.2 provided by SimaPro. Full breakdown of secondary data used can be found in the supplementary tables (Appendix A in Supplementary material).

The ALCA analysis was carried out using SimaPro 8.3.0.0 Software and methods outlined in (Guinée et al., 2002). SimaPro was selected as it is the most widely utilised software for LCA analysis in scientific studies (Parker, 2012). The CML-IA baseline methodology was considered the most appropriate for the focus of this study due to the impacts explored in this methodology and the motivation behind the study. These choices would allow for the most accurate comparisons with other seafood LCAs by maintaining the closest methodological similarities.

When undertaking an LCA, all aspects of a system (e.g. capital goods, electricity usage, fuel burned etc.) including processes and all end products are input into the software. This enables the assessment of environmental impacts caused by these inputs and processes relative to the end product. This information is captured in a series of impact categories (categories each focus on measuring various outputs that relate to a specific environmental impact, Table 1) that are specified by the investigator and dependent on their area of interest. Impact categories can range from those reflecting environmental sustainability, such as GWP and ocean acidification (AP), to more traditional categories such as seafloor impact (SI) and use of finite resources (ADP, ADPFF). Similarly, SimaPro provides various associated databases which can be used for raw materials or processes. An investigator can therefore choose the resolution of their study with primary data and the provided secondary data by the system. Databases utilised by SimaPro are generally independent but guaranteed to be maintained and updated regularly. In this study the Ecoinvent 3.3 and ELCD 3.2 databases were utilised for

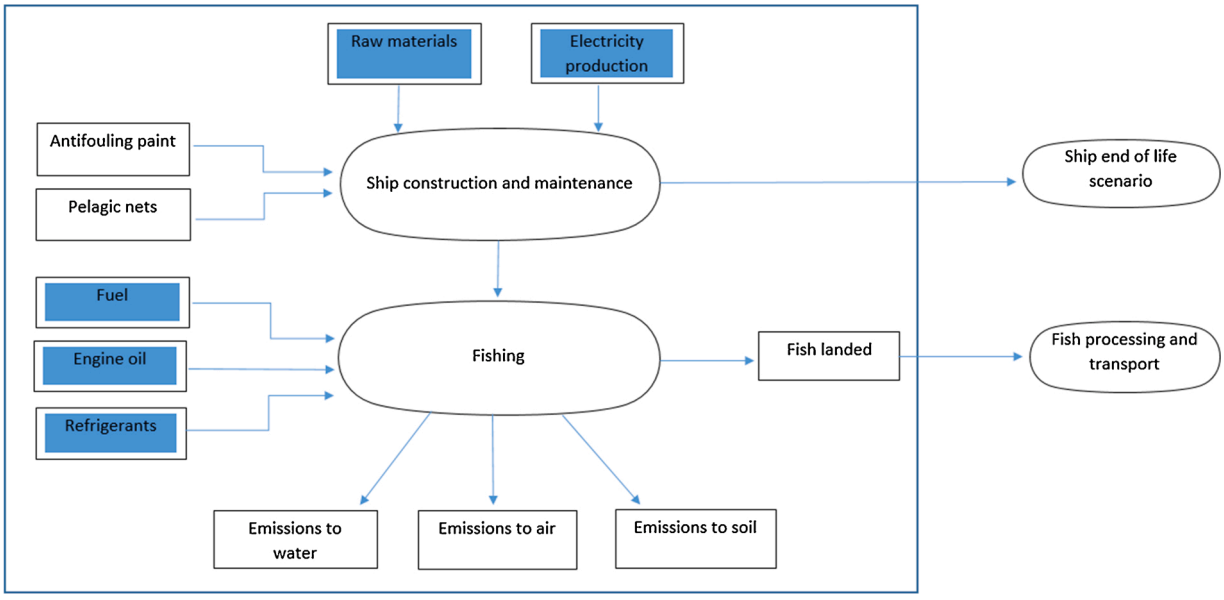

Fig. 1. Illustration of system boundaries where the large boxed area represents this study's system boundary and everything outside representing downstream events. Shaded boxes indicate where background data was used. In terms of fuel, engine oil and refrigerants, background data was used for their initial production from raw materials. Primary data was used thereafter for quantities consumed during the fishing phase. Arrows indicate direction of pathway for resource use, with products indicated in square boxes and processes in oval ones.

Table 1
List of impact categories selected for ALCA analysis.

Impact category	Acronym	Measured in	Units
Abiotic depletion	ADP	kg of Antimony equivalent	kg Sb eq.
Abiotic depletion (fossil fuels)	ADPFF	Megajoules	MJ
Global warming	GWP	kg carbon dioxide equivalent	kg CO_2 eq.
Ozone layer depletion	ODP	kg equivalent of CFC- 11	kg CFC-11 eq.
Human toxicity	HTP	kg 1,4 dichlorobenzene equivalent	kg 1,4-DB eq.
Fresh water aquatic ecotoxicity	FETP	kg 1,4 dichlorobenzene equivalent	kg 1,4-DB eq.
Marine aquatic ecotoxicity	METP	kg 1,4 dichlorobenzene equivalent	kg 1,4-DB eq.
Terrestrial ecotoxicity	TETP	kg 1,4 dichlorobenzene equivalent	kg 1,4-DB eq.
Photochemical oxidation formation	POMF	kg ethene equivalent	kg C_2H_4 eq.
Acidification	AP	kg sulphur dioxide equivalent	kg SO_2 eq.
Eutrophication	EP	kg phosphate equivalent	kg PO_4— eq.

secondary data.

Each impact category selected in an LCA is calculated independently to the others. They cover one possible environmental impact (such as GHG emissions, measured under the category GWP), though they may share several contributing factors. These contributors are converted to a single metric to allow for a single score per impact. Using global warming as an example, all greenhouse gasses possess different warming factors in that they all contribute towards global warming at a different intensity. To allow for cross comparison they are all converted to the relative quantity of carbon dioxide it would take to achieve the same level of warming. In some cases, the warming factor can be as high as a thousand times or more than that of the same weight of carbon dioxide (such as in the case of some CFCs). As such, units for CF are given in kilograms of carbon dioxide equivalent or kg CO_2 eq. In the LCA analysis, all raw materials, processes and constructs are analysed to determine how much they would cause or create contributions towards each specific impact, such as the quantity of GHGs released during creation, usage or disposal. This ultimately gives the figure for each impact category.

For this study eleven impact categories (Table 1) were considered the most relevant to the study focus of climate-related environmental impacts. Preference was given towards commonly used impacts to allow comparison with other studies. Of the 11 impact categories selected, six were chosen because they were measures of direct threats to continuing food security and because they are seen to appear in many LCA studies in the area. These six were as follows: global warming potential (GWP – also known as CF); ozone layer depletion potential (OD), marine ecotoxicity potential (METP), acidification potential (AD), eutrophication potential (EP), photochemical oxidation formation (POMF). Of the remaining five impact categories, two were selected because of their importance for climate change and sustainability, as they represent depletion of finite resources including fossil fuels (abiotic depletion, ADP and abiotic depletion of fossil fuels, ADPFF). Three further impact categories represented toxicity (human toxicity: HTP, freshwater ecotoxicity: FETP, and terrestrial ecotoxicity: TEPT). These categories were deemed important as no food system could be considered sustainable if it causes high toxicity. As there is a tendency for fisheries LCA studies to consider only a small number of specific indicators, it was considered important to report on all impact categories explored. It was felt this would help to increase the available information on the lesser used impact categories for future reference.

The issue of allocation of emissions is an important methodological decision that can have a strong influence on the end LCA results (Svanes et al., 2011). However, as the functional unit of this study was 1 kg of whole mixed pelagic fish, the issue of allocation was largely avoided. The only aspect which required any allocation was when calculating the impact of the capital goods of the vessels themselves as it was common practice in the Scottish fleet to commission a new build vessel every 10–15 years although the lifespan of the ship itself extended far beyond this. In this case, economic allocation was used due to the long downstream lifespan and uncertain end of life scenarios.

Secondary data from the Ecoinvent 3.3 database, supplemented where necessary with data from the ELCD 3.2 database were used to proxy for the following: raw materials for capital goods; emissions from the production of raw fuel and oil; emissions from burning diesel in a diesel engine; emissions related to the production of antifouling paint. The following assumptions were made after discussion with industry members with experience of onward sale of vessels: 1) lifespan of vessels is approximately 40 years; 2) resale of value of vessels is as follows, 2/3 purchase value after 10 years with no major enhancements and in good condition or 1/3 purchase value after 15 years with no major enhancements and in good condition. The functional unit of this study was 1 kg of landed whole pelagic fish to allow for maximum comparison with other existing seafood LCA studies.

In this study the absolute impact figures were run for the study fleet as a whole, for each year and for each individual vessel (overall and per year) to allow for temporal comparisons as well as intra-fleet fluctuations. A component analysis was also run to explore the biggest contributing factors to each impact category. Finally using the statistics given in FAO (1989), an average was calculated for the percentage edible yield (taken to be 61 %) and protein content of the pelagic species landed (taken to be 18.7 % of edible yield), to convert this study's findings in order to explore the impacts as per 40 g protein. This calculation allowed for a better comparison of nutrition across different meat types.

Other studies have found that that pelagic purse seiners have typically lowered CFs compared to pelagic trawlers,(Parker and Tyedmers, 2014) though other studies have not confirmed this finding (Jafarzadeh et al., 2016; Schau et al., 2009; Winther et al., 2020, 2009). A comparison between the different fishing methods could not be undertaken here due to the small number of purse seiners (three) and the fact that they used a mixed purse seine and pelagic trawl method with the latter being dominant. Weather was also not factored in at time of data collection, though this too might have played an effect on the outcome and should be explored at a later date.

3. Results

The results of each of the selected impact categories used in the LCA analysis for the study fleet are shown in Table 2. Each impact category is displayed in its own units relative to a kilogram of whole fish landed. The accumulative CF (here the GWP) was 0.452 kg CO_2 eq. per kilogram of whole fish landed for the Scottish pelagic fleet.

Table 2
LCA results detailing total impact scores per impact category for the Scottish Pelagic Fleet per kg of whole landed pelagic fish, over the years 2015-2017.

Impact category	Acronym	Units	Total Impact
Abiotic depletion	ADP	kg Sb eq.	2.40E-06
Abiotic depletion (fossil fuels)	ADPFF	MJ	5.61E+00
Global warming	GWP	kg CO_2 eq.	4.52E-01
Ozone layer depletion	ODP	kg CFC-11 eq.	4.88E-08
Human toxicity	HTP	kg 1,4-DB eq.	2.67E-01
Fresh water aquatic ecotoxicity	FETP	kg 1,4-DB eq.	1.29E-01
Marine aquatic ecotoxicity	METP	kg 1,4-DB eq.	1.19E+03
Terrestrial ecotoxicity	TETP	kg 1,4-DB eq.	1.34E-03
Photochemical oxidation Formation	POMF	kg C_2H_4 eq.	1.66E-04
Acidification	AP	kg SO_2 eq.	2.76E-03
Eutrophication	EP	kg PO_4— eq.	7.38E-04

The LCA component analysis (Fig. 2) indicates that the single biggest contributing factor to GWP, and all other impact categories investigated, is the use of fuel during fishing. Fuel use contributed to over 92 % of the total of all the impact categories, and over 95 % in all categories except abiotic depletion. While engine oil use was a visible contributor in several categories, it is minimal in comparison to other contributors. Antifouling and refrigeration leakage also contributed less than 1 % each of the total impact. The contribution of vessel construction (Capital Goods) varied greatly between impact categories, with the highest value (approximately 6 %) in the ADP category while the lowest was in the FETP category at under 1 %. The contribution of nets also varied across the impact categories, with the highest impact HTP, at approximately 3 % and the lowest in ODP, at under 1%.

Inter-vessel comparisons (Table 3) revealed variability in emission quantities. GWP rates ranged from a minimum of 0.279 kg CO_2 eq. (Vessel 9) to a maximum of 0.737 kg CO_2 eq. (Vessel 4), with a similar spread of results found for each of the impact categories. Individual vessels also displayed considerable inter-annual fluctuations over the study period (Fig. 3, with the highest recorded result at 1.969 kg CO_2 eq. and the lowest at 0.232 kg CO_2 eq.). Only two of the eleven vessels had a consistent GWP for each of the three years (Vessels 8 and 10 at approximately 0.343 and 0.335 kg CO_2 eq. respectively), with another two (7 and 9) displaying a small fluctuation. Four of the 11 vessels had their lowest GWP in 2017 while 5 vessels had the highest GWP in 2016. In both cases GWP for the other vessels varied between the remaining two years. One unusual observation, Vessel 2's GWP of 1.969 kg CO_2 eq. in 2016, was a clear outlier, given that the second highest value was 1.031 kg CO_2 eq. Furthermore, Vessel 2 showed only a small difference (0.012 kg CO_2 eq.) between 2016 and 2015 GWP results. Comparison with Table 4 reveals this instance to be linked with unusually low figures for both fuel and catch. A sensitivity analysis was undertaken to explore the effect that removing the outlier had on the results. However, while the individual GWP estimation itself was high, its effect overall on the vessel's total CF over the time period, and that of the fleet as a whole were minimal (dropping the 2016 GWP results from 0.490 to 0.476 kg CO_2 eq. and the results for Vessel 2 from 0.689 to 0.653 kg CO_2 eq.). It was subsequently deemed appropriate to retain the outlier within the analyses.

Correlations between selected elements of the impact analyses are presented in Fig. 4. A strong correlation ($R^2 = 0.85$, $p = 0.001$) can be seen between the total fuel burned, and the number of trips. Once again, the outlier identified in Fig. 3 has an effect on this relationship. Removal of this value still leaves a positive linear relationship and reasonably strong correlation between number of trips and total fuel spent ($R^2 = 0.70$, $p = 0.024$). There were no other significant relationships between GWP, trip number, total fuel burned by vessels, vessel length, vessel weight or vessel age. A weak correlation was detected between GWP and trip number ($R^2 = 0.534$), though it was not found to be significant ($p = 0.085$) and not indicative of any particular relationship. In this analysis LPT (litres of fuel spent per tonne of fish landed) was not included as it can be considered virtually analogous with GWP, with LPT making up approximately 96 % of the impact of GWP (refer to fuel use in Fig. 2).

There was a very strong correlation between fuel spent per tonne of fish landed (fuel use) and GWP as is seen in Fig. 5 ($R^2 = 0.998$, $p < 0.001$). Given the strong effect of the fuel use identified in Fig. 2, with approximately 96 % of GWP the direct result of fuel production and burning, a significant correlation is to be expected. This result is not independent, as fuel use is used to calculate GWP. However, the relationship still remains highly significant and illustrates how strongly GWP can be predicted by kilograms of fuel used per kilogram of fish landed.

The possible effects of travel to different landing ports on GWP were also explored (Table 5). Port preference varied markedly from vessel to vessel, but no relationship could be found between GWP and a preference for either non-domestic ports or domestic ports for landing. Non-domestic ports were marginally favoured over domestic ones (approximately 54 % of landings were to non-domestic ports), with Norway being the single most common area for vessels to land (37 % of landings being on average to Norwegian ports). The second most common port utilised was Peterhead at approximately 24 % of the landings. VMS data was sought after to better explore the influence of distance travelled on emissions but unfortunately gaining this data was deemed to be unfeasible. Of the ships that have the lowest GWP values (Vessels 7, 8, 9 and 10), all but one (Vessel 8) do show an increased incidence of landing to domestic ports. However, the percentage of visits to domestic ports versus non-domestic varies between all four vessels, with Vessel 8 showing a strong (70 %) preference for non-domestic ports and retaining a low GWP. Given that three of the vessels (9, 10 and 11) also utilise different fishing gear, it is not possible to conclude anything more on the effect of port choice on emissions at this point in time.

Finally, the results of the Scottish pelagic fleet for 1 kg of pelagic were converted to a functional unit of 40 g of protein (Table 7) to allow for better cross comparisons with studies on other meat types which use this functional unit (Section 4.3).

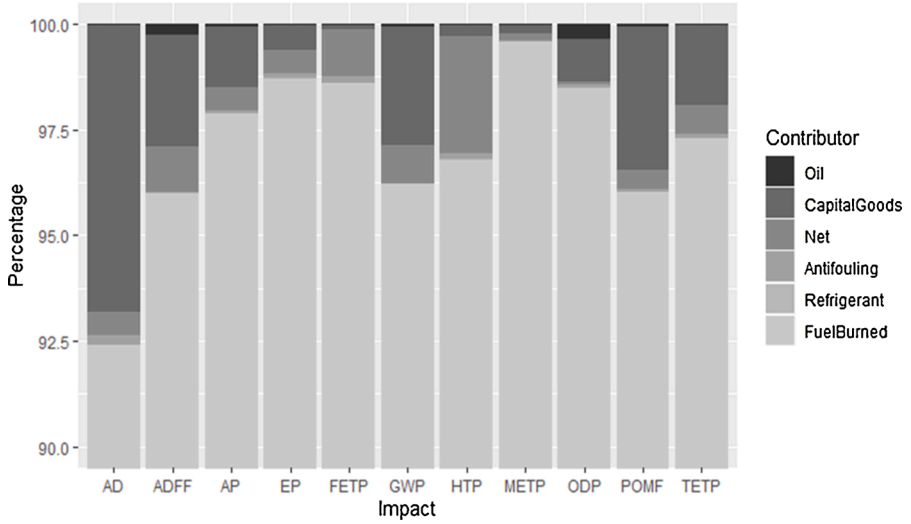

Fig. 2. Component analysis of LCA results for the Scottish Pelagic Fleet 2015–2017 showing the impact categories of Abiotic depletion (ADP), Abiotic depletion of fossil fuels (ADPFF), Global warming (GWP), Ozone layer depletion (ODP), Human toxicity (HTP), Fresh water aquatic ecotoxicity (FETP), Marine aquatic ecotoxicity (METP), Terrestrial ecotoxicity (TETP), Photochemical oxidation (POMF), Acidification (AP) and Eutrophication (EP), with y axis beginning at 89.5 %.

Table 3
LCA results detailed by impact category for each vessel in the study fleet over time period 2015-2017, with categories measured in the following: Abiotic depletion - kg of Antimony equivalent; Abiotic deletion of fossil fuels – megajoules; Global warming – kg carbon dioxide equivalent; Ozone layer depletion - kg equivalent of CFC- 11; Human toxicity - kg 1,4 dichlorobenzene equivalent; Freshwater aquatic ecotoxicity - kg 1,4 dichlorobenzene equivalent; Marine aquatic ecotoxicity - kg 1,4 dichlorobenzene equivalent ; Terrestrial ecotoxicity - kg 1,4 dichlorobenzene equivalent; Photochemical oxidation - kg ethylene equivalent; Acidification – kilograms sulphur dioxide equivalent ; Eutrophication - kg phosphate equivalent.

Impact category	Unit	Mean	coefficient of variation	Vessel 1	Vessel 2	Vessel 3	Vessel 4	Vessel5	Vessel 6	Vessel 7	Vessel 8	Vessel 9	Vessel 10	Vessel 11
Abiotic depletion	kg Sb eq.	2.76E-06	3.50E-01	3.76E-06	3.63E-06	3.93E-06	3.89E-06	2.51E-06	3.14E-06	1.66E-06	1.81E-06	1.51E-06	1.74E-06	2.77E-06
Abiotic depletion (fossil fuels)	MJ	6.46E+00	3.47E-01	8.82E+00	8.54E+00	9.14E+00	8.97E+00	5.87E+00	7.40E+00	3.92E+00	4.25E+00	3.46E+00	4.15E+00	6.58E+00
Global warming	kg CO2 eq.	5.21E-01	3.47E-01	7.11E-01	6.89E-01	7.37E-01	7.23E-01	4.74E-01	5.97E-01	3.16E-01	3.43E-01	2.79E-01	3.35E-01	5.31E-01
Ozone layer depletion	kg CFC-11 eq.	5.64E-08	3.45E-01	7.68E-08	7.47E-08	7.93E-08	7.75E-08	5.12E-08	6.48E-08	3.43E-08	3.72E-08	2.98E-08	3.66E-08	5.78E-08
Human toxicity	kg 1,4-DB eq.	3.08E-01	3.47E-01	4.21E-01	4.08E-01	4.35E-01	4.24E-01	2.79E-01	3.52E-01	1.87E-01	2.02E-01	1.63E-01	1.99E-01	3.14E-01
Fresh water aquatic ecotoxicity	kg 1,4-DB eq.	1.49E-01	3.45E-01	2.04E-01	1.98E-01	2.10E-01	2.05E-01	1.35E-01	1.71E-01	9.09E-02	9.85E-02	7.87E-02	9.70E-02	1.53E-01
Marine aquatic ecotoxicity	kg 1,4-DB eq.	1.38E+03	3.44E-01	1.88E+03	1.83E+03	1.94E+03	1.89E+03	1.25E+03	1.59E+03	8.42E+02	9.14E+02	7.27E+02	9.02E+02	1.42E+03
Terrestrial ecotoxicity	kg 1,4-DB eq.	1.55E-03	3.46E-01	2.11E-03	2.04E-03	2.18E-03	2.13E-03	1.40E-03	1.77E-03	9.39E-04	1.02E-03	8.23E-04	9.97E-04	1.58E-03
Photochemical oxidation	kg C2H4 eq.	1.92E-04	3.47E-01	2.61E-04	2.53E-04	2.71E-04	2.66E-04	1.74E-04	2.19E-04	1.16E-04	1.26E-04	1.03E-04	1.23E-04	1.95E-04
Acidification	kg SO2 eq.	3.19E-03	3.45E-01	4.34E-03	4.22E-03	4.49E-03	4.39E-03	2.89E-03	3.66E-03	1.94E-03	2.10E-03	1.69E-03	2.06E-03	3.26E-03
Eutrophication	kg PO4— eq.	8.53E-04	3.44E-01	1.16E-03	1.13E-03	1.20E-03	1.17E-03	7.74E-04	9.81E-04	5.19E-04	5.63E-04	4.51E-04	5.54E-04	8.75E-04

4. Discussion

4.1. LCA component analysis

Fuel usage was the largest contributing factor in all impact categories, consistent with other studies (Avadí and Fréon, 2013; Parker, 2012; Parker et al., 2018). Fuel was consistently >92 % of the contribution to any impact category. In GWP it contributed ~96 % of the overall impact. Earlier studies have found refrigeration to be a large contributor to environmental impacts (Iribarren et al., 2011; Winther et al., 2009), particularly GWP. However, our study found the assumed leakage rate to have little impact on any of the measured impacts. This is likely due to the Regulation (EC) No 2037/2000 (EU, 2000) and No 1005/2009 (EU, 2009) decreasing the use of substances that deplete the ozone layer. Vessels built post 2004 were no longer utilising the high impact R22 refrigerant method, instead using the lower impact ammonia method as a refrigerant. Only two vessels in this study were built prior to 2000 and they were converted to ammonia in late 2014, prior to the beginning of the data utilised in this study, from January 2015 onwards.

Capital goods and net construction were the two next highest contributors to GWP after fuel use. However, the variation in their contribution to the other impact categories is considerable, with their greatest contribution to any impact category at 6% and 3%, respectively, and their lowest under 1 %. The remaining two contributors (engine oil use and antifouling use) contributed <1 % in all categories. This clearly illustrates the importance of fuel efficiency in both predicting and reducing the CF of this fishery.

4.2. Inter-vessel and other sources of variability

All the impact categories examined in the study show distinct inter-vessel variability: GWP ranged from 0.279 – 0.737 kg CO_2 eq. per kg of landed round fish between vessels over the study period and this variability is representative of that seen in all impact categories. This was similar to what has been seen in the results of other studies (Vázquez-Rowe et al., 2012). The skipper effect is an acknowledged phenomenon (Oliveira et al., 2016) and could result in the differences between vessels in our study. Inter-annual fluctuations were found to be relatively small for the fleet, (with GWP ranging from 0.425 kg CO_2 eq. to 0.490 kg CO_2 eq. per kg whole fish over the study period). The low annual fleet fluctuation despite fluctuations in individual vessel's annual impacts, is most likely due to the internal buying and selling of quota during low or non-fishing phases. Overall, this suggests a reasonably stable fleet-wide CF.

Because the kg fuel spent per kg of fish landed is a factor used to calculate GWP, there was a very strong correlation between GWP and kg of fuel spent per kg of fish landed. Fuel usage by the vessel has been proposed as an adequate proxy for GWP in lieu of full data to the point of landing (Parker, 2012). As long as total annual fuel usage and total landings were known for any vessel in the Scottish fleet, a reliable approximation of CF could be made. This would allow for an expansion of the study set used in this research with minimal time and resource requirements, should data access be gained, giving a more detailed look at the CF for the Scottish pelagic fleet as a whole.

4.3. Comparison with other animal protein sources

The pelagic species caught by the Scottish pelagic fleet have a low CF in comparison to those of demersal fish, farmed salmon, and to shellfish caught in mobile gears (Table 6, though this is subject to the caveat that the studies in Table 6 vary in allocation methodology, which may have a significant effect on the results, Svanes et al., 2011). Relative to Scottish pelagics, demersal fisheries typically result in over 1 kg (over 121 %) more of CO_2 eq. per kg of whole landed fish (Winther et al., 2009), salmon (to the point of farm gate measured in live weight) are over

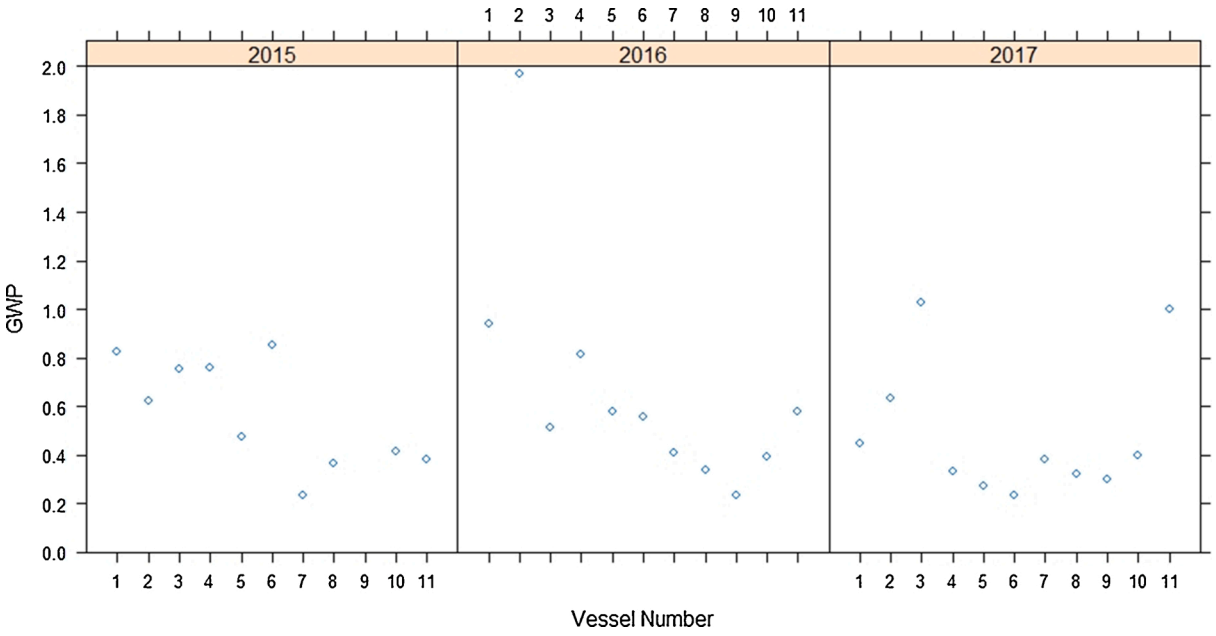

Fig. 3. Comparison of yearly fluctuations in carbon footprint between vessels in the study fleet measured in kg CO_2 eq. per kg of whole fish.

Table 4
Yearly fuel purchase (to the nearest litre) and total catch (to the nearest tonne) by study vessels.

Vessel	2015		2016		2017	
	Fuel	Catch	Fuel	Catch	Fuel	Catch
1	747,809	7170	781,382	6560	490,423	8800
2	498,565	6420	282,779	1200	1,744,286	21,310
3	787,087	8288	451,257	7100	632,781	4900
4	851,277	8880	945,674	9210	98,312	2970
5	898,454	14,910	1,375,689	18,580	330,146	10,100
6	1,618,534	14,780	1,664,950	23,225	212,488	8050
7	824,643	29,219	853,540	16,435	883,907	18,180
8	1,104,955	23,820	1,003,697	23,240	991,773	24,130
9	0	0	544,931	19,020	1,246,352	32,788
10	1,510,930	28,485	1,711,964	33,848	1,182,768	25,460
11	1,402,852	28,726	999,282	13,581	991,763	7772
Total	**10,245,104**	**170,698**	**10,615,145**	**171,999**	**8,804,999**	**164,461**

2.818 kg (623 %) higher (Pelletier et al., 2009), and shrimp are approximately 28.550 kg (6316 %) higher (Ziegler et al., 2011). The variation across different categories of seafood is likely due to several reasons. Demersal fish are associated with differing fishing methods such as pelagic trawling, resulting a higher associated CF (Hilborn et al., 2018; Parker et al., 2018). In contrast, the comparatively higher CF for farmed salmon is due to the production and consumption of the fish feed. This is of particular significance due to the suggested importance that farmed fish may play in addressing the growing food demand globally (FAO, 2018). It also poses global significance for its impacts due to the wide ranging origins of its components (Newton and Little, 2018) which often includes pelagic fish. The much higher impacts of the shrimp is due to a combination of factors including a fuel intensive capture method, with a higher value species resulting in increasing the acceptable fishing effort.

Our study found 40 g of protein from the mixed pelagic fisheries to have a CF of 0.158 kg CO_2 eq. (Table 7). This agrees with values given in Hilborn et al. (2018) indicating that pelagic fish are lower than other seafood protein. Only other small pelagics, molluscs and whitefish are found to typically show similar values to Scottish caught pelagic fish. In contrast, livestock CF's ranges to up to 10 kg CO_2 eq. (2212 %) higher. A similar trend is observed in the other impact categories when converted to 40 g of protein (Hilborn et al., 2018). Overall, the values for Scottish caught pelagic fish is one of the lowest recorded when compared to both aquatic and terrestrial meat products.

Low CFs are often associated with species that exhibit characteristics such as shoaling in tight, often 'clean' shoals allowing for minimal bycatch, and being migratory, allowing for capture in known grounds at advantageous times, such as is found with pelagic fisheries. Furthermore, due to the European pelagic sector being a high value sector, regular modernisation of vessels is normal practice in the Scottish fleet. This has reduced fuel costs, which are the fleet's biggest contributor to their environmental impacts (Fig. 2).

4.4. Comparison with other fishing fleets

4.4.1. Comparison of CF

The overall fleet value of 0.452 kg CO_2 eq. estimated here for the Scottish pelagic fleet is slightly below the figure of 0.610 kg CO_2 eq. reported for the Galician purse seine fleet and approximately half of that of the Galician pelagic trawl fleet (Iribarren et al., 2011). However, in contrast to that of the Scottish fleet, the Galician fleet was comprised of older, less efficient and likely smaller vessels. Vázquez-Rowe et al. (2010) found similarly high values when looking at horse mackerel (*Trachurus trachurus*) also landed in Galicia by both purse seiners and by costal bottom trawlers (0.797 and 2.28 kg CO_2 eq. respectively). The

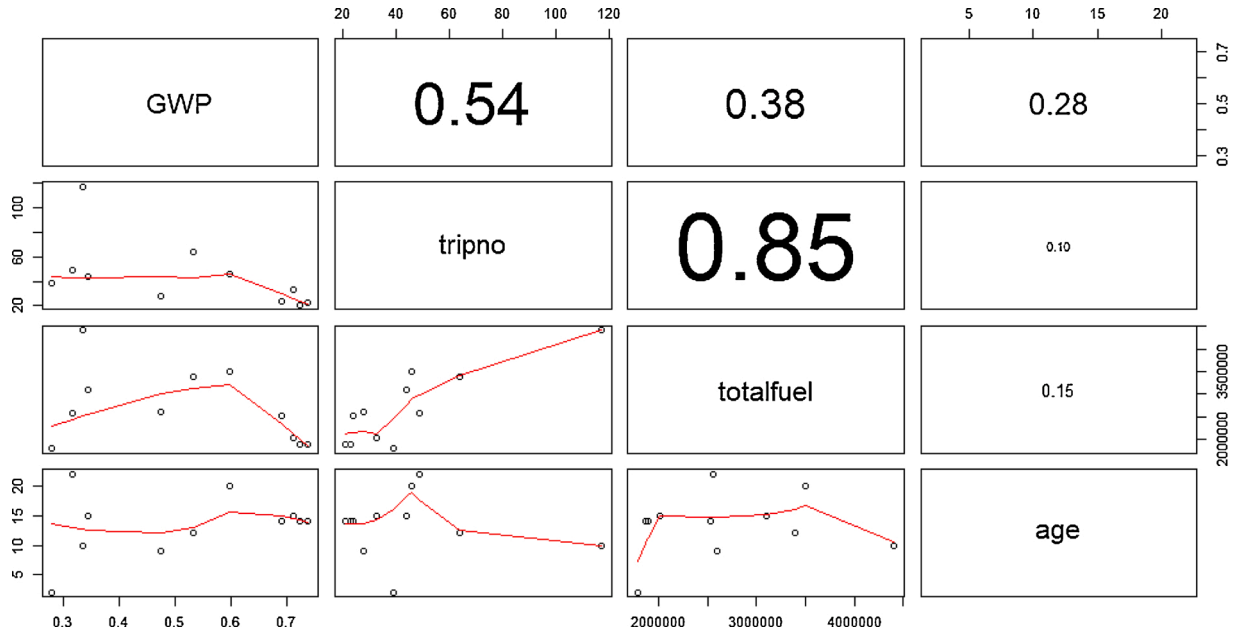

Fig. 4. Correlations between selected factors (GWP, number of trips, total fuel burned and age of vessel) for the study fleet 2015-2017, with absolute correlations given in the upper right panels and Lowess smoother applied in left.

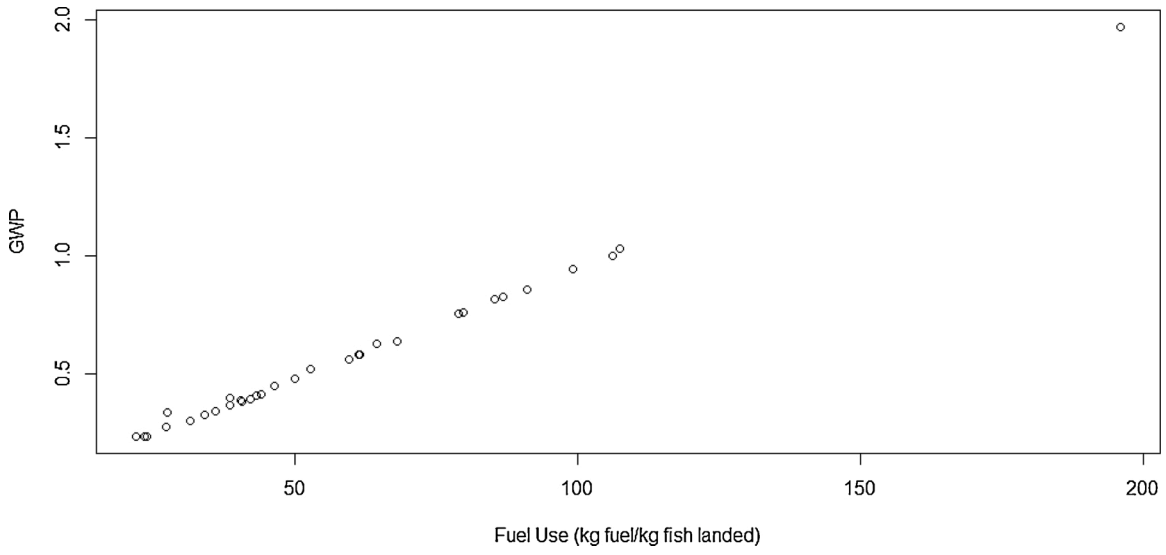

Fig. 5. Correlation between vessel fuel usage to land one kilogram of whole fish versus GWP.

Table 5
Trip and landing port breakdown by vessel in study fleet, 2015-2017 contrasted against Vessel GWP (measured in kg CO_2 eq.) for overall period, where F = Fraserburgh, P = Peterhead, S = Shetland, D = Denmark ports, I = Irish ports and N = Norwegian ports.

Vessel	Number of trips	% Port break down								Overall GWP (kg CO_2 eq.)
		F	P	S	Total % Domestic ports	D	I	N	Total % Non-Domestic ports	
1	33	0	6	48	55	15	0	30	45	0.711
2	24	0	0	29	29	21	0	50	71	0.689
3	23	0	0	9	9	0	9	83	91	0.737
4	21	0	19	19	38	14	10	38	62	0.723
5	28	0	0	32	32	7	0	61	68	0.474
6	46	0	2	7	9	15	2	74	91	0.597
7	49	0	2	53	55	16	0	29	45	0.316
8	44	0	30	0	30	23	2	45	70	0.343
9	39	8	72	0	79	0	21	0	21	0.279
10	117	19	64	0	83	0	17	0	17	0.335
11	64	11	70	0	81	0	17	0	17	0.531

Table 6
Adjusted GWP figures (in kg CO_2eq. per kg of fish) for assorted seafood products from comparable seafood LCA studies.

Fish type	Place of study	Fishing method	Carbon Footprint (kg CO_2eq kg^{-1})	Allocation Method	Authors
Small pelagic	Scotland	Pelagic trawl	0.452	Mass	This Study
Atlantic Mackerel	Galicia	Pelagic trawl	0.880	Economic	Iribarren et al. (2011)
Atlantic Mackerel	Galicia	Purse seine	0.610	Economic	Iribarren et al. (2011)
Atlantic Mackerel	Basque Country	Purse seine	Typically, > 0.200	Temporal	Ramos et al. (2011)
Horse Mackerel	Galicia	Purse seine	0.797	Mass	Vázquez-Rowe et al. (2010)
Horse Mackerel	Galicia	Bottom trawl	2.28	Mass	Vázquez-Rowe et al. (2010)
Farmed Salmon	UK	Farmed	3.27	Economic	Pelletier et al. (2009)
Cod	Norway	Mixed	1.60	Mass	Winther et al. (2009)
Haddock	Norway	Mixed	1.75	Mass	Winther et al. (2009)
Shrimp	Senegal	Trawl	~29	Mass	Ziegler et al. (2011)

Table 7
Conversion of environmental impact scores per 1 kg of fish to environmental impact scores per 40 g of protein, assuming an edible yield of 61 % and a protein content of 18.7 %), based on 2015-2017 landings of whole pelagic fish by the Scottish pelagic fleet.

Impact categories	Units	Weight of fish (g)	Edible yield (g)	Protein content (g)	Total impact	Impact score per 40 g protein
ADP	kg Sb eq.	1000	610	114	2.40E-06	8.42E-07
ADPFF	MJ	1000	610	114	5.61E+00	1.97E+00
GWP	kg CO2 eq.	1000	610	114	4.52E-01	1.58E-01
ODP	kg CFC-11 eq.	1000	610	114	4.88E-08	1.71E-08
HTP	kg 1,4-DB eq.	1000	610	114	2.67E-01	9.36E-02
FETP	kg 1,4-DB eq.	1000	610	114	1.29E-01	4.52E-02
METP	kg 1,4-DB eq.	1000	610	114	1.19E+03	4.17E+02
TETP	kg 1,4-DB eq.	1000	610	114	1.34E-03	4.70E-04
POMF	kg C2H4 eq.	1000	610	114	1.66E-04	5.82E-05
AP	kg SO2 eq.	1000	610	114	2.76E-03	9.68E-04
EP	kg PO4— eq.	1000	610	114	7.38E-04	2.59E-04

GHG emissions reported by Vázquez-Rowe et al. (2010) differ from those reported in the Iribarren et al. (2011) study for the same species (0.98 and 1.44 kg CO_2 eq., respectively). However, this difference could be due to the differences in methodology (such as allocation method) and/or the datasets utilised. Tuna purse seine fisheries produce a higher CF than small pelagics, burning an average of 463 L of fuel per tonne of whole fish landed (Hospido and Tyedmers, 2005), resulting in a CF of 1.6 kg CO_2 eq. per kg of whole fish.

The GWP reported by Ramos et al. (2011), is approximately 0.252 kg CO_2 eq. (or 56 %) per kg of fish landed lower than that of this study. However, Ramos et al. (2011) acknowledge that the fleet examined in their study shows a unusually low CF. They attributed this to the nature of the fishery whereby the pelagic fish are caught just offshore and landed to local ports, thereby minimising fuel expenditure. Additionally, their fleet figures, while lower than the Scottish fleet average in this study, are similar to some of the lower GWP values found by individual vessels during the study period (Table 3). Unfortunately, our study could not address the issue of distance travelled in more detail due to the resolution of the data. Ideally, any future studies would allow for more exact data gathering, such as fuel used per trip and the co-ordinates while fishing, so that these variables along with that of gear type could be better explored.

Winther et al. (2009) also reported a slightly lower GWP for Norwegian-caught Atlantic mackerel and herring of approximately 0.4 kg CO_2 eq. per kg of whole round fish to landing. At the time of the study, the Norwegian fleet were reported to comprise of large modern vessels and, as with Ramos et al. (2011), were shown to have CF values lower than most other supply chains. The comparatively small difference between the results reported here and the study by Winther et al. (2009) (0.052 kg CO_2 eq. per kg of fish landed), suggests that Scotland has a relatively fuel-efficient fishery for small pelagics as well. However, there are several explanatory factors that have not been factored into this comparison that may have a pronounced effect, such as economic influence on fishing behaviour (Abernethy et al., 2010; Cheilari et al., 2013), the skipper effect and experience level of the general fishing fleet (Ruttan and Tyedmers, 2007), and the effects of species value, distance to fishing grounds and awareness of the importance of on board decision making (Ziegler et al., 2018). It should be noted that an updated report has recently been released by SINTEF (Winther et al., 2020) which cautions that, due to methodological differences, the results cannot be directly comparable to the previous one, though there seems to have been little change in the CF found for the pelagic fish to the point of landing.

4.4.2. *Comparison of other environmental impact categories*

When compared to studies with a similar methodology focusing on fisheries for other pelagic species, this study is found to have consistently low impacts across most categories (Table 8). When compared to the horse mackerel purse seine fishery described in Vázquez-Rowe et al. (2010) this study was found to have lower impact scores for all categories except METP and FEPT, where the current study was slightly higher. There is not a clear reason for these differences, however, it could be due to small differences in calculations or in impacts from non-fuel contributors. In contrast, when this study is compared to the tuna fishery (Hospido and Tyedmers, 2005), the results for the Scottish fleet were found to be lower in all shared categories.

When contrasted with other seafood LCAs using similar methodologies (Table 8), our study had lower impacts in the shared categories of GWP, AP and EP than farmed salmon (Pelletier et al., 2009), and in all impacts than the mixed seafood of Abdou et al. (2018,) with the exceptions of FETP and ADPFF which it did not cover. No comparable studies were found to use the impact category of ADPFF, so no cross-comparisons could be undertaken. However, due to the long-term importance of depleting fossil fuel reserves, it is important to report this value even if not immediately relevant. Overall, our results highlight that Scottish-caught pelagic fish are lower than or equal to most impact categories assessed for other similar seafood.

4.5. *The effect of port choice on the results*

More than half of all landings by the sampled fleet in our study were to non-domestic ports, with Norway being the single most common

Table 8
Comparison between impact category scores across selected seafood LCAs, with categories measured in the following: ADP - kg of Antimony equivalent; ODP - kg equivalent of CFC- 11; HTP - kg 1,4 dichlorobenzene equivalent; METP - kg 1,4 dichlorobenzene equivalent; TETP - kg 1,4 dichlorobenzene equivalent; FETP - kg 1,4 dichlorobenzene equivalent; POMF – kg ethylene equivalent; AP – kilograms sulphur dioxide equivalent ; EP - kg phosphate equivalent; GWP – kg carbon dioxide equivalent.

Impact Category	Unit	Farmed Salmon (Pelletier et al., 2009)	Tuna (Hospido and Tyedmers, 2005)	Horse mackerel (Vázquez-Rowe et al., 2010)	Mixed small pelagics (This Study)	Mixed seafood (Abdou et al., 2018)
ADP	kg Sb eq.	N/A	N/A	4.99E-03	2.4E-06	3.35E-01
OD	kg CFC-11 eq.	N/A	1.40E-03	8.70E-07	4.88E-08	1.00E-05
HTP	kg 1,4-DB eq.	N/A	N/A	2.00E+02	2.67E-01	1.47E+01
METP	kg 1,4-DB eq.	N/A	5.60E+01	1.78E+02	1.19E+03	5.67E+03
TETP	kg 1,4-DB eq.	N/A	N/A	1.34E-03	1.34E-03	3.18E-01
FETP	kg 1,4-DB eq.	N/A	N/A	7.33E-02	1.29E-01	N/A
POMF	kg C_2H_4 eq.	N/A	1.20E-04	2.10E-04	1.66E-04	4.97E-03
AP	kg SO_2 eq.	2.97E-02	2.00E-02	1.01E-02	2.76E-03	5.56E-01
EP	kg PO_4— eq.	6.27E-02	3.40E-03	1.84E-03	7.38E-04	3.30E-02
GWP	kg CO_2 eq.	3.27E+00	1.60E+00	7.96E-01	4.52E-01	4.92E+01

landing destination for the pelagic fleet (with the second most common destination being a domestic port: Peterhead). While no significant relationship could be found between non-domestic port selection and GWP, a previous study (Ramos et al., 2011) suggested that landing to nearest port can offer the potential to lower CFs further. However, while increasing landings to local ports would be the ideal outcome in terms of theoretically lowering emissions, there are many economic and practical reasons whereby this is not feasible or preferable. These include, but are not limited to, obtaining the best price for the fish, the tendency of some vessels to sign landing contracts with specific fish processors, skipper preference, time constraints, weather constraints and the limit to how much fish any processor can take on at any one time.

4.6. The role of Scottish caught pelagic fish in achieving net zero

Our results indicate that Scottish pelagic fish can be considered as an example of climate smart food production that contributes to the societal goal of achieving net zero carbon emissions for Scotland, provided that the fish are harvested in accordance with other established principles of sustainability (e.g., MSY definitions). There are obvious limits to production capacity of all wild capture fisheries and it also unclear how these stocks and other commercial pelagic fisheries will react to changing climate (Muhling et al., 2017). Nevertheless, strategies for maximizing the environmental benefits of pelagic fisheries should be developed.

As fuel has such an overwhelming effect on the CF of Scottish caught pelagic fish, reducing fuel use has the greatest potential to lower the CF further. While localised landing port selection may reduce fuel usage, ongoing improvement in fuel efficiency technology potentially offers a better option. Given that fuel usage also contributes one of the greatest financial costs for the industry, there are multiple benefits to improving fuel efficiency even further. This incentivises innovation in vessel design, gear design, and engine improvement focused on burning fuel cleaner

No notable differences were identified in fuel usage between newly purchased vessels and the older vessels they replaced, however only one vessel was replaced during the years included in the study. Future research to track any improvements in fuel use and GWP after launching any new vessels would be beneficial. Personal communication with the net maker indicated that a more efficient net design, intended to minimise weight and drag in the water, was created and deployed by several vessels in 2018 (Swann Net Gundry, pers. comm., 2018) and also might have future effects on the fishing related environmental impacts of the fleet. On longer time scales, there is also the potential for hydrogen or liquid gas-powered engines to lower emissions even further still.

5. Conclusion

Using standardised methodology for quantifying impacts (ACLA) this study has found Scottish-caught pelagic fish (herring, mackerel and blue whiting) to have a low CF and environmental impact when compared to other similar seafood including farmed salmon, demersal fish and shellfish. Given that seafood products generally have a low CF in comparison to other animal proteins (Garnett et al., 2016; Parker et al., 2018), Scottish-caught pelagic fish can be considered a climate smart, low carbon food source that can contribute to achieving national goals for decarbonisation. The current study has confirmed that fuel consumption in the fishing phase to be the dominating factor across all impact categories. Efforts to reduce fuel efficiency, either by increasing engine efficiency or fishing efficiency, would reduce the overall impacts of fishing even further.

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CRediT authorship contribution statement

Frances Sandison: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization, Project administration. **Jon Hillier:** Conceptualization. **Astley Hastings:** Methodology, Writing - review & editing. **Paul Macdonald:** Conceptualization, Writing - review & editing, Funding acquisition. **Beth Mouat:** Writing - review & editing, Funding acquisition. **C. Tara Marshall:** Conceptualization, Writing - review & editing, Funding acquisition, Supervision.

Declaration of Competing Interest

This work was undertaken as part of PhD studies and funded by the following institutions: Scottish Pelagic Sustainability Group, Shetland Islands Council, University of Aberdeen, University of the Highlands and Islands, Shetland Fish Producers' Organisation.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fishres.2020.105850.

References

Abdou, K., Gascuel, D., Aubin, J., Ms, R., Lasram, F., Le Loc'h, F., 2018. Environmental life cycle assessment of seafood production: a case study of trawler catches in Tunisia. Sci. Total Environ. 610-611, 298–307.

Abernethy, K.E., Trebilcock, P., Kebede, B., Allison, E.H., Dulvy, N.K., 2010. Fuelling the decline in UK fishing communities? Ices J. Mar. Sci. 67, 1076–1085.

Audsley, E., Brander, M., Chatterton, J., Murphy-Bokern, D., Webster, C., Williams, A., 2009. In: WWF (Ed.), How Low can We Go? An Asssessment of the Greenhouse Gas Emissions from the UK Food System and the Scope Reduction by 2050. WWF, UK.

Avadí, A., Fréon, P., 2013. Life cycle assessment of fisheries: a review for fisheries scientists and managers. Fish. Res. 143, 21–38.

BSI, 2012. PAS 2050-2:2012, Assessment of Life Cycle Greenhouse Gas Emissions, Suplimentary Requirements for the Application of PAS 2050:2011 to Seafood and Other Aquatic Food Products. BSI standards LImited, 2012.

Cheilari, A., Guillen, J., Damalas, D., Barbas, T., 2013. Effects of the fuel price crisis on the energy efficiency and the economic performance of the European Union fishing fleets. Mar. Policy 40, 18–24.

Dulvy, N.K., Rogers, S.I., Jennings, S., Stelzenmüller, V., Dye, S.R., Skjoldal, H.R., 2008. Climate change and deepening of the North Sea fish assemblage: a biotic indicator of warming seas. J. Appl. Ecol. 45, 1029–1039.

Estes, J.A., Tinker, T., Williams, T.M., Doak, D.F., 1998. Killer whale predation on sea otters linking oceanic and nearshore ecosystems. Science. 282, 473–476.

EU, 2000. Regulation (EC) No 1005/2009 of the European parliament and of the council official journal of the European Union. On Substances That Deplete the Ozone Layer, pp. 1–31.

EU, 2009. Regulation (EC) No 1005/2009 of the European Parliament and of the Council Official Journal of the European Union L286, pp. 1–30.

European Comission, 2019. In: Comission E (Ed.), North-East Atlantic Coastal States Reach Agreement on Mackerel, Blue Whiting and Atlanto-Scandian Herring Quotas for 2020. European Comission. Online:

FAO, 1989. Yield and Nutritional Value of the Commercially More Important Fish Species. Food and Ariculture Organisation of the United Nations. Fisheries Technical Paper. Torry Research Station, Aberdeen (UK). Food and Ariculture Organisation of the United Nations.

FAO, 2018. The State of World Fisheries and Aquaculture 2018 - Meeting the Sustainable Development Goals. Meeting the Sustainable Development Goals. Food and Ariculture Organisation of the United Nations, Rome.

Garcia, S.M., Rosenberg, A.A., 2010. Food security and marine capture fisheries: characteristics, trends, drivers and future perspectives. Philos. Trans. Biol. Sci. 365, 2869–2880.

Garnett, T., 2011. Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? Food Policy 36, S23–S32.

Garnett, T., 2014. Three perspectives on sustainable food security: efficiency, demand restraint, food system transformation. What role for life cycle assessment? J. Clean. Product. 73, 10–18.

Garnett, T., Smith, P., Nicholson, W., Finch, J., 2016. Food Systems and Greenhouse Gas Emissions (Foodsource: Chapters). University of Oxford, UK.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327, 812–818.

Guinée, J.B.G., Heijungs, R., Huppes, G., Kleijn, R., Koning, Ade, Oers, Lvan, Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.A., Bruijn, Hde, Duin, R.van, Huijbregts, M.A. J., 2002. Part III: scientific background. In: Guinée, J.E. (Ed.), Handbook on Life Cycle AssesSment Operational Guide to the ISO Standards. Kluwer AcademicPublishers, Dordrecht. Centrum Milieukunde Leiden (CML), Leiden University.

Hilborn, R., Banobi, J., Hall, S.J., Pucylowski, T., Walsworth, T.E., 2018. The environmental cost of animal source foods. Front. Ecol. Environ. 16, 329–335.

Hospido, A., Tyedmers, P., 2005. Life cycle environmental impacts of Spanish tuna fisheries. Fish. Res. 76, 174–186.

International Organisation for Standardisation, 2006a. Environemental Management - Life Cycle Assessment - Requirements and Guidelines. Online. Accessed 03/02/2020. https://www.iso.org/standard/38498.html.

International Organisation for Standardisation, 2006b. Environmental Management - Life Cycle Assessment - Principles and Framework. Online. Accessed 03/02/2020. https://www.iso.org/standard/37456.html.

IPCC, 2018. Summary for policymakers of ipcc special report on global warming of 1 5c approved by governments. In: IPCC (Ed.), Special Report on Global Warming of 1 5c. IPCC. Online:Accessed 02/11/2020. https://www.ipcc.ch/2018/10/08/summary-for-policymakers-of-ipcc-special-report-on-global-warming-of-1-5c-approved-by-governments/.

Iribarren, D., Vázquez-Rowe, I., Hospido, A., Moreira, M.T., Feijoo, G., 2011. Updating the carbon footprint of the Galician fishing activity (NW Spain). Sci. Total Environ. 409, 1609–1611.

Jafarzadeh, S., Ellingsen, H., Aanondsen, S.A., 2016. Energy efficiency of Norwegian fisheries from 2003 to 2012. J. Clean. Prod. 112, 3616–3630.

Kerr, J.T., Pindar, A., Galpern, P., Packer, L., Potts, S.G., Roberts, S.M., Rasmont, P., Schweiger, O., Colla, S.R., Richardson, L.L., Wagner, D.L., Gall, L.F., Sikes, D.S., Pantoja, A., 2015. Climate change impacts on bumblebees converge across continents. Science. 349, 177–180.

Klytchnikova, I.I.S., Townsend, M.P., Edmeades, R., Choudhary, S., Hussain, V., Kray, S., Fernandes, H.A., Moses, E.C.M., Cantrell, E., Morales, J.T., Pietrowski, X.Z., Sue, M., 2015. Future of food: shaping a climate-smart global food system. In: Group W.B (Ed.), Future of Food. Washington DC.

Lizumi, T.A., Ramankutty, N., 2015. How do weather and climate influence cropping area and intensity? Glob. Food Sec. 4, 46–50.

Madin, E.M.P., Macreadie, P.I., 2015. Incorporating carbon footprints into seafood sustainability certification and eco-labels. Mar. Policy 57, 178–181.

MMO, 2017. UK Sea fisheries statistics 2016. In: Organisation M.M (Ed.), UK Sea Fisheries Statistics. Marine Management Organisation., London.

MSC, 2020a. MINSA North East Atlantic Mackerel. Online. Accessed 10/10/2020. https://fisheries.msc.org/en/fisheries/minsa-north-east-atlantic-mackerel/@@view.

MSC, 2020b. PFA, DPPO, KFO, SPSG & Compagnie Des Pèches St Malo Northeast Atlantic Blue Whiting Pelagic Trawl. Track a Fishery. Online. Accessed 10/10/2020. https://fisheries.msc.org/en/fisheries/pfa-dppo-kfo-spsg-compagnie-des-peches-st-malo-northeast-atlantic-blue-whiting-pelagic-trawl/@@view.

MSC, 2020c. PFA, SPSG, SPFPO, DFPO and DPPO North Sea Herring. Track a Fishery. Online. https://fisheries.msc.org/en/fisheries/pfa-spsg-spfpo-dfpo-and-dppo-north-sea-herring/.

MSC, 2020d. SPSG, DPPO, PFA, SPFPO & KFO Atlanto-Scandian Purse Seine and Pelagic Trawl Herring. Track a Fishery. Online. Accessed 10/10/2020. https://fisheries.msc.org/en/fisheries/spsg-dppo-pfa-spfpo-kfo-atlanto-scandian-purse-seine-and-pelagic-trawl-herring/.

Muhling, B., Lindegren, M., Clausen, L.W., Hobday, A., Lehodey, P., 2017. Impacts of climate change on pelagic Fish and fisheries. In: Phillips, B.F., Pérez-Ramírez, M. (Eds.), Climate Change Impacts on Fisheries and Aquaculture a Global Analysis. https://doi.org/10.1002/9781119154051. Online. Chapter 23.

Myers, R.A., Hutchings, J.A., Barrowman, N.J., 1997. Why do fish stocks collapse? The example of cod in Atlantic Canada. Ecol. Appl. 7, 91–106.

Newton, R.W., Little, D.C., 2018. Mapping the impacts of farmed Scottish salmon from a life cycle perspective. Int. J. Life Cycle Assess. 23, 1018–1029.

Nicholls, R.J., Cazenave, A., 2010. Sea-level rise and its impact on coastal zones. Science 328, 1517–1520.

Nijdam, D., Rood, T., Westhoek, H., 2012. The price of protein: review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. Food Policy 37, 760–770.

Oliveira, M.M., Camanho, A.S., Walden, J.B., Gaspar, M.B., 2016. Evaluating the influence of skipper skills in the performance of Portuguese artisanal dredge vessels. Ices J. Mar. Sci. 73, 2721–2728.

Pandolfi, J.M., 2005. ECOLOGY: Enhanced: Are U.S. Coral Reefs on the Slippery Slope to Slime? Science 307, 1725–1726.

Parker, R., 2012. Review of Life Cycle Assessment Research on Pruducts Derived From Fisherins and Aquaculture. Seafish Industry Athority, Edinburgh.

Parker, R.W.R., Tyedmers, P.H., 2014. Fuel consumption of global fishing fleets: current understanding and knowledge gaps. Fish Fish. 684–696.

Parker, R.L., Blanchard, J., Gardner, C., Green, B., Hartmann, K., Tyedmers, P., Watson, R., 2018. Fuel use and greenhouse gas emissions of world fisheries. Nat. Clim. Chang. 8, 333–337.

Pelletier, N., Tyedmers, P., Sonesson, U., Scholz, A., Ziegler, F., Flysjo, A., Kruse, S., Cancino, B., Silverman, H., 2009. Not all salmon are created equal: life cycle assessment (LCA) of global salmon farming systems. Environ. Sci. Technol. 43, 8730–8736.

Ramos, S., Vázquez-Rowe, I., Artetxe, I., Moreira, M.T., Feijoo, G., Zufía, J., 2011. Environmental assessment of the Atlantic mackerel (Scomber scombrus) season in the Basque Country. Increasing the timeline delimitation in fishery LCA studies. Int. J. Life Cycle Assess. 16, 599–610.

Ramsden, N., 2019. MSC Suspends All North East Atlantic Mackerel Certifications…. Undercurrent News. Online. Accessed 1/10/2020. https://www.undercurrentnews.com/2019/01/31/msc-suspends-all-north-east-atlantic-mackerel-certifications/#:~:text=The%20Marine%20Stewardship%20Council%20(MSC,suspended%20on%20March%202%2C%202019.text=Mackerel%20caught%20on%20or%20after,for%20fisheries%20across%20eight%20countries.

Ruttan, L., Tyedmers, P., 2007. Skippers, spotters and seiners: analysis of the "skipper effect" in US menhaden (Brevoortia spp.) purse-seine fisheries. Fish. Res. 73–80.

Schau, E.M., Ellingsen, H., Endal, A., Aanondsen, S.A., 2009. Energy consumption in the Norwegian fisheries. The Sustainability of Seafood Production and Consumption. J. Clean. Product. 17, 325–334.

Scottish Government, 2019a. Scotland to Become a Net-zero Society. Environment and Climate Change. Online. Accessed 25/09/2020. https://www.gov.scot/news/scotland-to-become-a-net-zero-society#:~:text=The%20new%20Climate%20Change%20Bill,to%20balancing%20carbon%20dioxide%20emissions.&text=The%20Scottish%20Government%20climate%20change,15%20year%20period%20from%20publication.

Scottish Government, 2019b. Scottish Sea Fisheries Statistics 2018. Marine and Fisheries. Online: Marine Scotland Directorate. Accessed 25/09/2020. https://www.gov.scot/publications/scottish-sea-fisheries-statistics-2018/pages/3/.

Seafish, 2014. Seafish - Seafood GHG Emissions Profiling Tool. Online. Accessed 01/09/2020. http://www.seafish.org/GHGEmissionsProfiler/v2/index.php.

Smith, P., Haberl, H., Popp, A., Erb, K.-h., Lauk, C., Harper, R., Tubiello, F.N., de Siqueira Pinto, A., Jafari, M., Sohi, S., Masera, O., Böttcher, H., Berndes, G., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Mbow, C., Ravindranath, N.H., Rice, C.W., Robledo Abad, C., Romanovskaya, A., Sperling, F., Herrero, M., House, J. I., Rose, S., 2013. How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? Glob. Chang. Biol. 19, 2285–2302.

Svanes, E., Vold, M., Hanssen, O.J., 2011. Effect of different allocation methods on LCA results of products from wild-caught fish and on the use of such results. Int. J. Life Cycle Assess. 16, 512–521.

Thrane, M., 2004. Environmental Impacts from Danish Fish Products - Hotspots and Environmental Policies. PhD Thesis. University. Denmark. Aalborg.

Tyedmers, P., 2000. Salmon and Sustainability : the Biophysical Cost of Producing Salmon Through the Commercial Salmon Fishery and the Intensive Salmon Culture Industry. Phd Thesis. University of British Columbia, Vancouver, BC, Canada.

Tyedmers, P.H., Watson, R., Pauly, D., 2005. Fueling global fishing fleets. Ambio A J. Hum. Environ. 34 (635), 638.

UN, 2018. The Paris agreement. In: Nations U (Ed.), Climate Change. Online: United Nations. Accessed 29/07/2020. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

UN, 2019. The Sustainable Development Goals Report. Accessed 28/07/2020. The United Nations, New York, USA. http://un.am/up/library/SDG_Report_2019.pdf.

UNFCCC, 2015. Adoption of the Paris agreement. In: UN (Ed.), Conference of the Parties. Paris: UNFCCC.

Vázquez-Rowe, I., Moreira, M.T., Feijoo, G., 2010. Life cycle assessment of horse mackerel fisheries in Galicia (NW Spain): comparative analysis of two major fishing methods. Fish. Res. 106, 517–527.

Vázquez-Rowe, I., Hospido, A., Moreira, M.T., Feijoo, G., 2012. Best practices in life cycle assessment implementation in fisheries. Improving and broadening environmental assessment for seafood production systems. Special Section. Food Integr. Traceab. 28, 116–131.

Winther, U., Ziegler, F., Hognes, E.S., Emanuelsson, A., Sund, V., Ellingsen, H., 2009. Carbon Footprint and Energy Use of Norweigen Seafood Products. SINTEF Fisheries and Aquaculture.

Winther, U., Hognes, E.S., Jafarzadeh, S., Ziegler, F., 2020. Greenhouse Gas Emissions of Norwegian Seafood Products in 2017. SINTEF Fisheries and Aquaculture.

World Bank Group, 2015. In: World Bank Group (Ed.), The Future of Food: Shaping a Climate-Smart Global Food System. World Bank Group, Washington DC.

Ziegler, F., Valentinsson, D., 2008. Environmental life cycle assessment of Norway lobster (Nephrops norvegicus) caught along the Swedish west coast by creels and conventional trawls—LCA methodology with case study. Int. J. Life Cycle Assess. 13, 487–497.

Ziegler, F., Nilsson, P., Mattsson, B., Walther, Y., 2003. Life cycle assessment of frozen cod fillets including fishery-specific environmental impacts. Int. J. Life Cycle Assess. 8, 39–47.

Ziegler, F., Emanuelsson, A., Eichelsheim, J.L., Flysjö, A., Ndiaye, V., Thrane, M., 2011. Extended life cycle assessment of southern pink shrimp products originating in Senegalese artisanal and industrial fisheries for export to Europe. J. Ind. Ecol. 15, 527–538.

Ziegler, F., Groen, E.A., Hornborg, S., Bokkers, E.A.M., Karlsen, K.M., de Boer, I.J.M., 2018. Assessing broad life cycle impacts of daily onboard decision-making, annual strategic planning, and fisheries management in a northeast Atlantic trawl fishery. Int. J. Life Cycle Assess. 23, 1357–1367.