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The greenhouse gas emissions of the most remarkable Finnish fish product chains

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This study focuses on counting the greenhouse gas emissions of the most common Finnish fish products. The selected fish species were rainbow trout (Oncorhynchus mykiss), Baltic herring (Clupea harengus membras), pikeperch (Sander lucioperca), perch (Perca fluviatilis) and vendace (Coregonus albula). Rainbow trout was farmed, and all the other fish species were captured wild fish. At the product level, this study was limited to cover fresh fillets and gutted fish (vendace). The data were collected by surveys from typical enterprises from fisheries sector, like fishermen, aquaculture and fish processing companies. The LCA methodology was used to assess the greenhouse gas emissions. Farmed rainbow trout had the highest greenhouse gas emissions with 3.7 kg CO2 eq/kg/functional unit and Baltic herring caught with fish trap had the lowest emissions with 0.7 kg CO2 eq/kg/functional unit. In average, the farmed product (rainbow trout) had higher greenhouse gas emissions than the captured species. Gillnet fishing had higher greenhouse gas emissions than the action of trawling, seine and fish traps. The main reason for the higher impact for farmed fish was feed consumption. The differences between captured fish species were caused by different distance to fishing areas and volumes of the catch. According to the results, the carbon footprint of the consumption of Finnish citizens can be lowered by using domestic captured fish.

Keywords Fishing, Aquaculture, Carbon footprint

Human population is growing rapidly and there is an urgent need to change food production to more sustainable direction. This transition would affect a variety of aspects including the greenhouse gas emissions and other impacts to our environment. It has been shown there should be a shift from animal-based products to plant-based ones in the diet[1]. However, fish products and aquaculture could have potential to be part of the sustainable and healthy diet if the production is directed to products with lower impact to environment and climate[2]. All actions for changing diet and production will need reliable data for verifying the direction and the target to be achieved. In this article, we calculate the greenhouse gas emissions of Finnish fish products and assess how the resulted impacts are distributed in the product chain and what the difference between farmed and captured fish products is. The data based on the calculations were collected from fish farming statistics and interviews with fishermen and fish processing and feed processing companies.

Globally the amount of aquaculture products has grown from 20 million tonnes in 1990 to 120 million tonnes in 2022[3] Fish farming is dominated by Asia, which has produced 89% of the global total amount in the last 20 year[4]. Total global fish production including farmed and captured products is estimated to have reached about 200 million tons in 2020[3]. Of the overall total, 156 million tons were used for human consumption, equivalent to an estimated annual supply of 20.5 kg per capita. The remaining 22 million tons were destined for non-food uses, mainly to produce fishmeal and fish oil. Aquaculture accounted for 46% of the total production volume of fish products and 52% of fish for human consumption[5].

In Finland, in the year 2021, the consumption of fish products was about 62 000 t, and about 80% of this was imported. The consumption of Finnish farmed rainbow trout was about 6 700 t and captured wild fish about 5 000 t[6]. The highest catch is Baltic herring (Table 1), but only 5% of the catch goes for the human consumption in Finland, while the remaining part goes to fish meal production, fur animal feed and export. Altogether, fish was consumed 14.5 kg/cap annually and about 4 kg of that is domestic. Further, over about 50% of the domestic consumption is from small-scaled fisheries. The human consumptions of the studied fish species are shown in Table 1. For comparison, the consumption of meat products was 77.4 kg/cap[7].

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	Million kg	kg/ca.
Rainbow trout, farmed	15.3 (2022)	1.5
Baltic herring, brackish water	68.2 (2022)	0.2
Perch, brackish water	1.0 (2022)	0.6
Pikeperch, freshwater	0.9 (2021)	0.4
Vendace, freshwater	2.0 (2021)	0.2

Table 1. Production volumes of professional fisheries and fish farms and domestic consumption amounts per capita of the most important Finnish fish species. (Luke 2023b, Luke 2024).

Product	Fillet yield %	Functional unit
Rainbow trout, farmed	60	Fillet with skin
Baltic herring, brackish water	37	Fillet with skin
Perch, brackish water	30	Fillet without skin
Pikeperch, freshwater	42	Fillet without skin
Vendace, freshwater	70*	Gutted fish with skin

Table 2. Fillet yield and functional units of the studied products[17]* gutting yield.

For information on Atlantic herring fishing, there are recent publications, including[8–10]. The greenhouse gas emissions of farmed Atlantic salmon and rainbow trout have been published recently e.g. in Norway[9,11,12], and there are also other recent studies on different kinds of captured fish[15,18].

In an earlier fish production study, the average greenhouse gas emissions of freshwater and brackish water scaled fish, pike (Esox lucius), pikeperch, perch and whitefish (Coregonus lavaretus), captured in Finland, were investigated[19]. That study was based on quite narrow data sources and was based on generalized estimates e.g. about fuel consumption, so more comprehensive data were needed. Earlier, a Finnish LCA investigation on Baltic Herring fillet was published with the same system boundaries and functional units as in the current study[19]. In that study, the data source was the fuel consumption statistics and the amounts of catch by trawling. In a previous Finnish study, where the greenhouse gas emissions of the Finnish rainbow trout were evaluated, feed production chain was found to be the most contributing component of the life cycle[19]. In the current study, all relevant life cycle parts were included in the calculation.

The aim of this study was to calculate greenhouse gas emissions for the main domestic fish products used in Finland and find out, which are the most sustainable domestic fish products in Finnish market. The novelty value of this study is high, because there was lack of greenhouse gas emissions studies for small-scale fishing. Especially for freshwater fishing, there was not any kind of data on greenhouse gas emissions. The study was carried out because the expected results could be utilized in multiple ways by different actors, for instance by decision makers concerning blue economy, consumers in their plans for climate-friendly diets as well as actors of fish industry in their marketing.

Materials and methods

Goal and scope

In this study, the climate change impact of the most important Finnish fish products was calculated. The background data were based on surveys made for the most relevant catching, processing and farming methods.

The analysed fish species were rainbow trout, Baltic herring, pikeperch, perch and vendace. Rainbow trout was farmed, and all the other fish species were caught wild fish. Functional unit for the different fish species was chosen based on how the fresh fish products are mainly sold in the Finnish fish market (Table 2). The study covered gutted vendace and fresh fillets of other fish species. The fillet yield (the amount of fillet in relation to the amount of whole fish) was lowest for perch and highest for rainbow trout (Table 2).

1.1 methodological aspects

The methodology used in study was Life Cycle Assessment (LCA), which is a comprehensive tool used to evaluate the environmental impacts of a product, service, or process throughout its entire life cycle, from raw material extraction to end-of-life disposal[21]. LCA can be used in decision-making, marketing and product development[21], All methods were carried out in accordance with relevant guidelines and regulations, in accordance with ISO 14,067 and PAS 2050 for land use change[22,23]. The SimaPro 9.6 software was used for the calculations. The LCA methodology was used because it provides tools to marketing and decision making and contains all parts of the life-cycle of the product system. Amongst the environmental impacts, only greenhouse gas emissions were assessed. although it should be noted that there are also other important sustainability aspects in fisheries and aquaculture.

The most significant greenhouse gas emissions, CO_2, CH_4 and N_2O were converted to CO_2- equivalents by multiplying the emissions by gas-specific characterization factors. For characterization, the EF 3.1 factors were used and the most important of them are shown in Table 3.

Factor	kg CO_2 eq/kg
CO_2, fossil	1
CO_2, fossil	1
CO_2, biogenic	0
CH_4, fossil	29.8
CH_4, biogenic	27
N_2O	273

Table 3. Characterization factors in this study.

¨Feed ingredient	%	Product	Data source
Animal based ingredients	19	By-products of slaughtering (beef, chicken, pork)	Ecoinvent 3.8
Fish-based ingredients	23	Fish meal and fish oil	Ecoinvent 3.8, primary data
Plant-based ingredients	54	e.g. Soya, wheat and corn products	Ecoinvent 3.8, Proagria database
Other ingredients	4	Vitamines, minerals	Ecoinvent 3.8

Table 4. Finnish fish feed ingredients.

In this study, economic allocation (based on monetary value) was used for feed raw materials, except for fish meal and oil, where the emissions were allocated using mass allocation (based on quantity). Allocation between the main product and the by-products of the fish was done by economic allocation. For target species and by-catches, economic allocation was also used. Economic allocation was used because the use and prices are highly different between the main product and the by-products of fish processing and slaughtering. This was not the case for fish meal and fish oil, where the prices vary, and it is not always clear, which one is the main product.

Data collection

The data were collected from the feed raw material production, feed processing, fish farming and fisheries, hatchery, transports and packaging. The system boundaries were the same as in many previous studies, e.g[12,20]., where the trade, consumer and food waste after processing were excluded from the system boundaries. The data were collected from fishermen by surveys and interviews, concerning fuel consumption of the fisheries, logistics and the package use. The collected data were yearly averages and for the inland fisheries, part of the data concerns winter fishing under the ice cover. Especially for vendace caught by seine, the part of the winter catch under ice was remarkable. The fish farming data were mainly based on national statistics and previous studies. The fish processing data were collected from leading processing companies by surveys and interviews. Processing data of fish-based raw materials of feed were based on surveys with one Finnish processing plant and ecoinvent 3.10[24], which is a global comprehensive databank of life-cycle assessment processes. The inventory data are presented in the Results Chap. 3.1.

The data on contents of feed, the inputs and outputs of feed production and the transport of feed and its ingredients were collected from two leading fish feed producing companies, which deliver almost all fish feed used by Finnish fish farmers. The feed composition and the data sources are presented in Table 4. More detailed information was not allowed to be published because of confidentiality reasons. Economic allocation was used for all feed raw materials except fish meal and oil products For Finnish rainbow trout, the feed conversion ratio was 1.15 according to the statistics of the Centre for Economic Development, Transport and the Environment in South-West Finland[25] The origin and transport equipment of the feed raw materials was obtained from the feed processing companies.

The data of production volumes and nitrogen excretion were taken from statistics of Local Employment and Economic Development Office of SW-Finland[25] The materials of the fish farming equipment were based on[19]. The N_2O-emissions from the N-excretion of the of rainbow trout were assumed to be 0.005 kgN_2O-N/kg N excreted based on IPCC (2006) estimate of the emission of treated wastewater[26]. N-excretion has been calculated by following equation[27]:

$Nsurplus = 10 \times fcr \times Ndiet - Nfish$, where.

fcr Feed conversion ratio.

Ndiet N content of feed, whole diet (%).

Nfish N content of fish (kg N/tonne of produced fish). Default value: 27.5 kg N/tonne of produced fish[28].

CH_4-emissions of fish farming were not considered, because there are no methodologies to calculate them, but CH_4-emissions of the crop production and animal production phases were included. Fish farming inputs and outputs like electricity and diesel consumption originated from the analysis of unpublished financial statements of farming companies. The data of hatcheries were based on interview of a major Finnish producer.

The data of fuel consumption of Baltic herring trawling were based on interviews of the two biggest trawling companies (Table 5). The data included both the actual fishing and transports to the landing place. The calculation of perch fishing fuel consumption was based on the interviews of fishermen and the analysis of nine perch fishers' fishing and fish landings areas and the interviews concerning the fish collection routes of fish processing companies. The data of material quantities concerning boats and fishing traps were obtained from

Fish species, fishing equipment	Number of fishermen groups (staff of the boats) interviewed	Area
Baltic herring, trawl	2	SW-Finland
Baltic herring, fish-trap	8	SW-Finland
Perch, net	9	SW-W-Finland
Vendace, trawl	5	Central Finland
Vendace, seine	10	North Savo, Lapland
Pikeperch, net	5	Central Finland

Table 5. Number of fishermen groups in investigations.

Product	L/kg fish, fisheries	L/kg, transports to processing
Farmed rainbow trout		0.008
Baltic herring, brackish water, trawl	0.11	0.003
Baltic herring, brackish water, fish-trap	0.01	0.003
Perch, brackish water, gillnet	0.15	0.016
Pikeperch, freshwater, gillnet	0.13	0.073
Vendace, freshwater, trawl	0.32	0.034
Vendace, freshwater, seine	0.08	0.034

Table 6. Fuel consumption of the main products in Finnish fisheries and transports to the processing. Around Finland Baltic sea was considered as brackish water because of low salt content.

the fish equipment producers. The data on fishing of vendace were based on interview of five trawlers and seven seine fishers and the fishing of pikeperch interview of four fishers. The interviews were made during 2018–2019 and the participated groups of fishermen were selected so that they represent as typical fishermen in Finland as possible.

The data concerning logistics of fish raw materials from fish farms and harbors to processing and transport of the final products to central warehouses were based on interviews with fishermen, fish processing and aquaculture companies, concerning transport equipment, fuel consumption, distances and amounts of transported products.

Low and medium voltage Finnish residual emission factors were used for electricity (modified based on ecoinvent 3). For fuels used for logistics and for heat energy, emission factors based on studies of[28–30] were used.

Packages are used both in the transport of fish from farm or catch area to the processing plant and in the transport of the final product. The energy and water use data and use of packages for chosen products were inquired from the processing companies: one large processing company for each product. For the production of packaging materials, average data from different databases were used[28,31–33]. The most common package type is polystyrene box, which is used for transport of fish, especially perch and pikeperch. Some larger transport units like skipping containers are reusable, but not so commonly used. Vacuum package and cardboard boxes were also used for transports of fillets to central stores. The quantity of packages was based on questionnaires to fishermen, fish processing companies and aquaculture companies. The greenhouse gas emissions of packages were based on surveys to the biggest package producers of Finnish market and this data was confidential. For polystyrene-packages, greenhouse gas emissions were based on[15].

Results

Fuel consumption of fisheries

The results for fuel consumption of the fisheries varied a lot. For trawled vendace, the fuel consumption was as 0.32 L/kg (live weight), while for Baltic herring caught by fish-trap the value was 0.01 L/kg^{-}(live weight) (Table 6). The variation between fuel consumption of vendace trawlers was large, (0.16–0.80 L/kg whole fish). Deviation of pikeperch fishing was large too, (0.11–0.57 L/kg whole fish) and vendace caught by seine 0.02–0.11 L/kg whole fish. The energy inputs for an average Finnish fish farm were 0.054 L diesel/kg and 0.16 kWh electricity/kg.

Fuel consumption during transport to processing site was lowest for Baltic herring fishery (Table 6). High volumes of Baltic herring are landed with trawlers to central fish harbors, and therefore also transport is cost effective, and in spite of long fishing trips and high fuel consumption, the fuel consumption per fish unit is still low. Volumes of Baltic herring fishing with trap net are also relatively high while transporting distances from fishing sites to harbor is short, leading to low fuel consumption per unit. The volumes are much lower in small scale fisheries (perch and pikeperch fishing), and the transport distances normally are longer in dispersed inland fisheries. Thus, the fuel consumption per kilo fish were higher for small scale gillnet fishing and inland fishing.

Packaging and transports

The amounts of used packaging materials are presented in Table 7. The high use of package for perch fillets is due to very low filleting yield and small package size being transported.

Fish species	Catch method tai origin	Use of polystyrene boxes, kg/kg⁻final product	Use of cardboard boxes, kg/kg⁻final product	Use of plastic packages kg/kg final product
Rainbow trout	Farmed	0.03	0.04	0.008
Baltic herring	Fish-trap	0.02	0	0
Baltic herring	Trawl	0.02	0	0
Perch	Gillnet	0.10	0	0.001
Pikeperch	Gillnet	0.03	0	0.003
Vendace	Seine	0.02	0	0
Vendace	Trawl	0.04	0	0

Table 7. Amount of the packaging used in the whole product chain.

Fish product	Greenhouse gas emissions, kg CO_2 eq/functional unit
Rainbow trout fillet	3.7
Baltic herring fillet, fish trap	0.4
Baltic herring fillet, fish trawl	1.3
Perch fillet, net	2.5
Pikeperch fillet, net	2.0
Gutted vendace, seine	0.8
Gutted vendace, trawl	1.9

Table 8. Greenhouse gas emissions of studied products in relation to the functional unit.

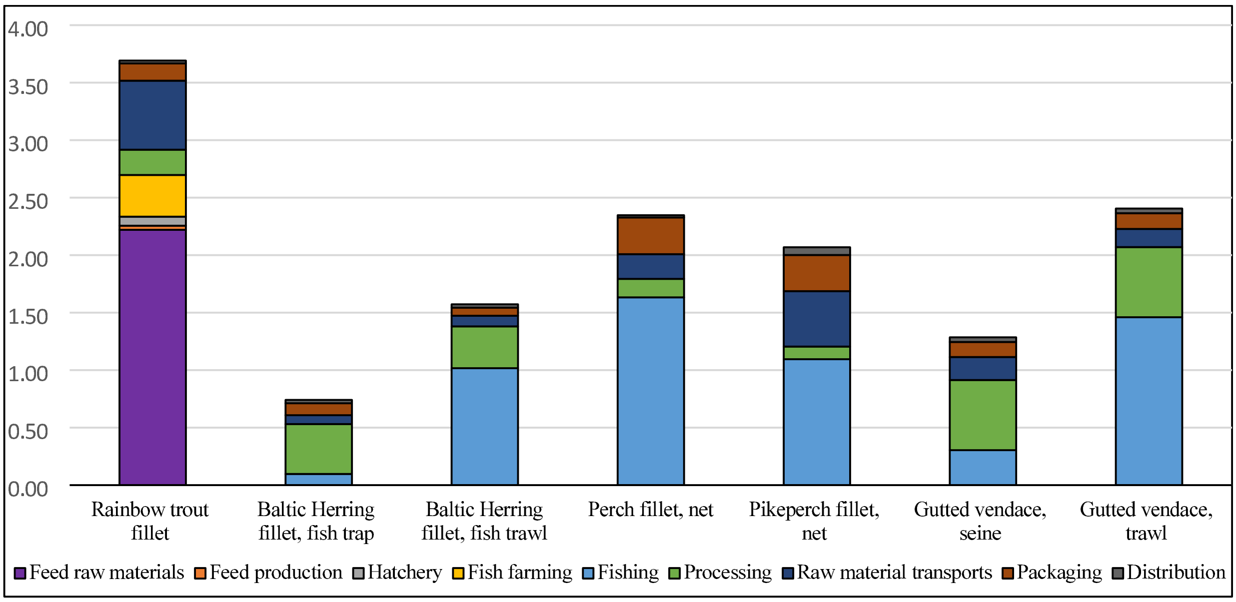

Fig. 1. Greenhouse gas emissions of fish products and the contribution of product chain, kg CO_2 eq/kg.

Greenhouse gas emissions

The highest greenhouse gas emissions were found for farmed fish, 3.7 kg CO_2 eq/kg. The second highest emissions were for fish caught by gillnet (2.1–2.4 kg CO_2 eq/kg functional unit) and the lowest carbon footprint was found in products caught by seine, trawl and fish-trap (0.7–1.6 kg CO_2e q/kg functional unit). The exception was vendace caught by trawl, which had the same greenhouse gas emissions as gillnet fishing (2.4 kg CO_2 -eq/kg functional unit).

The product chain of feed raw materials was the most important source of greenhouse gas emissions, 60% of the total emissions (Table 8; Fig. 1). The emissions of dinitrogen monoxide in farming process were 0.17 g N_2O-N/kg whole fish. The greenhouse gas emissions for the liveweight of rainbow trout was 2.1 kg CO_2 eq/kg fish. Fishing was usually the most important source of greenhouse gas emissions for captured fish while the feed raw material production was the biggest source of emissions for farmed fish. (Table 8; Fig. 1). The share of fishing varied between 16% and 70%. The share of processing, which includes filleting and packaging, was 6–71%, and it was the lowest for the rainbow trout fillet and the highest for Baltic herring caught by fish-trap. The overall results for greenhouse gas emissions of fish products and the contribution of the product chain are presented in the Supplementary materials Table S1.

Discussion

According to the results, the climate change impact of farmed fish was higher than the greenhouse gas emissions of captured fish. The largest part of the emissions of farmed fish comes from the product chain of feed raw materials. For caught fish, the distance to mainland and catch volumes were essential: for fish species which can be caught in higher volumes, the greenhouse gas emissions are usually lower than for fish species with lower catch volumes. The results of the study show that the catch volumes by seine, fish-trap or trawl are higher than catch volumes by gillnet. That is why the greenhouse gas emissions of Baltic herring and vendace were lower than those of perch and pikeperch. The fillet yield had also effect on the results: despite the fuel consumption for perch and pikeperch fishing were almost the same, due to the low fillet yield the greenhouse gas emissions for perch fillet were higher than those for pikeperch fillet. Higher transport volumes mean usually lower greenhouse gas emissions of transports. Therefore, the greenhouse gas emissions of Baltic herring fillet and rainbow trout fillet transport were especially low. The greenhouse gas emissions of Baltic herring fillet caught by trawl was higher than those for Baltic herring trap net. The main inland pikeperch fishing areas are located rather far away from the main market areas in Southern Finland cities. Therefore, transport distances for pikeperch were longer than for any other investigated products and the share of transport greenhouse gas emissions was high (24%). Gutted vendace caught by seine had average greenhouse gas emissions of 1.2 kg CO_2 eq/kg and vendace seined during winter had greenhouse gas emissions 0.9 kg CO_2 eq/kg. The average value for vendace trawling was 2.4 kg CO_2 eq/kg functional unit and varied between 1.6 and 4.6 kg CO_2 eq/kg.

One thing to keep in mind is that the products are not fully comparable with each other because vendace was analysed as gutted fish and other fish products as fillets. The greenhouse gas emissions per kilogram of gutted fish is lower than that filleted fish of the same fish species. The vendace is the only fish that is typically cooked and served as gutted rather than fillet.

When compared to the previous study in Finland[19], the greenhouse gas emissions for rainbow trout seem to have decreased considerably, by 1.8 kg CO_2 eq/kg from 5.5 kg CO_2 eq/kg to 3.7 kg CO_2 eq/kg. However, the reasons for that are mainly methodological changes. In the previous study, the functional unit was different from this study, 1 kg of edible product. Further, the N_2O-emissions of N-excretion of the metabolism of rainbow trout were assumed to be 10 times higher in previous study[19,34] and the characterization factor of N_2O has lowered from 298 to 273. The share of N_2O in the previous study was 1.2 kg CO_2 eq/kg fish fillet, so this had a remarkable effect on the results. On the other hand, in some similar studies, the N_2O-emissions were not included at all, e.g[12,16,35]. The CH_4-emissions were not considered in this study and there might be some changes in the results if the data concerning the CH_4-emissions will be available in the future. One remarkable change since the previous investigation was the amount of soya in feed, which has declined to almost zero. The main replacing raw materials are animal-based by-products and some plant protein products.

There has been published value 5.3 kg CO_2 eq/kg for farmed salmon in Norway with mass allocation[12,35] which means that the results would have been much higher, if it had been done by economic allocation. Reasons for higher results are caused by use of input-output model, different feed conversion factor, different modeling of N_2O in farm level, different content of soya in the feed and species-based modeling of fish meal and fish oil. Higher amount of soy in feed causes remarkable greenhouse gas emissions because of land use change, which were minimal in our study. The fish meal and fish oil and their raw materials were modeled in this study by average ecoinvent-values[24], but separate LCA-data of each fish species raw materials have been published[12,35]. This species-specific data had higher climate change impact than global averages of ecoinvent 3[24]. Furthermore, in this study some share of greenhouse gas emissions was allocated to roe production, which is not essential for salmon cultivation. There were also differences in functional units: in a recent Norwegian study[12] the functional unit is edible part of the fish (fillet without skin) and in this study unit was fillet with skin.

When this study is compared to other studies, some show higher and some lower emissions than this study. In Central Europe, Spain and France, the size of the rainbow trout is smaller[36], which can cause differences in greenhouse gas emissions because lower feed conversion ratio is dependent on the size of the fish[37]. For smaller fish, in Central Europe there has been a published value 1.18 kg CO_2 eq/kg for liveweight rainbow trout[38] and 1.78 kg CO_2 eq/kg for liveweight rainbow trout in Spain[14] and 1.76–1.85 in France[37], which are lower than the value of this study (2.1 kg CO_2 eq/kg fish). On the other hand, in Norway, higher emissions were found than this study[35], 3.8 kg CO_2 eq/kg liveweight, similarly as in Germany 2.24–3.56 kg CO_2 eq/kg for liveweight rainbow trout[17]. In the same study, also a recirculating aquaculture system in Denmark was included in the assessement and the value there was 13.6 CO_2 eq/kg liveweight. In a review article of LCA-investigations of cultivated salmonids[39], the climate change impact was 1.7–3.3 kg CO_2 eq/kg liveweight and in one Norwegian study of LCA of Atlantic Salmon[40] the result was 2.0 kg CO_2 eq/kg liveweight, which are at the same level as in this study.

The greenhouse gas emissions are highly dependent on the farming system[17,41] and the marketing size[14]. In the Central and South Europe rainbow trout is normally farmed in inland ponds and the marketing size is then below 500 grammes (portion size fish)[41] Higher marketing size means higher feed conversion rate, which means higher climate change impact[14,38] The Finnish marketing size is 2–3 kilos[42], and it is mostly farmed in net pens in brackish water. Functional unit is not in general the same in seafood life cycle assessment (LCA) investigations, which make it difficult to do comparisons between different LCA-studies and it has been edible part of fish or liveweight in most of the studies. Harmonized methods for LCA investigations of seafood are needed to make the results comparable to each other.

The LCA inventory results of this study were in general in line with previous climate change studies of captured fish products. In this study, the average value of fuel consumption for gillnet fishing was 0.13 L/kg for pikeperch and 0.15 L/kg for perch, which is slightly lower than generic values in Norway 0.19 kg fuel/kg fish for gillnet fishing[11] and in Denmark, 0.2–0.4 L/kg[18]. For seine, this study gives a consumption between 0.04 (winter) and 0.08 (summer) l/kg fish and these values are lower than generic value 0.09 kg l/kg fish in Norway[11] and in Denmark[18], where the value was 0.11–0.16 L/kg fish. In pelagic trawl, the fuel consumption value was 0.09 L/kg fish, when the value for this study was in freshwater trawl fishery was 0.32 L/kg fish. In the trawling case the fuel consumption is higher in freshwater fishing than in pelagic fishing However, it is essential to notice that fishing conditions in the deep Atlantic coast with various fish species are very different compared to shallow coastal and inland waters in Finland.

The greenhouse gas emissions in this study vary between fishers even for the same species and fishing methods. For example, the variation of pikeperch fillet was between 1.6 and 3.6 kg CO_2 eq/kg functional unit and vendace caught by trawl 1.6–4.6 kg CO_2 eq/kg functional unit. The variation of vendace caught by seine was 1.0–1.4 kg CO_2 eq/kg functional unit. This means that at highest the greenhouse gas emissions of captured fish can be higher than of farmed fish in some cases. This large variation should be taken in account when making LCA-assessment for specific fish products. This also reveals possibilities to fishers to lower their greenhouse gas emissions by intensifying fishing and choosing climate friendly fishing methods.

According to results, by selecting captured low-emission fish products to diet, it is possible to reduce the greenhouse gas emissions of diets. However, the amount of fishermen has been continuously declining, which has an impact on the availability of domestic fish in Finland[43].

When compared to meat products, Finnish captured fish products have lower greenhouse gas emissions than Finnish chicken (3.4 kg/kg edible part), pork (5.0 kg/kg edible part) and beef (31.2 kg/kg edible part) according to[44–46]. Rainbow trout fillet has a lower greenhouse gas emissions (3.7 kg CO_2eq/kg edible part) than pork and beef, but higher than chicken. Further, in a comparison of different protein sources in a review article[47] the greenhouse gas emissions of animal products like chicken was 3.1–5.2 kg CO_2eq/kg edible part, pork 4.1–6.2 kg CO_2eq/kg edible part and beef 28.0–31.0 kg CO_2 eq/kg edible part. It means that by selecting more low-emission wildfish products to diet, it is possible to reduce greenhouse gas emissions of food consumption.

There are also several ways to regulate fishery to keep it sustainable. With herring, the coastal EU countries get annual quotas to the main areas of the Baltic Sea from the Council of Europe. The quotas are mainly based on stock assessments and advice from the International Council for the Exploration of the Sea (ICES). Due to decreasing stock size, the catch quotas were reduced at the end of 2010 s and in 2020.

The are also regulations for fishery of more local species such as perch or pikeperch to keep the fishery sustainable and to share fishing rights between fishers[48]. In the monitoring of fisheries, attention is paid on e.g. the possible bycatch of protected, endangered and threatened species by randomly examining catches onboard and in harbour. There are limited numbers of permits granted to gears, e.g. gillnets or trap nets for free-time fishermen and e.g. for gillnets the maximum is 240 m gillnet per fisherman. Further, there is minimum national allowed catch length for pikeperch, which in Finland is 42 cm (total length), but of which local variations are possible to both larger and smaller sizes depending on the local conditions. There are often also local limitations in the physical features of gears like mesh size of gillnets.

One key sustainability aspect in LCAs of seafood production is eutrophication. Results of previous studies have shown that environmental benefits would occur by fishing in Baltic Sea area, because fishing removes excess nutrients from the Baltic Sea[19]. On the other hand the production of farmed fish and meat products cause high eutrophication impacts to the water systems[19,43,44].

The Nordic Nutrition Recommendations[49] advised for increasing intake from sustainably managed stocks supported both by effects on health outcomes and environmental footprint. It also recommended fish and seafood from sustainably managed farms and that wild stocks should be prioritized and consumption of species with high environmental impact should be limited. In Finland these advises could be fulfilled by consuming herring, perch, pikeperch and some other freshwater species like roach.

Conclusion

In general, greenhouse gas emissions for captured fish are principally lower than for cultivated fish. Moreover, fish products caught by gillnet have higher climate impact than fish products caught by seine, trawl and fish traps, with the exception of vendace caught by trawl, which has the same climate impact as fish products caught by gillnet. According to the study, however, there is a big variation in distances to fishing place, catch and transport volumes and transport distances. Captured fish, for example vendace captured by trawl and pikeperch captured by gillnet, can, however have higher greenhouse gas emissions than farmed fish in specific circumstances. On the other hand, the greenhouse gas emissions of captured fish are seldom high when the catch amount is high. Therefore, the greenhouse gas emissions for fish captured by different fishermen can vary significantly. This finding encourages fishermen to analyse their fishing to develop climate friendly fishing methods and practices.

Data availability

Yes. The datasets used and analysed during the current study available from the corresponding author on reasonable request.

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References

1. Willet, W. et al. Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. Lancet. 2019;393(10170):447–492. doi: 10.1016/S0140-6736(18)31788-4. Epub 2019 Jan 16. Erratum in: Lancet. 2019;393(10171):530. (2019). https://doi.org/10.1016/S0140-6736(19)30212-0. Erratum in: Lancet. 2019;393(10191):2590. doi: 10.1016/S0140-6736(19)31428-X. Erratum in: Lancet. 2020;395(10221):338. doi: 10.1016/S0140-6736(20)30144-6. Erratum in: Lancet. 2020;396(10256):e56. doi: 10.1016/S0140-6736(20)31828-6. PMID: 30660336.
2. Koehn, J., Allison, E., Golden, C. & Hilborn, R. The role of seafood in sustainable diets. *Environ. Res. Lett.* **17** (3). https://doi.org/10.1088/1748-9326/ac3954 (2022).
3. FAO. The state of world fisheries and aquaculture 2022. Towards blue transformation. *Rome FAO*. https://doi.org/10.4060/cc0461en (2022). (accessed 9.6.2023).
4. FAO. Consumption of Fish and Fishery Products. Fisheries and Aquaculture Division Rome. Trade 2022. World fisheries and aquaculture production (2023).
5. FAO. https://www.fao.org/news/story/en/item/1279179/icode/ (2020). accessed 14.9.2023).
6. [Luke. Kalamarkkinakatsaus 2023. (2023). https://jukuri.luke.fi/bitstream/handle/10024/553302/Luke-luobio_43_2023.pdf?sequence=1 (accessed 14.9.2023).
7. Luke Tilastotietokanta. (2023). https://statdb.luke.fi/PXWeb/pxweb/fi/LUKE/ (Accessed 14.9.2023).
8. Luke Kalan kulutus 2023 [verkkojulkaisu]. Luonnonvarakeskuksen tilastotietokanta, Helsinki: Luonnonvarakeskus [viitattu: 18.11.2024]. Saantitapa: (2024). https://www.luke.fi/fi/tilastot/kalan-kulutus/kalan-kulutus-2023
9. Suomen virallinen tilasto (SVT). Kaupallinen kalastus sisävesillä. Helsinki: Luonnonvarakeskus http://www.stat.fi/til/aksis/index.html (accessed 19.7.2021).
10. : Suomen virallinen tilasto (SVT): Vesiviljely. Helsinki & Luonnonvarakeskus http://www.stat.fi/til/vvilj/index.html (accessed 19.7.2021).
11. Schau, E. M., Ellingsen, H., Endal, A. & Aanondsen, S. A. Energy consumption in the Norwegian fisheries. *J. Clean. Prod.* **17**, 325–334 (2009).
12. Ziegler, F., Jafarzadeh, S., Skontorp Hognes, E. & Winther, U. Greenhouse gas emissions of Norwegian seafoods: from comprehensive to simplified assessment. *J. Ind. Ecol.* **26**, 1908–1919. https://doi.org/10.1111/jiec.13150 (2021).
13. Schmidt, J. & Thrane, M. LCA study of pickled herring. in Kørnøv, L., Thrane, M., Remmen, A., Lund, H. (Eds.), In Tools for Sustainable Development. Aalborg Universitetsforlag, pp. 241–266. (2006).
14. Sanchez-Matos, J., Regueiro, L., González-García, S. & Vázquez-Row, I. Environmental performance of rainbow trout (*Oncorhynchus mykiss*) production in Galicia-Spain: A life cycle assessment approach. *Sci. Total Environ.* **856**, 159049 (2023). Part 2.
15. Winther, U. et al. *Carbon Footprint and Energy Use of Norwegian Seafood Products* (SINTEF Fisheries and Aquaculture, 2009). http://www.sintef.no/upload/Fiskeri_og_havbruk/Internasjonalt_R%C3%A5dgivning/2009_Carbon%20footprint%20of%20seafood%20products.pdf
16. Winther, U., Hognes, E., Jafarzadeh, S. & Ziegler, F. *Carbon Footprint and Energy Use of Norwegian Seafood Products in 2017* (SINTEF Fisheries and Aquaculture, 2020).
17. Samuel-Fitwi, B., Nagel, F., Meyer, S., Schroeder, J. P. & Schultz, C. Comparative life cycle assessment (LCA) of Raising rainbow trout (Oncorhynchus mykiss) in different production systems. *Aquac Eng.* **54**, 85–92 (2013).
18. Bastardie, F., Hornborg, S., Ziegler, F., Gislason, H. & R Eigaard, O. Reducing the fuel use intensity of fisheries: through efficient fishing techniques and recovered fish stocks. *Front. Mar. Sci.* **9** https://doi.org/10.3389/fmars.2022.817335 (2022). Sec. Marine Fisheries, Aquaculture and Living Resources.
19. Silvenius, F. et al. Impact of feed Raw material to climate and eutrophication impacts of Finnish rainbow trout farming and comparisons on climate impact and eutrophication between farmed and wild fish. *J. Clean. Prod.* **164**, 1467–1473 (2017).
20. Commission of the European communities. Comparative study of conversion coefficients used for estimating the live weight of the fish caught by Community fishing vessels. Directorate Gerneral for Fisheries, Project 95/02, Final report. (1996). https://www.fao.org/fishery/en/collection/global_fish_consump (accessed 10.3.2023).
21. ISO 14006. ISO 14044. Environmental Management. Life cycle assessment (2006).
22. ISO. *ISO 14067:2018: Greenhouse gases – Carbon Footprint of products – Requirements and Guidelines for Quantification* (The International Standards Organisation, 2018).
23. PAS 2050(. *Specification for the Assessment of the Greenhouse Gas Emissions of Goods and Services* (Publicly available specification, 2008).
24. (Ecoinvent v3.10. Ecoinvent database 3.10, (2025). https://ecoinvent.org/ecoinvent-v3-10/, assessed 3 March 2025.
25. Kallioniemi, H., Employment, L. & Economic Development Offices (TE Offices). and, Personal comment 17.5. 2021Luke 2022. https://www.luke.fi/fi/tilastot/ravintotase/ravintotase-2021-lopullinen-ja-ennakko-2022 (accessed 14.9.2023).
26. IPCC Guideline for. national Greenhouse Inventory, Volume 5, Chap. 6.
27. Mäkinen, T. & Ruohonen, K. Rehun ja ruokinnan optimointi. In Pursiainen, M. Rahko-nen, R. Kalanviljely, vesiensuojelu ja valvonta. Kalanviljelyn XIV neuvottelupäivät. Riista- ja kalatalouden tutkimuslaitos. Kalantutkimuksia No. 56. Yliopistopaino Helsinki 192: 84–97 (1992).
28. Seppälä, J. et al. Kirjolohen tuotanto ja ympäristö. Suomen ympäristö 529. 164 s. (2001).
29. Alakangas, E., Hurskainen, M., Laatikainen-Luntama, J. & Korhonen, J. Properties of fuels used in Finland. (In Finnish, Suomessa käytettävien polttoaineiden ominaisuuksia. VTT technology 258. (2016).
30. Sokka, L., Correia, S. & Koljonen, T. Lämmityspolttoaineiden Elinkaariset kasvihuonekaasupäästöt. *VT. Technol.* 336. (2018).
31. FEFCO. 2021: Calculation of a carbon footprint for corrugated packaging https://www.fefco.org/calculation-%E2%80%9Ccarbon-footprint%E2%80%9D-corrugated-packaging. (2021). Cited 1.3.2021.
32. Plastics Europe High-density polyethylene (HDPE). Low-density polyethylene (LDPE) Linear Low-density polyethylene (LLDPE) Eco-Profiles and Environmental Product Declarations of the Europen Platics Manufacturer. Plastics Europe April 2014. Decemer 2016: update water balance. (2016).
33. Plastics Europe. Polypropylene (PP). Eco-Profiles and Environmental Product Declarations of the Europen Platics. Manufacturer. Plastics Europe April 2014. December 2016: update water balance (2016).
34. Hu, Z., Lee, J. W., Chandran, K. & Khanal, S. K. Nitrous oxide (N_2O) emission from aquaculture: A review. *Environ. Sci. Technol.* **46**, 6470–6480 (2012).
35. Johansen, U. et al. Greenhouse gas emissions of Norwegian salmon products. SINTEF report 2022 01198. (2022).
36. Wind, T., Schumann, M., Hofer, S., Schulz, C. & Brinke, A. Life cycle assessment of rainbow trout farming in the temperate climate zone based on the typical farm concept. J. Clean. Prod. 380, Part 1. (2022). https://doi.org/10.1016/j.jclepro.2022.134851
37. Papatryphon, E., Petit, J., Van der Werf, H. & Kaushik, S. Life Cycle Assessment of trout farming in France: a farm level approach. Life Cycle Assessment in the Agrifood sector. Proceedings from the 4th International Conference Dias Report 61, 71–77. (2003). http://www.lcafood.dk/lca_conf/DJFrapport_paper_2_poster.pdf
38. Aubin, J., Paptryphon, E., Werf, Chatziforis, H. & C Assessment of the environmental impact of carnivorous finfish production systems using life cycle assessment. *J. Clean. Prod.* **17** (3), 354–361 (2009).
39. D'Orbaster, R., Ruyet, P. L., Le Bayon, J., Blancheton, N. & J.-P Comparative growth and welfare in rainbow trout reared in recirculating and flow through rearing systems. *Aquacultular Eng.* **40** (2), 79–86 (2009).

40. Pelletier, N. et al. Not all salmon are created equal: life cycle assessment (LCA) of global salmon farming systems. *Environ. Sci. Technol.* **43**, 8730–8736 (2009).
41. Kankainen, M. & Niukko, J. Kalankasvatuksen tuotanto-olosuhteet Suomen rannikolla. Riista- ja kalatalous: Tutkimuksia ja selvityksiä 8/2014. Saatavissa (2014). http://jukuri.luke.fi/handle/10024/519800
42. Virtanen, J., Setälä, J., Saarni, K. & Honkanen, A. *Finnish Salmon Trout – Discriminated in the European Market* (Thalassorama. Finnish Game and Fisheries Resesrch Institute, 2005).
43. Luke Tilastotietokanta (2023). https://statdb.luke.fi/PxWeb/pxweb/fi/LUKE/LUKE__06%20Kala%20ja%20riista__02%20Rakenne%20ja%20tuotanto__02%20Kaupallinen%20kalastus%20merella/1a_meri_saalis_toimijat.px/table/tableViewLayout2/ (Accessed 14.9.2023).
44. Usva, K. et al. Environmental life cycle assessment of Finnish broiler chicken production – Focus on climate change and water scarcity impacts. *J.]Clean Prod.* **410** https://doi.org/10.1016/j.jclepro.2023.137097 (2023).
45. Hietala, S. et al. Environmental life cycle assessment of Finnish beef – cradle-to-farm gate analysis of dairy and beef breed beef production, Agric. Syst., Volume 194, 2021, (2021). https://doi.org/10.1016/j.agsy.2021.103250
46. Hietala, S. et al. Sian- jabroilerinlihan ympäristökilpailukyky. Luonnonvara- ja biotalouden tutkimus 67/2022. Luonnonvarakeskus. Helsinki. 78 s. (2022).
47. Hartikainen, H. & Pulkkinen, H. Summary of the chosen methodologies and practices to produce GHGE-estimates for an average European diet. Natural Resources Institute Finland. Natural resourcesand bioeconomy studies, Vol. 58, pp. 38. (2016).
48. Ministery af Agiculture and Forestry of Finland. (2015). The Finnish Fishing Act 379/2015.
49. Blomhoff, R. et al. *Nordic Nutrition Recommendations 2023* (Nordic Council of Ministers, 2023). https://doi.org/10.6027/nord2023-003(accessed 9.6.2023).

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Declarations

Competing interests
The authors declare no competing interests.

Ethical declaration
In the survey of fishermen. • all methods were carried out in accordance with relevant guidelines and regulations. • all experimental protocols were approved by Natural Resources Institute Luke. • informed consent was obtained from all subjects and their legal guardians.

Additional information
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