Carbon footprint of fish from the New Zealand Deepwater Trawl Fleet: A preliminary study

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Contents

Executive Summary

The total greenhouse gas emissions (or carbon footprint) from fish production for the quota owners in the Deepwater Group (DWG) were estimated. To do so, a Life Cycle Assessment (LCA) study was done considering a total of 21 fishing vessels. The system boundary was "cradle to gate", including all activities in the boat (boat use and maintenance, fishing and processing the fish on-board). The main functional units were one kg of catch (whole fish) and one kg of edible fish (processed on-board) landed at the wharf. Only one vessel landed whole fish without processing. The study followed the most recent LCA methodology guidelines (PEFCR, 2022) for wild fish. Results for all greenhouse gases were converted to carbon dioxide equivalents (CO_2e) using the latest IPCC global warming potential factors.

The results are summarised in Table i. The main source of emissions (92-95% of the total footprint) was the fuel used by the trawlers, representing the largest opportunity for reduction or mitigation of the footprint. Refrigerant use and packaging were of much lesser importance (3-6% and 2-3% of total carbon footprint, respectively), followed by the life cycle of the vessel (i.e., accounting for the vessel's production and maintenance over its lifetime; at 1% of the carbon footprint).

Table i: Weighted average (based on the total catch for each vessel) for the carbon footprint per kg of greenweight catch landed (not allocated; 21 vessels) and kg of edible fish landed after processing on-board (allocated; for nine vessels with more complete data). Data in brackets are for 20 vessels using extrapolations from the nine vessels that provided comprehensive data).

	kg CO_2e / kg catch	**kg CO_2e / kg edible fish**
Fuel	1.14	2.06 (1.92)[1]
Refrigerant	0.04	0.13 (0.07)[2]
Vessel	0.01	0.01 (0.01)[1]
Packaging	-	0.03 (0.03)[1]
Total	**1.19**	**2.24 (2.03)**[1]

[1] for 20 vessels using relative economic and processed fish weight data from 9 vessels
[2] likely underestimated since zero emissions were used for unreported results

The weighted average carbon footprint for edible fish from the deepwater fleet is at the low-end of the published range when compared to other seafood. The range of the carbon footprint values for whole fish across 21 vessels (0.4 to 3.3 kg CO_2e / kg catch) was similar to that for the range from other published studies for wild and farmed fish. The corresponding range for processed fish (0.9-5.1 kg CO_2e / kg edible fish) was at the low end of the range for fish published in a recent detailed meta-analysis. The global literature review showed that the carbon footprint of edible fish per 100 g of protein is substantially lower than for red meat (beef and sheep), milk and pork, but similar to that for poultry.

1. Introduction

Greenhouse gas (GHG) emissions are of global concern due to impacts on climate change (e.g. IPCC, 2018). Food production has been identified as a significant contributor to global GHG emissions at around 30% of the total (Poore and Nemecek, 2019), and it is also important for New Zealand (NZ) as a major exporter of food products (MfE, 2021). There is a desire by producers and consumers to understand the emissions associated with food products.

The Deepwater Group (DWG) represents quota owners of New Zealand deepwater fleet, targeting mainly hoki, jack mackerel, squid and orange roughy. DWG works in partnership with the Ministry for the Primary Industries (MPI) to manage the sustainability of the wild fisheries. One of the indicators for sustainability is the carbon footprint (or total GHG emissions) from all activities related to fishing. Life Cycle Assessment (LCA) is the recommended method to calculate a product's carbon footprint. LCA provides a holistic approach to evaluating the environmental performance of a production system. Also, LCA can be used to look at different environmental burdens, such as eutrophication (water quality) and energy use, among others. It achieves this by considering the potential impacts from all life cycle stages of a product or system. An LCA of the whole product life cycle is called a "cradle-to-grave" LCA. However, some studies only focus on critical stages or stages over which the user of the analysis has an influence. For example, many analyses have only been carried out for a "cradle-to-gate" boundary (e.g., to farm gate) for food systems and products.

This project aimed to estimate the carbon footprint of edible fish that is landed at the wharf by the deepwater fleet (i.e., the cradle-to-gate footprint). It involved the development of detailed models and the application of LCA using primary data from 21 vessels. This report outlines the methodology, key input data used, and the results of the analyses. The data analysis and literature review for this scientific report were conducted utilizing information available up until December 2022.

2. Methods

This LCA study followed the approach developed by the European Union and outlined by the Product Environmental Footprint for Marine Fish (PEFCR, 2022) and ISO14067. The most recent version of the document is available at the Marine Fish PEFCR website (https://www.marinefishpefcr.eu/). A Product Environmental Footprint Category Rule (PEFCR) is a set of rules that specify which methods shall be applied for a specific product category. We followed the recommended methodology for wild and marine fish in this study.

2.1 Goal and scope

The study boundary is the "cradle to gate", with the final stage being the processed fish landed at the wharf. The focus was to understand the main sources of GHG emissions and possible improvements. The life cycle of the product analysed in this LCA study is represented in Figure 1. The life cycle includes all activities associated with the fishing vessel to be able to deliver fish to shore, i.e., construction of the vessel, transport of the fishing vessel to and from fishing grounds, maintenance operations, catching of fish, on-board preparation of fish (including gutting, filleting and packaging), on-board refrigeration and end-of-life of the vessel. The processing of fish can happen both on the fishing vessel and onshore. For the deepwater fleet, only one vessel delivered whole fish at the wharf, with all others delivering processed fish to the wharf.

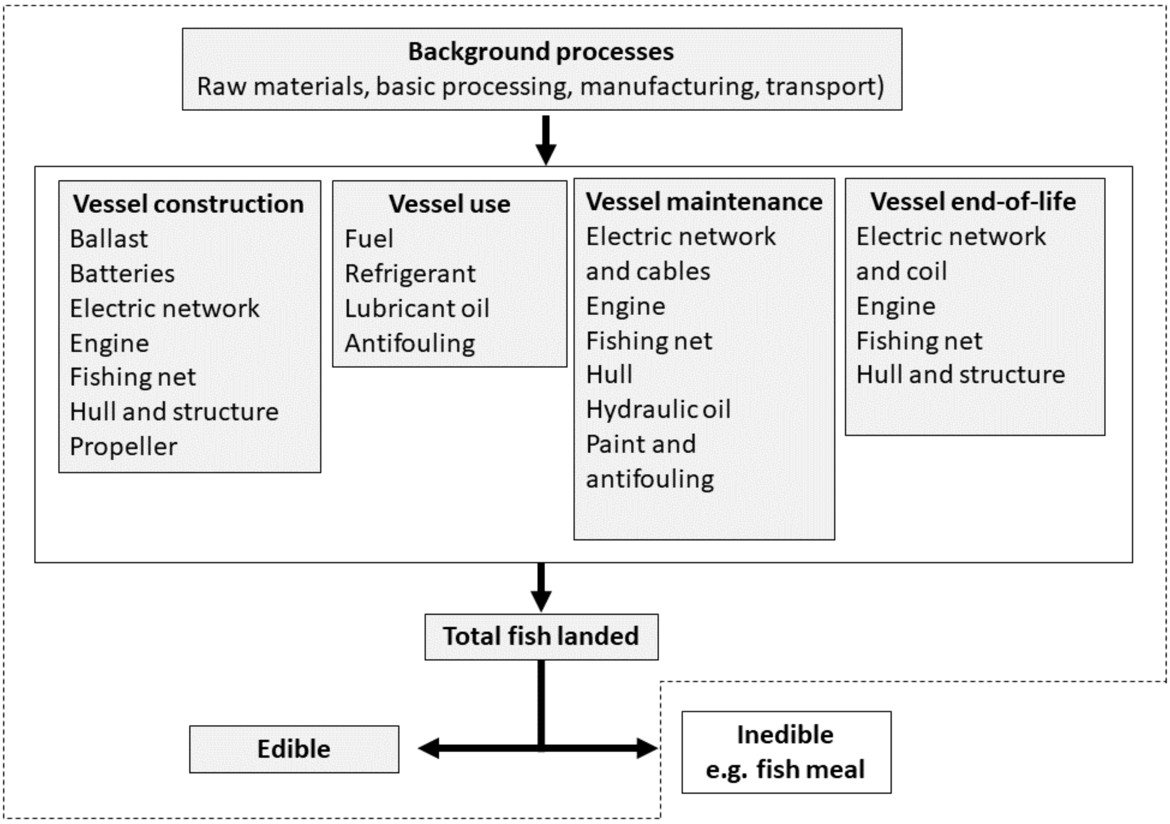

Figure 1 – System boundary of the Deepwater Group fleet analysis

Two main functional units are presented, with one being for one kg of catch (no allocation) and the other for one kg of edible fish (with allocation between edible and non-edible components of the fish). An economic allocation was used (according to internationally agreed methodology) to separate total emissions between the edible and non-edible parts (e.g., fish meal - Ayer et al., 2007; PEFCR, 2022).

2.2 Life Cycle Inventory

All data were collected using a data template spreadsheet based on the recommended data from the PEFCR (2022). This covered all activities or factors illustrated within Figure 1. A total of 21 vessels were analysed. Primary data on catch of raw fish and fuel use was provided for all vessels, but most other data categories were incomplete. Specific refrigerant data was provided for seven vessels while packaging data was provided for seven vessels. Inadequate data was provided on consumables use and therefore it was excluded from the analysis (thereby representing a minor overall underestimation). Data for the life cycle of the vessels (construction, maintenance and end-of-life) was also absent. A sensitivity analysis was performed to estimate the effect of the lack of data in the final footprint.

Default values and secondary data were used based on the PEFCR (2022) recommendations when primary data were not available. Since data for the vessel's construction, maintenance and end-of-life data were unavailable, secondary data from the literature were used based on the size of each vessel (Freon et al., 2014). For example, for some main contributors relating to maintenance of fishing nets, paint+antifouling, and hydraulic oil this equated to 762.7, 43.1 and 34.2 g/t raw fish, respectively. End-of-life estimates for nylon and lead from fishing nets equated to 542.3 and 122 g/t raw fish, respectively. When possible, specific emission factors for NZ were used (e.g., fuel emissions derived from Barber and Stenning [2022]); otherwise, emissions factors were extracted from an international LCA reputable database (ecoinvent - Wernet et al., 2016).

2.3 Life Cycle Impact Assessment

The carbon footprint (equivalent to Global Warming Potential (GWP)) for a 100-year time horizon (GWP100) expressed in carbon dioxide equivalent (CO_2e) was calculated following the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR5), using multiplication factors of CO_2 1, nitrous oxide (N_2O) 265, biogenic methane (CH_4) 27.75 and fossil CH_4 30 (Stocker et al., 2013). These will be the GWP factors used in the NZ GHG Inventory from next year. Additionally, GWP100 values for the refrigerants R22 and R407f of 3960 and 2020 kg CO_2e/kg refrigerant were used based on IPCC (Stocker et al., 2013).

The results obtained in this study were summarised as a simple and weighted average (based on the individual footprint and total catch for each vessel) and compared to other LCA studies assessing the same protein source (fish) using kg of catch or kg of edible fish as functional units. When compared to other sources of animal protein (beef, lamb, sheep meat, chicken and pork), a third functional unit (100 g of protein) was also calculated.

3. Results and Discussion

3.1 Carbon footprint results for the deepwater fleet – greenweight equivalent

The weighted average carbon footprint for the 21 vessels was 1.19 kg CO_2e/kg catch (Table 1), ranging from 0.38 to 3.28 kg CO_2e/kg catch.

Table 1: Simple and weighted averages (based on the total catch for each vessel) for the carbon footprint per kg of catch (or kg of greenweight landed) for all 21 vessels. Bracketed values refer to the range between vessels.

	Simple	**Weighted**
	kg CO_2e / kg catch	
Fuel	1.38	1.14 (0.37-3.19)
Refrigerant	0.04	0.04 (0-0.21)
Vessel[1]	0.01	0.01 (0.007-0.013)
Total	**1.42**	**1.19 (0.38-3.28)**

[1] values will be a minor underestimation due to lack of data for antifouling agents and consumables

Emissions from the production and combustion of fuel represented 96% (range of 84% to 99%) of the total carbon footprint of the deepwater fleet catch. Other studies also reached similar conclusions regarding fish production for single-day and multi-day trawler operations (Watanabe and Tahara, 2016, Ravi et al., 2020). Most of the fuel energy is for a sterkoder vessel and is used for propulsion (69%), while other activities represent 10% or less of the total, such as other electric loads (10%), boiler (7%), refrigeration and compressors (8%), winches (6%) and lighting (less than 1%) (DWG, pers. comm.). Bastardie et al. (2022) discussed efficient fishing techniques and their impact on fuel use intensity. According to these authors, bottom trawling is more fuel intense. The dominance of the fuel contribution to the carbon footprint means that different strategies to reduce fuel use (e.g. more fuel-efficient vessels - Bastardie et al., 2022) would significantly impact the carbon footprint of fish production. The use of fuels with a component of renewable-sourced fuel (e.g. from biofuels produced from plant crops or wastes) would also decrease the fuel contribution to the carbon footprint (Bastardie et al., 2022). However, there was no significant correlation between the carbon footprint of catch and annual fuel use by the vessels in this study (Figure 2A). In contrast, there was a strong significant correlation at the $p < 0.01$ level ($R^2 = 0.46$) between the carbon footprint and total catch (Figure 2B), indicating that the annual catch size is an important determinant of fuel use efficiency.

Fuel use efficiency averaged 0.33 L/kg catch (range 0.11-0.64) in this study, which was lower than the global fleet average for 2011 of 0.53 L/kg catch for all fish or 0.43 L/kg catch for pelagic fish, reported by Parker et al. (2018). The lowest fuel use was reported for a modern Scottish fleet, averaging 0.06 L/kg catch (range 0.03-0.29; Sanderson et al., 2021).

A previous study for DWG by Sustainable Horizons Ltd. (2021) showed similar or slightly higher fuel-related emissions per kg catch than identified in this study. The previous analysis was conducted across a larger number of vessels (approximately 40) and estimated emissions at about 1.40 kg CO_2e/kg catch using a lower fuel emission factor than in the current study. The simple average obtained in this study was 1.42 kg CO_2e / kg catch, while the weighted average was 1.19 kg CO_2e / kg catch (Table 1). A global evaluation of fuel use efficiency over more than 60 years showed lower estimated fuel-related emissions for Oceania of 1.30 kg CO_2e/kg catch compared to the global average of 2.50 kg CO_2e/kg catch (Greer et al., 2019). It noted that the Oceania value is likely to be an overestimate for deepwater fishing since it was associated with a high fuel use intensity from Australian trawling of crustaceans. Similarly, the global review by Parker et al. (2018) showed a global average of 2.20 kg CO_2e/kg catch, with Australian fleets at 5.20 kg CO_2e/kg catch and the average USA fleet at 1.60 kg CO_2e/kg catch.

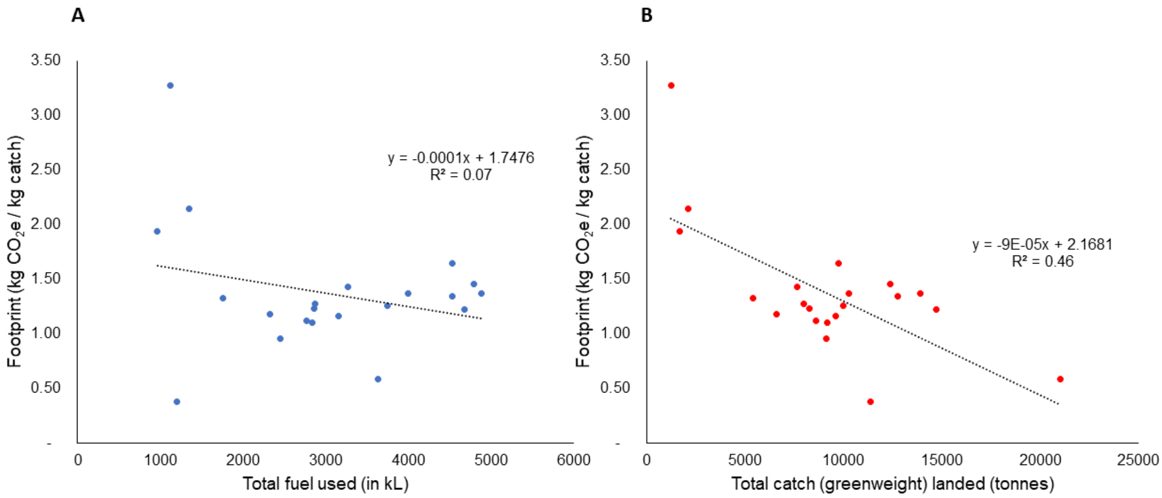

Figure 2 – Correlation between A) carbon footprint (kg CO_2e / kg catch) and total annual fuel used (in kL); and B) carbon footprint (kg CO_2e / kg catch) and total catch landed (in tonnes). Data points are for individual vessels.

The next main contributor to the carbon footprint was the production of refrigerants at an average of 3% of the total carbon footprint. This would be required for fish whether whole fish only or processed on-board the ship, although may be higher for processed fish. Data on refrigerant use was very variable, with only seven vessels reporting use (i.e., annual replacement rate) of one or more refrigerants. Similarly, the quantities reported per kg fish were variable, resulting in a variation of emissions related to refrigerant use of 0-0.21 kg CO_2e/kg fish or 0-15% of the total footprint (Table 1). This was influenced in part by the type of refrigerant used, with the emission factors varying between 2,020 and 3,960 kg CO_2e/kg refrigerant for R407f and R22 (different types of refrigerants), respectively.

The vessel construction, maintenance and end-of-life represented 1% of the final footprint. This is in line with other studies (Freon et al., 2014; Ravi et al., 2020; Abdou et al., 2021), and it is mainly because the vessels have a long lifetime of 30 to 50 years, so that they capture millions of tons of fish during this time. When these data are considered, the vessel's construction and maintenance impact on the final footprint becomes minimal. Although the vessel doesn't represent a significant source of the carbon footprint of fish, it has nevertheless been incorporated as a convenient system boundary for LCA studies in previous research (Ruiz-Salmon et al., 2021) in the interest of having a complete picture. The vessel had a larger but relatively small impact (3% of the total footprint) for small wooden trawlers where the fish were not processed in the vessel but instead stored in ice boxes (Watanabe and Tahara, 2016).

Iribarren et al. (2010) showed that the average footprint for coastal fishing activity in Galicia (Spain) ranged from 0.55 to 3.99 (average of 1.25) kg CO_2e/kg whole fish. The same study showed that the range for offshore fish was from 2.19 to 13.30 (average of 5.55) kg CO_2e/kg whole fish and for deep-sea fish was 1.21 to 1.70 (average of 1.44) kg CO_2e/kg whole fish. The fishing method also showed an important impact on the final footprint, with the highest footprint for lining, followed by trawling and seining (5.51, 3.92 and 1.01 kg CO_2e/kg whole fish, respectively).

A recent study from Scotland (Sandison et al., 2021) showed that the carbon footprint of pelagic fish was 0.45 kg CO_2e/kg whole fish, with a range of 0.28 to 0.74 kg CO_2e/kg whole fish. This study looked at data over three years and found that only two of the eleven vessels assessed had a consistent carbon footprint over time with others showing variability associated with variation in catch and fuel-use efficiency A Norwegian study (Winther et al., 2009) reported a carbon footprint of 0.40 kg CO_2e/kg whole fish for mackerel and herring.

As highlighted by Sandison et al. (2021), several factors can influence the final carbon footprint, such as the value of the fish species (which influences the economic allocation of the footprint), the skipper effect and the fishing expertise of the fleet (which influences the total fuel used and the areas explored). Other factors are the fishing type (single trawl, pair trawl, etc.), distance from fishing location to port and targeted species characteristics (e.g., hoki has a large volume but moderate value).

The carbon footprint of whole fish of 1.19 kg CO_2e/kg from this study was lower than the values of 6.0, 6.9 and 10.1 kg CO_2e/kg liveweight for sheep meat, dairy beef or traditional beef at the farm gate, by Mazzetto et al. (2023; 4.2, 7.1 and 7.1 kg CO_2e/kg, respectively, accounting for carbon sequestration by trees on-farm). However, this comparison has significant limitations and conversion to edible fish or meat is necessary, accounting for co-products during fish/meat processing.

3.2 Carbon footprint results for the deepwater fleet – edible weight equivalent

In order to compare the results obtained per kg of catch (section 3.1) with other seafood and protein sources, a conversion from kg of catch to kg of edible fish (or kg of protein) is required. From the initial 21 vessels, nine presented data for the processed fish weights or dressed weights (heads, guts and fins removed), and these were used to calculate the carbon footprint for the edible weight. These vessels also provided data on the weights of fish meal, and economic allocation was used to separate the emissions between edible fish and fish meal as recommended in the PEFCR (2022) for marine fish and applied in other studies. On average, 95% of the total GHG emissions were allocated to the edible weight of fish due to its higher commercial value than the inedible weight. However, some studies have also applied mass allocation (i.e., according to relative mass of the co-products) in sensitivity analyses (Ruiz-Salmon et al., 2021). In this study, for the nine vessels that provided economic and mass data the average % allocation to edible fish would have been 95% for economic allocation versus 76% for mass allocation. The effect of applying mass allocation would have been to decrease the carbon footprint per kg edible fish by 6%. The weighted average carbon footprint for the nine vessels was 2.24 kg CO_2e/kg edible weight (Table 2), ranging from 1.65 to 3.04 kg CO_2e/kg edible weight. This average was 2.04 kg CO_2e/kg edible weight for all 20 vessels calculated using the allocation and relative processing weight data from the nine vessels.

Table 2: Simple and weighted averages (based on the total edible weight for each vessel) for the carbon footprint per kg of edible fish for the nine vessels that presented the dressed weight data and for all 20 vessels using average edible:total weight data from the nine vessels. Bracketed values refer to the range between vessels.

	Simple (9)	**Weighted (9)**	**Simple (all)**	**Weighted (all)**
	kg CO_2e / kg edible fish		**kg CO_2e / kg edible fish**	
Fuel	2.14	2.06 (1.4-2.8)	2.26	1.93 (0.9-5.0)
Refrigerant	0.13	0.13 (0-0.39)	0.06[1]	0.07[1] (0-0.39)
Vessel	0.01	0.01 (0.008-0.015)	0.01	0.01 (0.008-0.021)
Packaging	0.04	0.03 (0.02-0.06)	0.04	0.03 (0.02-0.06)
Total	**2.32**	**2.24 (1.6-2.8)**	**2.37**	**2.04 (0.9-5.1)**

[1] probably underestimated due to lack of data and no assumed emissions from 13 vessels

For the weighted average results for the nine vessels with most complete data, the fuel, refrigerants, vessel and packaging contributed 92%, 6%, <1% and <2% of the total carbon footprint of edible fish, respectively (Table 2).

The carbon footprint of edible fish includes emissions from packaging materials. Other research has shown that packaging materials can have a significant influence on the carbon footprint of fish production, especially related to canned products (Laso et al., 2018a; Laso et al., 2018b). However, in this study, limited data was provided on specific packaging used and the final average used was based on data from only seven vessels. Thus, there is moderate uncertainty associated with this estimate. The relative contributions to total packaging emissions (with variation between vessels) from cardboard, high density polyethylene, low density polyethylene and polypropylene were 19-69%, 1-22%, 1-73% and 3-28%, respectively. The estimated emissions associated with packaging averaged 0.03 kg CO_2e / kg edible fish (range 0.02-0.06), which is less than the average for NZ beef based on detailed data from NZ abattoirs of 0.06 kg CO_2e / kg meat (Mazzetto et al., 2023). However, there may be some re-packaging at warehouse or retail stages, and this was not accounted for in the present study. In contrast, re-packaging for consumer sales was included in the NZ beef study.

Figure 3 shows the deepwater fleet data compared to a recent meta-analysis of data on the carbon footprint of wild-caught and farmed seafood products, drawing data from over 2,690 fish-farms and 1,000 unique fishery records (Gephart et al., 2021). The footprint was calculated per kg of edible weight and stopped at the landing of fish on the wharf. This meta-analysis showed a wide range in carbon footprint values, with results for this NZ study being at the lower end of the range. The range in the deepwater fleet carbon footprint values across the different vessels is between the low and the average footprint for fish species in the meta-analysis.

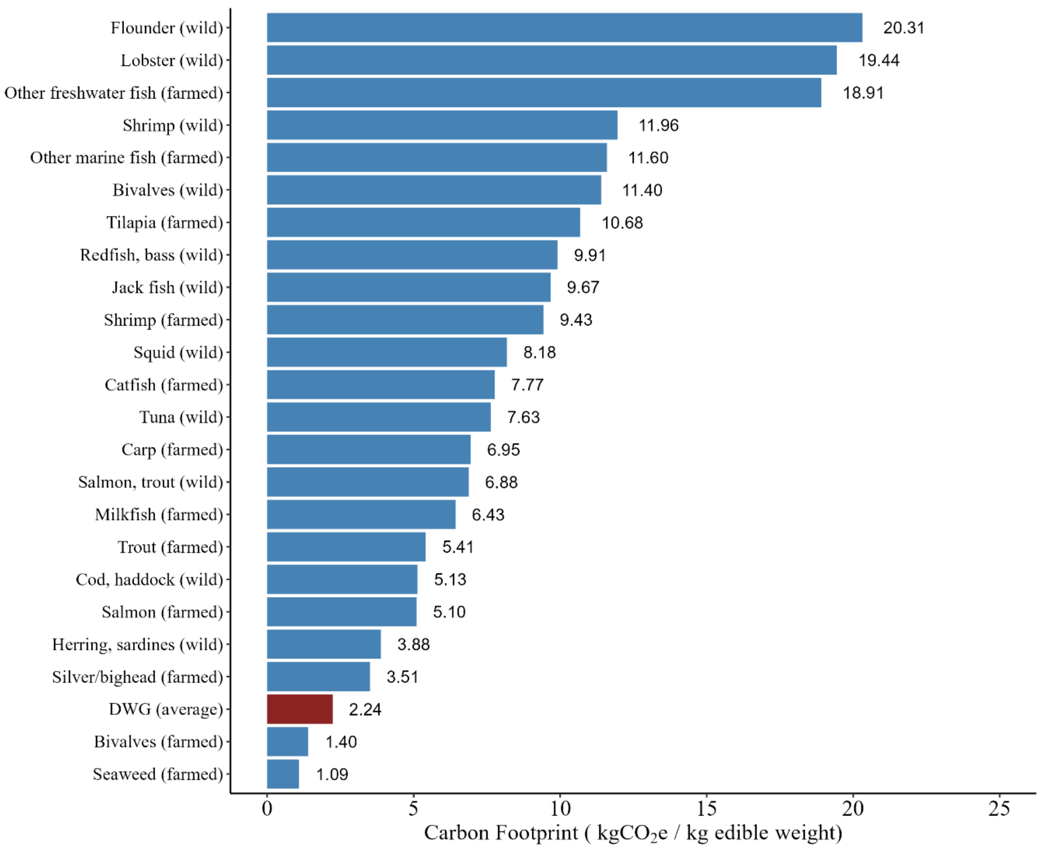

Figure 3 – Carbon footprint (in kg CO_2e / kg edible weight) for different seafoods from different origins (wild or farmed – in blue) compared to the deepwater fleet (DWG) weighted footprint (in red). Data are a meta-analysis of multiple studies by Gephart et al. (2021).

3.3 Comparison between deepwater fleet fish and other protein sources

Table 3 shows the carbon footprint of fish from the deepwater fleet compared to the other main protein sources produced in NZ using 100 g of protein as the functional unit. Specific data for NZ products were used; however, data for NZ-produced pork, poultry and eggs were not available. The deepwater fleet fish showed a lower footprint per 100 g of protein when compared to the other alternatives. Other studies reached similar conclusions at a global level (e.g., Poore and Nemecek, 2018). However, the global studies by Poore and Nemecek (2018) and Parker et al. (2019) showed that poultry and pork have a similar carbon footprint to that for fish and showed higher estimates for beef and lamb than in the NZ study. Hillborn et al. (2018) made a similar meta-analysis which showed variation for fish according to the studies and type of fish caught, being lowest for small pelagic fish and with the latter being lower than for chicken and pork. However, such meta-analyses summarise multiple studies but cover different methodologies applied (including different GWP factors) which affects the ability to make accurate comparisons. In the study of Mazzetto et al. (2023), data was also presented for beef and sheep meat from studies in other countries using similar methodologies (and the same GWP100 factors). That study showed values for beef and sheep meat (cradle-to-processor-gate) of 20.1-31.3 kg CO_2e/kg beef (covering Australia, Italy, Mexico and USA) and 15.3 kg CO_2e/kg sheep meat in an Australian study. Associated comparison of a wider number of beef and sheep studies covering the main cradle-to-farm-gate stage also showed variation between countries with NZ cattle and sheep being at the low end of the range of published results. Other studies have shown Oceanian livestock products at the low end of the range for global products (e.g., Opio et al., 2013) and illustrate that the difference between results for NZ fish in the present study and other protein sources (at least for beef and sheep meat) are even greater when compared with global average data.

It is important to highlight that most of the carbon footprint of products from ruminant animals (dairy, beef and sheep) is related to CH_4 (85 to 90% - Mazzetto et al., 2023, Mazzetto et al., 2021), a short-lived GHG (Allen et al., 2018), while for the footprint of the non-ruminants it is mostly related to CO_2, a long-lived GHG, mainly due to the production of feed (poultry and pork) and fuel (fish). This poses a different challenge for the fisheries sector (and other non-ruminant livestock sector), since to avoid/reduce future warming, the NZ government has imposed a net-zero target for the whole country by 2050 for long-lived GHGs, while short-lived GHGs have a smaller reduction target (24-47% by 2050).

Table 3: Carbon footprint (in kg CO_2e / 100 g protein) for different protein sources produced in New Zealand.

	Cradle to gate*	Protein**	Cradle to gate	Reference
	kg CO_2e / kg	**g / 100g**	**kg CO_2e / 100g protein**	**-**
Beef	22.69	20	11.34	Mazzetto et al. (2023)
Dairy beef	17.21	20	8.61	Mazzetto et al. (2023)
Sheep meat	13.83	21	6.59	Mazzetto et al. (2023)
Oysters	-	-	3.70	Warmerdam et al. (2021)
Milk (UHT)	1.27	3.5	3.63	Mazzetto et al. (2021)
Mussels	-	-	1.80	Warmerdam et al. (2021)
DWG	2.24	22 (20)[#]	1.02 (1.12)	This study

DWG: Deepwater Group; UHT: ultra-high temperature.
* for livestock products includes on-farm and processing stages. For oyster and mussels, the study boundary is "cradle to retail-gate", so it includes a minor contribution from the distribution stage.
** Data was obtained from an NZ nutritional database (https://www.foodcomposition.co.nz/)
[#] Some studies report similar protein% for fish and beef; bracketed values are for fish with 20% protein

4. Limitations

The major limitation of this study was access to detailed inventory data, with primary data for all vessels only covering total catch weight (unprocessed) and fuel use. Primary data on relative economic value of processed fish was provided for 15 vessels while edible weight:catch ration was provided for 9 vessels. This required extrapolation from vessels that supplied primary data to the remaining vessels to get estimates for the fleet. No primary data was provided on the construction, maintenance, consumables and end-of-life of the vessels. As described in the methodology section, we used data from literature (Freon et al., 2014) for estimating these vessel-related factors. However, as indicated by the results, the life cycle of the vessel has a minor impact (less than 2%) on the final carbon footprint of fish.

We performed a sensitivity analysis to investigate the degree of change in the footprint that would result if the data from Freon et al. (2014 - boats used for sardine fishing in Peru) is not representative of the deepwater fleet. To conduct this analysis, we gathered the data from Freon et al. (2014) and increased the amount of each source by 100%, i.e., doubled the number for all inputs related to the construction, maintenance and end-of-life of the vessel. The footprint increased by only 0.6% (Table 4), even with such large changes in the base assumptions, thus indicating that this stage has no significant impact on the estimated final carbon footprint. However, the method of Freon et al. (2014) was based on per-catch data, which leads to variability in its application. On average, the study by Freon et al. (2014) estimated that the average vessel contributed 6% to the carbon footprint of fish, while it was 3% in the study of Abdou et al. (2020).

Freon et al. (2014) showed that the vessel construction, maintenance and end-of-life can have a significant impact on other environmental impact categories, such as freshwater eutrophication, freshwater and marine ecotoxicity and metal depletion. One example is the use of antifouling compounds, which has a minimal impact on the carbon footprint, but accounted for 46% of the impacts for marine ecotoxicity (Hospido and Tyedmers, 2005). The carbon footprint is only one environmental impact category that can be assessed using LCA, and close attention should be paid to other impact categories to avoid pollution swapping. Overfishing is a potential serious issue that can lead to the depletion of fish stocks and have a negative impact on the environment. In contrast to the other protein sources mentioned in this report, the deepwater fleet product is not "farmed", which leads to a reduction in the number of inputs in the system (and consequently, a lower carbon footprint). However, a sustainable fishing quota (as exists in NZ) is necessary to ensure resource persistence and productivity over time.

Another aspect that should be considered is the potential emissions associated with bottom trawling. One of the major challenges in LCA is to account for the impact of trawling on sea-life biodiversity. Despite being an important environmental concern, the methodology to assess this impact is still in its early stages of development, and there are no dedicated case-studies available. A recent study has shown that bottom trawling can significantly contribute to GHG emissions from fisheries by seafloor disturbance, leading to increased organic carbon mineralisation and CO_2 release (Sala et al., 2021). However, there are limitations and uncertainties associated with the assumptions made in this study (Hilborn and Kaiser, 2021), and more evidence is needed to accurately quantify the impact of bottom trawling on GHG emissions (Epstein et al., 2022).From the total 20 vessels that processed fish on-board, only seven reported the use of refrigerants. Table 1 presented a weighted average considering that the refrigerant use for the other vessels was zero. We performed a second sensitivity analysis by re-calculating the footprint per kg of catch using data from the average for the seven vessels that reported the use of refrigerants (Table 4). The final footprint increased by 6.0% when considering only the vessels that provided data for refrigerant use.

Table 4: Effect of the sensitivity analysis of a 100% increase in the vessel data emissions and selecting the average for the vessels that provided data on the refrigerant use compared to the baseline (which included vessels with no reported refrigerant use) on the final carbon footprint of the catch (in kg CO_2e / kg catch). Data is for 21 vessels.

Source	**Baseline**	**Vessel increase**	**Refrigerants increase**
	kg CO_2e / kg catch		
Fuel	1.14	1.14	1.14
Refrigerant	0.04	0.04	***0.11***
Vessel	0.01	***0.02***	0.01
Total	**1.19**	**1.19**	**1.26**

Only one deepwater fleet supplier (total of seven vessels) provided data for packaging, so an average emission factor per kg of edible fish landed for the packaging was calculated based on the data from those seven vessels and applied across the other 13 vessels that processed fish on-board ship. We performed a sensitivity analysis by doubling the packaging emissions that were originally reported. The final weighted average carbon footprint increased by 1.6% (Table 5) when compared to the baseline footprint.

***Table 5**:* Effect of the sensitivity analysis of a 100% increase in the packaging use compared to the baseline on the final carbon footprint (in kg CO_2e / kg edible fish). Data is for 20 vessels.

Source	**Baseline**	**Packaging increase**
	kg CO_2e / kg edible fish	
Fuel	1.93	1.93
Refrigerant	0.07	0.07
Vessel	0.01	0.01
Packaging	0.03	***0.07***
Total	**2.04**	**2.07**

Different factors are important when comparing the carbon footprint of products, one of the main ones being the Global Warming Potential (GWP) of the different GHGs. The meta-analysis results used in this report (Poore and Nemecek, 2018; Gephart et al., 2021) did not mention a harmonisation process between the different studies. This means that different GWP factors were potentially used, and this can influence the magnitude of the footprint, especially for beef, sheep and dairy products, where most of the emissions are related to methane and nitrous oxide. However, the data in Table 3 comparing protein sources were all based on using the same recent GWP factors.

5. Conclusions

This study followed the most recent international LCA methodology guidelines (ISO 14067:2018 and PEFCR, 2022) for calculating the “cradle to gate” carbon footprint of fish produced by the deepwater fleet. The main source of emissions (92-96% of the total footprint) was the fuel used by the trawlers, representing the largest opportunity for reduction or mitigation of the footprint. Refrigerant use and packaging were much smaller contributors, followed by the life cycle of the vessel. The average carbon footprint of fish from the deepwater fleet is at the low-end of the range when compared to published data for other seafood. The range of the carbon footprint of the catch across the 21 vessels (0.4 to 3.3 kg CO_2e / kg catch) was similar to that from published values for other wild fish. The corresponding range for processed fish across 20 vessels (0.9-5.1 kg CO_2e / kg edible fish) was at the low end of the range published in a recent detailed meta-analysis (Gephart et al., 2021). The national and global literature review showed that the carbon footprint of edible fish per 100 g of protein is lower than for red meat (beef and sheep), milk and pork, but similar to poultry.

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