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The environmental impacts of pelagic fish caught by Scottish vessels

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Key words:

Carbon footprint; LCA; pelagic fish; Scotland

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

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 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 2016). As a result, there is growing interest in identifying climate smart food production (Klytchnikova 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 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 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. 14040 and 14044, (International Organisation for Standardisation 2006a, International Organisation for Standardisation 2006b), 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, MSC 2020b, MSC 2020c, MSC 2020d), 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 meters 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 - 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).

The ALCA analysis was carried out using SimaPro 8.3.0.0 Software and methods outlined in (Guinée 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 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 kilogram 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 40g 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 2020, Winther et al. 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.

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

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 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 40g of protein from the mixed pelagic fisheries to have a CF of 0.158kg 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 40g 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 (Figure 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 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 litres 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 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 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 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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