DOI: 10.1111/jiec.13150

RESEARCH AND ANALYSIS

JOURNAL OF INDUSTRIAL ECOLOGY WILEY

Greenhouse gas emissions of Norwegian seafoods

From comprehensive to simplified assessment

Friederike Ziegler[1] | **Sepideh Jafarzadeh**[2] | **Erik Skontorp Hognes**[3] | **Ulf Winther**[2]

[1] Agriculture and Food, RISE Research Institutes of Sweden, Göteborg, Sweden

[2] SINTEF Ocean AS, Department of Seafood Technology, Trondheim, Norway

[3] Asplan Viak AS, Trondheim, Norway

Correspondence
Friederike Ziegler, RISE Research Institutes of Sweden, Agriculture and Food, PO Box 5401, 402 29 Göteborg, Sweden.
Email: friederike.ziegler@ri.se.

Editor Managing Review: Ian Vázquez-Rowe

Funding information
The authors are grateful to the Norwegian Seafood Research Fund, FHF, for funding the work (Project number 202003889).

The copyright line for this article was changed on 14-JUNE-2021 after original online publication.

Abstract

The seafood sector is facing difficulties to meet the increasing demand for product greenhouse gas emission (GHG) assessments. We quantified GHGs of important seafood products of Norway, the world's second largest seafood exporter. We present results and improvement options for products of farmed salmon and wild-caught shrimp, king crab, cod, and herring, followed to their dominating markets, based on detailed data for 2017. To enable more frequent monitoring, without engaging in a full assessment, we then suggest a simplified approach, focusing on the main drivers of production-related emissions. The simplified approach is used to analyze temporal trends from 2007–2017 for fisheries and 1990–2017 for salmon aquaculture. Finally, the simplified approach was compared to the comprehensive assessment for 2017 to define species-specific upscaling factors. Results show that salmon and crustacean products in 2017 caused higher emissions than cod and herring products, with feed and fuel use being the main emission drivers, whereas airfreighted products had the highest emissions of all products. Large improvement potential from average to best performers within each production system exists. The simplified approach shows that the fuel-use intensity of Norwegian fisheries has increased by almost 50% for shrimp over the past decade whereas it has decreased for fish by 20% for demersal species such as cod and 5–10% for pelagic species such as herring. Feed-related emissions for salmon, on the other hand, have increased by almost 30% during the same period, because of an increasing feed conversion ratio and increased inclusion of emission-intensive feed inputs.

KEYWORDS
aquaculture, fisheries, fuel use intensity, greenhouse gas emissions (GHGs), industrial ecology, seafood

1 | INTRODUCTION

Norway is the second largest seafood exporting nation in the world, after China, measured in export value (total value of 10,770 MUSD in 2019) exporting 2.7 M tonnes of seafood to markets all over the world (FAO, 2020). Awareness about the role and potential of the seafood sector in global environmental impacts, including climate change, is growing rapidly (Hoegh-Guldberg, 2019; Poore & Nemecek, 2018). Seafood supply chain actors, including industry, processors, wholesalers, retailers, NGOs, and certification bodies are facing a rapid increase in demand for information about the greenhouse gas (GHG) emissions of their products from customers on different levels, investors and governmental agencies, at the same time as experiencing difficulties in delivering the information requested. A rapidly expanding body of literature on sustainability assessment of seafood products using the Life Cycle Assessment (LCA) framework has led to increased data availability and potential to identify overall patterns and improvement options in seafood systems and subsystems quantitatively and qualitatively (Avadí & Freón, 2013; Parker, 2012; Ziegler, Hornborg, Green et al., 2016). Still, clear challenges remain in using this literature to represent specific products: (1) a case study can only represent a product if it is very similar in terms of technology used, biology, and so forth, (2) each study is a snapshot in time that is outdated as soon as key parameters change and (3) minor or major method differences strongly compromise comparability across studies. Standardization/harmonization efforts, such as those led by the International Organisation of Standardization (ISO, 2006a, 2006b, 2020), British Standards (BSI, 2012), Standards Norway (2013) and the EU Product Environmental Footprinting initiative (Zampori & Pant, 2019) have only been able to partially relieve such challenges. Still, only supply chains modeled as part of the same study using the exact same methods are fully comparable and a strategy to keep data and results updated is required for every environmental footprinting effort.

In studies aggregating LCA results to compare the GHGs across food types, seafood is generally identified as the lower-emission option among animal-source foods even without considering these challenges (Hilborn et al, 2018; Tilman & Clark, 2014). However, there is notable variation within the diverse product group seafood or even between production methods for the same type of seafood, for example, fishing methods for cod or farming methods for salmon (Hallström et al., 2019; Hilborn et al., 2018). It is well established that seafood GHGs are highly dependent on fishing methods, stock status, feed use, and composition (Avadí & Fréon, 2013; Jafarzadeh et al., 2016; Parker, 2012; Ziegler, Hornborg, Valentinsson, et al., 2016). Based on the health benefits of eating seafood and its often positive sustainability profile compared to other forms of animal protein (Hallström et al., 2019), seafood will likely play an even larger role than today in future sustainable food systems (Costello et al., 2019; Costello et al., 2020; Hoegh-Guldberg, 2019).

In 2008, the Norwegian seafood industry initiated a study to quantify the GHG emissions of important Norwegian seafood products. The primary goal was to identify emission reduction opportunities within each supply chain and compare seafood products to each other as well as to competing livestock products. The assessments (results reported in Winther et al., 2009 and Ziegler et al., 2013) represent national averages for each type of seafood rather than product-specific footprints and, therefore, differentiated performance between producers cannot be extracted from the data collected. The results were most useful for overall improvement discussions and as a benchmark to rank products against and have been widely used. Results increased the knowledge about the effects of refrigerant use in fisheries and have been used to motivate measures aimed to phase out refrigerants with a high global warming potential from Norwegian fishing fleets (Hognes & Jensen, 2017).

In 2018, a new project was initiated with multiple aims, including increased knowledge and understanding in the sector and among decision makers about the current performance of important export seafood products and reduction opportunities. Another goal was to monitor GHG performance of Norwegian seafood over time. This type of assessment and approaches can be useful in measuring progress toward climate and wider sustainability goals, on the product level or aggregated for sectors or sub-sectors to be evaluated against national goals.

While the detailed methods, data, and results from this project are presented in Winther et al. (2020), also added as Supporting Information S1, here our aim is building on the results and we (1) present select novel results from this analysis and (2) develop an approach suitable for simplified monitoring of GHG performance over time of the seafood systems analyzed and use it to analyze temporal trends in production-related GHGs. Further, based on the detailed assessment for 1 year presented in Winther et al. (2020), we (3) extract and present species-specific upscaling factors to convert from the simplified, driver-based GHG assessment of production to a more comprehensive one.

2 METHODS

The study consists of two parts, first a detailed assessment of GHGs for full supply chains during 1 year (2017) are presented. While originally 24 seafood supply chains were studied in Winther et al. (2020), Supporting Information S1, the most important Norwegian seafood export products in value, only nine of these are presented here (Table 1). The selection which ones to include was based on our consideration of the minimum number needed to present the main conclusions from the work. Supply chains were defined as a combination of species, production technology, product form, market destination, and transport mode to a wholesaler. Using the outcome of the detailed analysis for 2017 to identify main drivers of production-related emissions, and to establish species-specific upscaling factors, the second part develops an approach to follow up GHGs over time in a simplified way based on these drivers, applying it to 2007–2017.

Species included are farmed salmon (*Salmo salar*) and fished Atlantic cod (*Gadus morhua*), Atlantic herring (*Clupea harengus*), Atlantic mackerel (*Scomber scombrus*), northern prawn (*Pandalus borealis*) and red king crab (*Paralithodes camtschaticus*). The assessment followed the products from production of supply materials (fuel and gear for fisheries and feed for salmon) until delivered to a wholesaler in the most important market of each product (Table 1).

TABLE 1 The seafood supply chains presented in this study

Product	Market/destination	Transport mode	Production technology
Salmon, fresh gutted	Paris	Truck	Aquaculture (netpen)
Salmon, fresh gutted	Shanghai	Air	Aquaculture (netpen)
Salmon, frozen gutted	Shanghai	Ship	Aquaculture (netpen)
Cod, frozen fillet	Paris	Truck	Capture fisheries (various fishing gears)
Cod, frozen fillet	Paris via China (for processing)	Ship	Capture fisheries (various fishing gears)
Herring, roundfrozen	Kiev	Ship+truck	Capture fisheries (all gears)
Shrimp, peeled frozen	Stockholm	Truck	Capture fisheries (demersal trawl)
King crab, live	Seoul	Air	Capture fisheries (trap)
King crab, frozen	Seoul	Ship	Capture fisheries (trap)

The functional unit was *one kg of edible product delivered to a wholesaler in the main market* identified for each product. This means that even when the product was whole salmon ("fresh gutted"), results were translated to the joint functional unit of edible seafood for comparability. Seafood systems contain several steps with multiple outputs, for example, fillet and cut offs, and in such cases all impacts up to that point are shared among the products. The relative mass was used as the basis for this allocation for both feed production and fish processing. This allocation separates between by-products that are somehow further utilized and waste flows that are not further utilized.

By-product utilization was considered both before and after export, so in two separate steps, through data on industrial utilization of export products obtained from seafood market analysts. When they were, by-products were assigned a part of the impacts generated earlier in the supply chain in proportion to their mass, that is, all co-products that were further utilized carry the same burden of upstream emissions. The choice of allocating based on mass was based on the prioritization of physical relationships over other relationships between co-products in the ISO standard as well as in other seafood GHG accounting standards (BSI, 2012; Standards Norway, 2013; ISO, 2020). The need for robust comparisons over time and across products to reflect true differences in resource intensity rather than, for example, the relative economic value of co-products in a specific point of time also points to mass-based allocation as the preferred method. Only transport packaging needed for transportation was included, as the products exported are exported for further processing and usually not yet consumer packaged.

For the detailed assessment of supply chains, data for the production year 2017, which was the most recent year for which data were available, was collected in a top-down approach, starting with national statistics from the Norwegian Directorate of Fisheries on aquaculture production and overall resource use, such as feed and medication in aquaculture. The Norwegian Directorate of Fisheries also hosts databases and collects data on fisheries' landings and the socioeconomic "profitability surveys," containing data on annual landings and fuel use for the fishing vessels taking part in the survey. The Norwegian fishing fleet is grouped in nine fleet segments, which are defined by the main fishing methods used, where they fish and in some cases the target species (see Table 2 for the segments that were used, while the segments ocean-going crab vessels and ocean-going shrimp vessels could not be used, as explained below). The survey is distributed to a representative sample of each segment, see Winther et al. (2020) for more details on the survey and sampling method (Supporting Information S1). The approach to calculate the fuel use intensity (l fuel/kg liveweight fish) in fisheries was to first estimate the fuel use intensity per fleet segment and then obtain a species-specific fuel use intensity by weighting based on how much of the species was landed by each fleet segment. A few adjustments had to be made to model the fuel use intensity of crustacean fisheries (i.e., shrimp and king crab), which often represent a small landing volume caught at low catch rate (catch per unit of effort), resulting in a higher fuel use intensity. King crab catches for example, represent a very small part of the annual catches of the segment "conventional vessels" and could not be represented by the fuel use intensity of these boats. The segment ocean-going crab vessels is a different fishery targeting snow crabs (*Chionocetes opilio*). Therefore, king crab quota holders were contacted one by one and interviewed about their fishery, resulting in a sample of four out of 30 fishers. Some fleet segments are more heterogeneous than others, since vessels are engaged in more than one fishery over a year, for example, the segment "cod trawlers" contains trawlers that in periods trawl for fish and in other periods for shrimp, a considerably more fuel-intensive fishery (Jafarzadeh et al., 2016; Ziegler et al., 2018). As the proportion of shrimp in overall landings of these vessels is very small, they were not considered representative for shrimp trawling and were left out while estimating fuel use intensity of catching shrimp. Unfortunately, in this case it was not possible to obtain fuel use data directly from shrimp fishers. The modeling of fuel use intensity of shrimp fishing was instead entirely based on the segment "coastal shrimp trawlers." Previous research has found that vessel size or proximity of fishery to coast does not significantly influence the fuel use intensity of shrimp fisheries (Ziegler et al., 2018). Therefore, the data for coastal shrimp trawlers was considered to represent also the offshore shrimp trawling of "cod trawlers." Since fish and shrimp trawling is mixed also in the coastal segment, we separated vessels whose annual landings were composed of 25% shrimp or more from the rest, to estimate the fuel use intensity of catching shrimp and other species, respectively, by this segment. While this leaves room for up to 75% other species in the catches, these data were used to represent shrimp trawling, and only shrimp trawling. The contribution of these vessels to total cod, haddock and saithe landings are very small so their exclusion is not expected to influence the values for other species significantly. For more details on the modeling of fuel use intensity in fisheries, see Winther et al. (2020), Supporting Information S1.

TABLE 2 Results of fuel use intensity calculations: (a) per fleet segment and proportion of landings of each species by fleet segments in 2017 and (b) the resulting weighted median fuel use per species

(a)

		Fuel use intensity (l fuel/kg liveweight catch)				Species [a] (% landed by each fleet segment)				
Fleet segment	**Gear types used by fleet segment**	**Min**	**Median**	**Max**	**Cod**	**Haddock**	**Saithe**	**Mackerel**	**Herring**	**Shrimp**
Coastal conventional vessels	Gillnet, traps, jig, longlines, seine	0.02	0.09	0.17	51.0	32.7	29.1	3.0	10.5	0.0
Ocean-going conventional vessels	Auto-line	0.20	0.23	0.29	8.6	15.0	3.1	0.0	0.0	0.0
Cod trawlers	Demersal trawl	0.22	0.35	0.51	35.2	49.9	48.5	0.0	0.0	NA
Coastal shrimp trawlers > 25% shrimp	Demersal shrimp trawl	0.39	1.01	2.25	NA	NA	NA	NA	NA	100.0[b]
Coastal seiners	Seine, gillnet	0.01	0.07	0.13	4.8	1.9	15.5	19.0	22.5	0.0
Purse seiners	Purse seine	0.06	0.09	0.13	0.1	0.0	1.6	73.1	58.3	0.0
Pelagic trawlers	Pelagic trawl	0.07	0.07	0.12	0.0	0.0	1.3	4.9	8.8	0.0

(b)

	Cod	**Haddock**	**Saithe**	**Mackerel**	**Herring**	**Shrimp**
Weighted fuel use intensity in 2017 (l/kg landed)[c]	0.189	0.237	0.215	0.088	0.086	1.013

[a] King crab fishing was treated separately, explained in methods. Minimum, median and maximum fuel use intensity of king crab were 0.167, 0.841, and 1.405 l fuel/kg liveweight catch, respectively.

[b] Shrimp fishing was treated separately, explained in methods.

[c] Based on median fuel use intensity of fleet segments weighted by contribution of fleet segments to landings of each species in 2017.

Where national data were not available, or for verification purposes, a complementary bottom-up approach was used and data from as many producers as possible, or in some cases literature data, were collected. Data on use of refrigerant use on fisheries for example, identified as an important emission source in Winther et al. (2009), were taken from Hognes and Jensen (2017) assuming an annual leakage rate of 20%. The modeling of other inputs to fisheries, such as fishing gear, vessel construction, and bait provisioning is described in Winther et al. (2020).

For salmon, for example, the three leading feed producers together producing over 90% of the salmon feed used in Norway in 2017 provided data on produced volumes and composition in terms of species and origin of each feed input. Official statistics on feed conversion ratios in Norwegian salmon farming (Directorate of Fisheries, 2020) were used. Salmon producers and aquaculture service providers were asked to provide data for of the grow-out phase in terms of use of feed, energy, veterinary treatment and activities of service vessels. The use of cleaner fish and hydrogen peroxide to treat sea lice was included in an approximative way (for details, see Winther et al., 2020, Supporting Information S1), more detailed knowledge on biological, mechanical and chemical treatment of sea lice is underway (Philis et al., 2021; Philis et al., in prep). Post-harvest data on primary and secondary processing and distribution to market was provided by leading producers in each sector: whitefish, pelagics, salmon, shrimp, and king crab.

Data for production of the agricultural feed ingredients from the Agri-footprint database (v4.0) was used, but had to be corrected, as described later. Modeling of marine inputs and micro-ingredients was based on literature, for methods and data, see Winther et al. (2020). For production of other materials and energy as well as transports, data from ecoinvent (v3.5) and the Network of Transport Measures (NTM) were used. The LCA model was built in SimaPro Developer MultiUser version (v9.0.0.48). Land use change (LUC) was included and modeled as in Agri-footprint using the Blonk Consultants LUC tool. Although demersal trawling releases organic carbon from sediments to the water column in a process that is not unlike direct land use change (Paradis et al., 2020; Sala et al., 2021), and parts of this carbon may eventually be released as carbon dioxide to the atmosphere, there are at present no methods that allow quantifying this in a reliable way (Sala et al., 2021). For full details on methods and inventory data, see Winther et al. (2020).

To develop a simplified method for GHG assessment that is suitable to follow up performance over time, it was decided to focus detailed inventory on the main emission drivers. Based on emissions from main drivers, total emissions are then estimated using upscaling factors, differentiated by species, calculated based on the comprehensive assessment for 2017. The main drivers identified in Winther et al. (2020) were, for capture fisheries, fuel use intensity, and for aquaculture, feed use, in line with previous research (Parker, 2012; Avadí & Freón, 2013; Ziegler, Hornborg, Green et al., 2016). Applying this approach helps focusing data collection efforts on the activities that make the greatest difference. Due to the dominance of a few inputs, it is more important to obtain a suitable data resolution and high-quality data for them than detailed modeling of other inputs to the system that will only marginally affect results.

The simplified approach stops at the dock, that is, the post-harvest supply chain is not included. This is motivated by the fact that supply chain emissions are usually dominated by emissions from production, meaning that when the goal is to understand overall trends over time, spending time on collecting detailed data for post-harvest activities is often not justified. There are of course exceptions to this general rule, for example, when post-harvest emissions are very high for example due to emission intensive processing or transport modes or when primary production is very efficient and post-harvest emissions become relatively more important. Post-harvest steps are often modeled through selecting a specific case rather than a "product average," which also makes it difficult to obtain representative data to include in a generalized model. While recognizing that post-harvest emissions can be considerable- and that producers can influence these emissions through product properties, the primary focus of the simplified approach was up to the producer. The simplified approach is applied to data from 2007–2017 to analyze the development of GHGs in Norwegian fisheries and aquaculture. For fisheries and fuel use intensity, this meant repeating the same procedure as described above for 2017 for all years. For feed use, the detailed composition data available for 2007 and 2017 was not available for the years in between. Therefore, a cruder composition data in terms of the major feed input groups: crop-based proteins, oils and starches, marine oils and meals and micro-ingredients, which was available for more years, was used (Aas et al., 2019) for the years 1990, 2000, 2010, 2012, 2013, and 2016 and it was assumed that each of these groups was composed as found in this study. The feed composition data from Winther et al., 2009 and 2020 was aggregated into the same main groups and used for 2007 and 2017. The implications of these assumptions will be discussed.

3 | RESULTS

Results are first presented as results of the data inventory for the most important emission drivers followed by supply chain GHG emissions. Table 2 shows the results of the calculations of the fuel use intensity in the Norwegian fisheries in 2017 per fleet segment. Of the fleet segments included here, coastal shrimp trawlers used most fuel per tonne of catch landed, a median of 1.01 l fuel/kg liveweight catch landed, while coastal seiners, pelagic trawlers, purse seiners and coastal conventional vessels used least fuel per kg, with medians between 0.07–0.09 l fuel/kg liveweight catch. Purse seiners and pelagic trawlers almost exclusively land pelagic species, while coastal seiners in addition to landing large amounts of herring and mackerel also land approximately 5% of the cod, 2% of haddock and 16% of saithe at very low fuel use intensities. Coastal conventional vessels land approximately half of cod landings and about a third of haddock and saithe. These latter two fleet segments are very fuel efficient per tonne landed, in part because they are engaged in pelagic fisheries. The rest of the cod is caught by cod trawlers (approximately 35%) and ocean-going conventional vessels (approximately 9%) at considerably higher fuel use intensities with an average of 0.24–0.36 l fuel/kg liveweight catch. These segments also catch approximately half of the haddock and saithe (cod trawlers) and 15% of the haddock (ocean-going conventional vessels).

Table 2 also shows the fuel use intensity per species, weighted by the contribution of each fleet segment to landings of each species. In 2017, pelagic species had the lowest fuel use intensity at approximately 0.09 l fuel/kg liveweight, crustaceans had the highest fuel use intensity, at approximately 0.8 and 1.0 l fuel/kg liveweight catch for king crab and shrimp, respectively with the whitefish species were found in between. The fact that cod had lower fuel use intensity than saithe and haddock is because approximately 55% of it is landed by coastal conventional vessels and seiners at a low fuel use intensity. Saithe is either landed by fuel intensive cod trawlers (approximately 49%) or comparatively fuel-efficient coastal conventional vessels and seiners, while approximately 65% of haddock is landed by the two most fuel-intensive fleet segments.

The detailed composition of salmon feed produced in Norway in 2017, based on data from the three main producers, provided information about species used and their origin. The data were grouped in eight feed input types of which crop-based protein represented the largest proportion (40%). All crop-based inputs, that is, proteins, oils and starches, represented 70%, and micro-ingredients, that is, vitamins, minerals, amino acids and pigments, represented 3%. This implies that the remainder, almost 30%, consisted of marine inputs. More than 17 species of fish and krill were used in Norwegian salmon feeds in 2017. Marine inputs are split into meals and oils from dedicated reduction fisheries (20%) and from fish processing by-products (9%). The inclusion of fish meals was larger (17%) than of fish oils (12%). By-products of other animals, for example, poultry, are since 2013 partly permitted to be included in Europe, but the salmon industry has concluded that consumer acceptance in Europe is low and therefore decided not to use them, while in the Americas and Australia livestock by-products are commonly used in salmon feed (Berg Lea, pers. comm. and Pelletier et al., 2009; Parker, 2018).

The average economic feed conversion ratio (eFCR) in 2017 varied between 0.9 and 1.6 kg feed/kg salmon between different salmon farmers with an average of 1.32 kg feed/kg LW salmon delivered to slaughter. All other inventory data are reported in Winther et al. (2020), Supporting Information S1.

Characterized results for the full supply chains show that salmon and crustacean products cause more emissions than cod and herring (Figure 1). Comparing cod first shipped 21000 km to China for processing, then back to Europe at 2.5 kg CO_2e/kg with shrimp trucked 2300 km from Norway to Sweden (4.0 kg CO_2e/kg) or king crab flown 10500 km to South Korea (29 kg CO_2e/kg) shows that distance travelled is a poor indicator of emissions. Products from fuel-efficient fisheries processed close to either fishery or market have the lowest emissions of the products assessed here (cod and herring shipped to France and Ukraine) and those airfreighted to Asian markets are found at the other end (Figure 1).

Only for airfreighted products, export dominates total supply chain emissions and shifting away from airfreight emerges as an obvious improvement option for these products. However, this would also entail a shift in product from fresh to frozen using current technology. Figure 2 also shows that except for airfreight, fuel use in fishing and feed use in aquaculture dominates supply chain emissions for these chains.

Leaving out the post-harvest steps of the supply chain, at landing/harvest, GHG emissions per kg liveweight rank between 0.37 kg CO_2e/kg for herring and 5.3 kg CO_2e/kg for salmon, Figure 3. Results are dominated by fuel production and combustion for species from capture fisheries (76–97%) and by feed production for salmon (85%). This means that reducing the data inventory to these two main inputs will still cover over three quarters of total impacts. Even for the products from pelagic fisheries with the lowest fuel use intensity, that is, least dominated by fuel use, fuel still represents 75% of fisheries emissions and about a third of total supply chain emissions.

Parker et al. (2018) stated that non- fuel GHG emission in fisheries represented between 10–40% of total fisheries emissions, with an average of 25%, implying that about a third of emissions should be added to a fuel-based GHG estimate to obtain total fisheries emissions. This means that by multiplying fuel-based emissions by 1.33, a factor we can call the “upscaling factor,” we obtain total fisheries emissions. In this study, we find that fuel intensive fisheries like those targeting crustaceans have a lower upscaling factor; 1.03, while average- and low-fuel fisheries, demersal and pelagic species, had higher factors, 1.2 and 1.3, respectively. These results suggest that differentiated factors should be used for different types of fisheries when this type of simplification is made. For salmon, the corresponding upscaling factor from feed-related to total GHGs in this study was 1.2.

Limiting the analysis to only studying the impact of feed and fuel use intensity to study temporal trends applying these upscaling factors, hence seems plausible, with limitations discussed later. Applying the same way of extracting fuel use intensities for the fishing fleets and subsequently species as in 2017 for the years 2007–2017 results in the data presented in Figure 4 after conversion to GHGs based on both production and combustion of the fuel. It shows that catching shrimp is consistently more fuel use intensive than harvesting other species. The fuel use intensity of shrimp fisheries (Figure 4a) has varied between approximately 0.7–1.3 L/kg shrimp landed, resulting in GHGs of approximately 2–4 kg CO_2e/kg shrimp landed, applying the upscaling factors from above. It is the most variable segment, without clear time trend. However, these numbers for fuel use intensity are in line with previous studies of Norwegian shrimp fisheries (Ziegler, Hornborg, Valentinsson, et al., 2016; Ziegler et al., 2018).

The other species (Figure 4b) fall into two groups: pelagic and demersal species, with demersal species showing a slight reduction over the period, while pelagics have been more stable. Greenhouse gas emissions of shrimp fishing have over the period increased by almost 50%, while GHGs of demersal fishing decreased by around 20%, and pelagics by 5–10%.

The fuel use intensities of the fleet segments influence this result as well as the proportion of landings of each species by each fleet segment. The proportion of herring and mackerel landed by coastal seiners which have a lower fuel use intensity than purse seiners has for example increased, while at the same time the fuel intensity of both these fleets has increased slightly between 2007 and 2017 (see Winther et al., 2020). The segments catching most demersal species have on the other hand, reduced their fuel use intensity considerably (14–31%), which explains the reduced GHGs

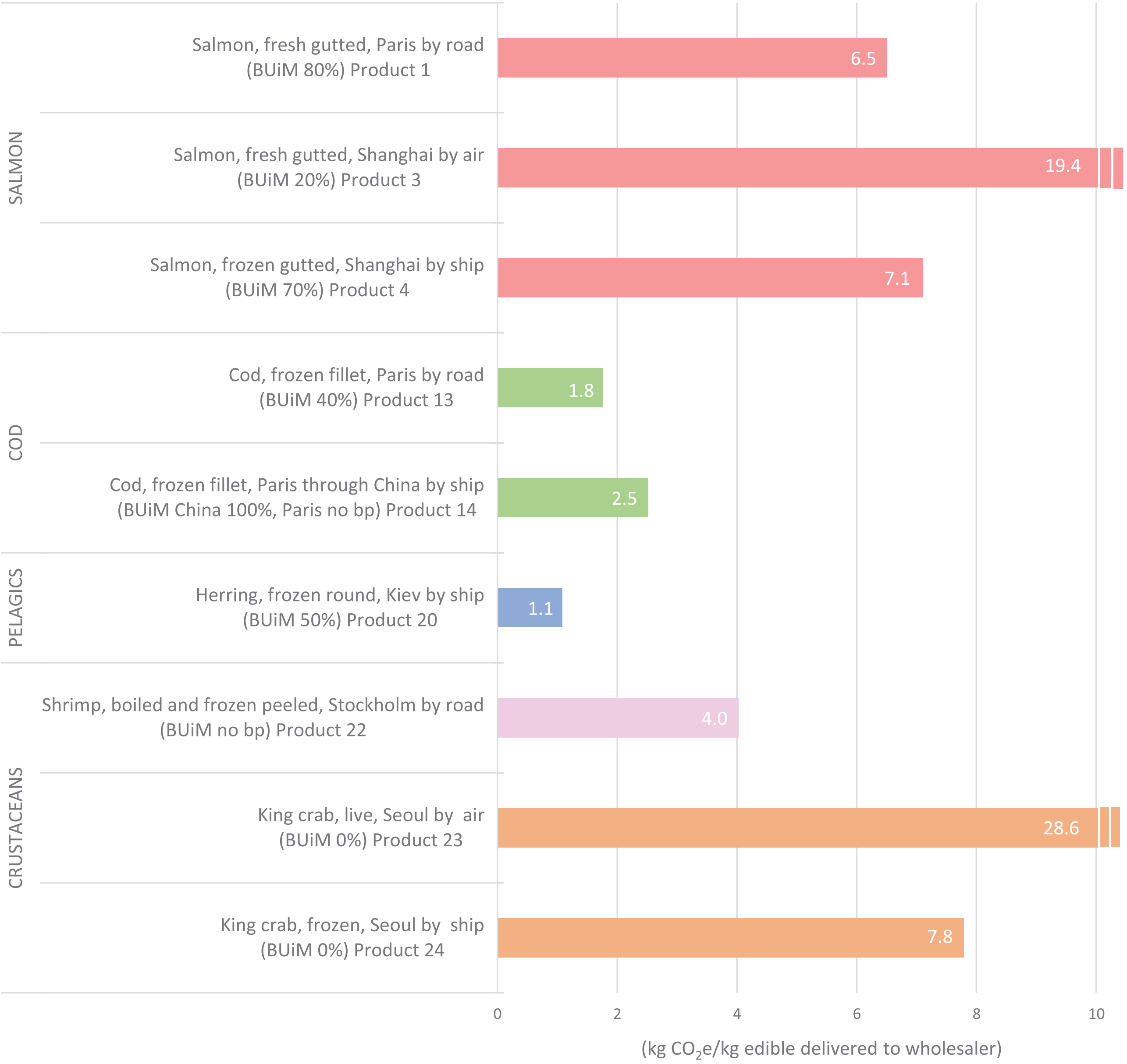

FIGURE 1 Supply chain greenhouse gas emissions, colored after species, with proportion of by-products used in market (BUiM) indicated in brackets. Product numbering as in Winther et al., 2020. Data found in Supporting Information S3

of these species. The increase in GHGs of shrimp from 2007 to 2017 is entirely due to the increased fuel use intensity of the segment coastal shrimp trawlers. The fuel efficiency of fleet segments is likely influenced by the availability of quotas, and the quotas per vessel were larger in 2017 than in 2007. Species biomass development show contrasting trends, with biomass of cod and haddock increasing, while saithe and herring biomass has declined over the period. These stock biomass trends do not seem to be reflected in the development of fuel use and greenhouse gas emission intensity over time.

For salmon, the critical data, eFCR and feed GHGs, - are multiplied and then multiplied by the upscaling factor that was calculated for salmon (1.2), resulting in the temporal trend shown in Figure 5. The estimated GHGs per tonne of salmon increased by about 50% since 1990 as a result of both the slight increase in eFCR, but more importantly due to increased inclusion of emission-intensive feed inputs such as soy, which is an important and increasing part of the crop-based protein, and micro-ingredients, see Figure 6.

4 | DISCUSSION

Our comprehensive assessment of supply chains in 2017 showed that the GHG emissions of Norwegian seafoods vary widely, from 1.1 to 29 kg CO_2e/kg product delivered to a wholesaler in markets around the world. Emission intensity depends mainly on the fuel efficiency of the fishery, the

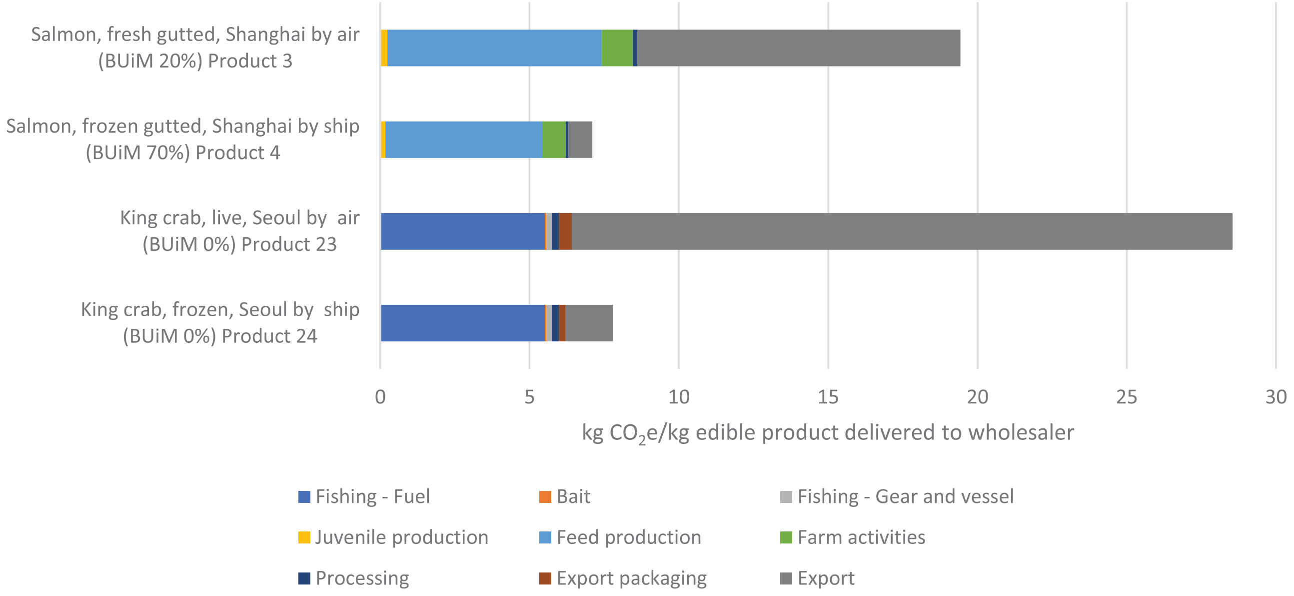

FIGURE 2 Greenhouse gas emissions of fresh and frozen seafood supply chains shipped by air or ship to their respective markets. Product numbering as in Winther et al., 2020. Data found in Supporting Information S3

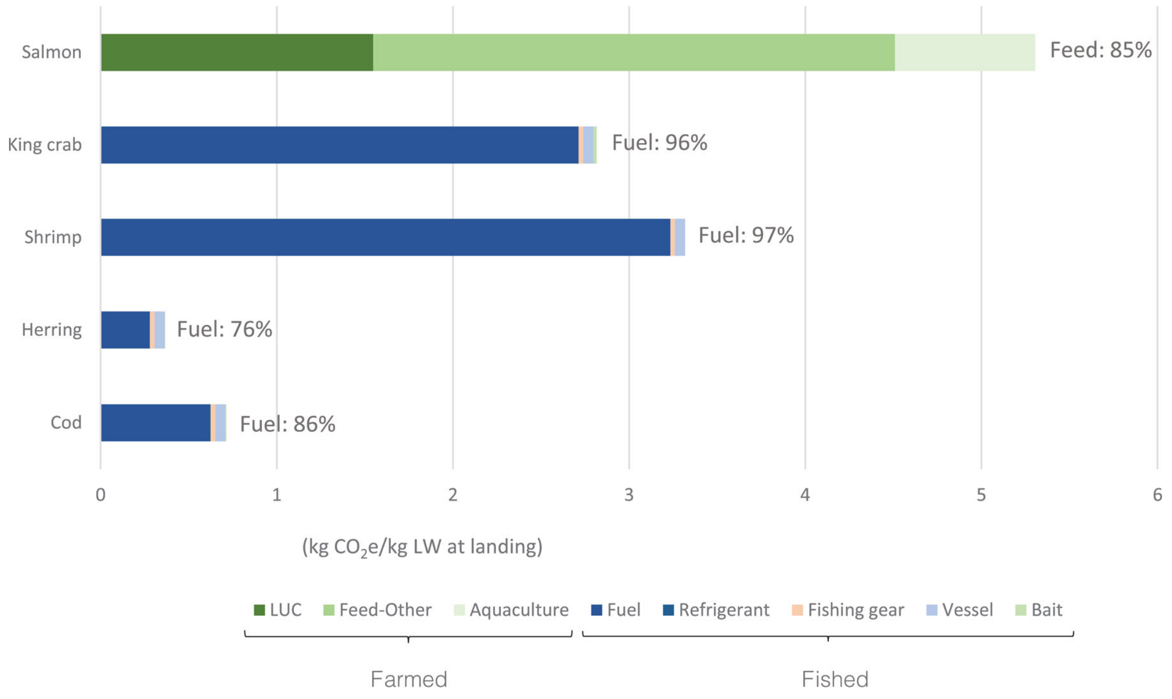

FIGURE 3 Greenhouse gas emissions per liveweight at landing, with proportion of total represented by fuel and feed use (feed use = sum of LUC and Feed-Other). Data found in Supporting Information S3

feed use in aquaculture, the product form, transport distance and mode, edible yield and utilization of by-products in different steps in the supply chain. Salmon and crustacean products had the highest emissions and herring and cod products the lowest. For all products, there was considerable variability between average and best performers, which highlights a significant improvement potential. A simplified, driver-based approach showed that fisheries, except for shrimp, have become more fuel-efficient, resulting in lower GHGs; while salmon farming and shrimp have increased emissions over the past 10 years. For king crab, only 2017 data were available. Shrimp fisheries and products in this study give rise to lower emissions than other studies of shrimp fisheries (Ziegler et al., 2018) and this could in part be due to the fact that it was not possible to entirely separate the shrimp fishing from other fishing activities on the same vessels, which would imply that shrimp results may be underestimated. Results for farmed salmon, on the other hand, are found at the higher end of the range of open netpen culture, which is around 3 kg CO_2e/kg liveweight salmon (Philis

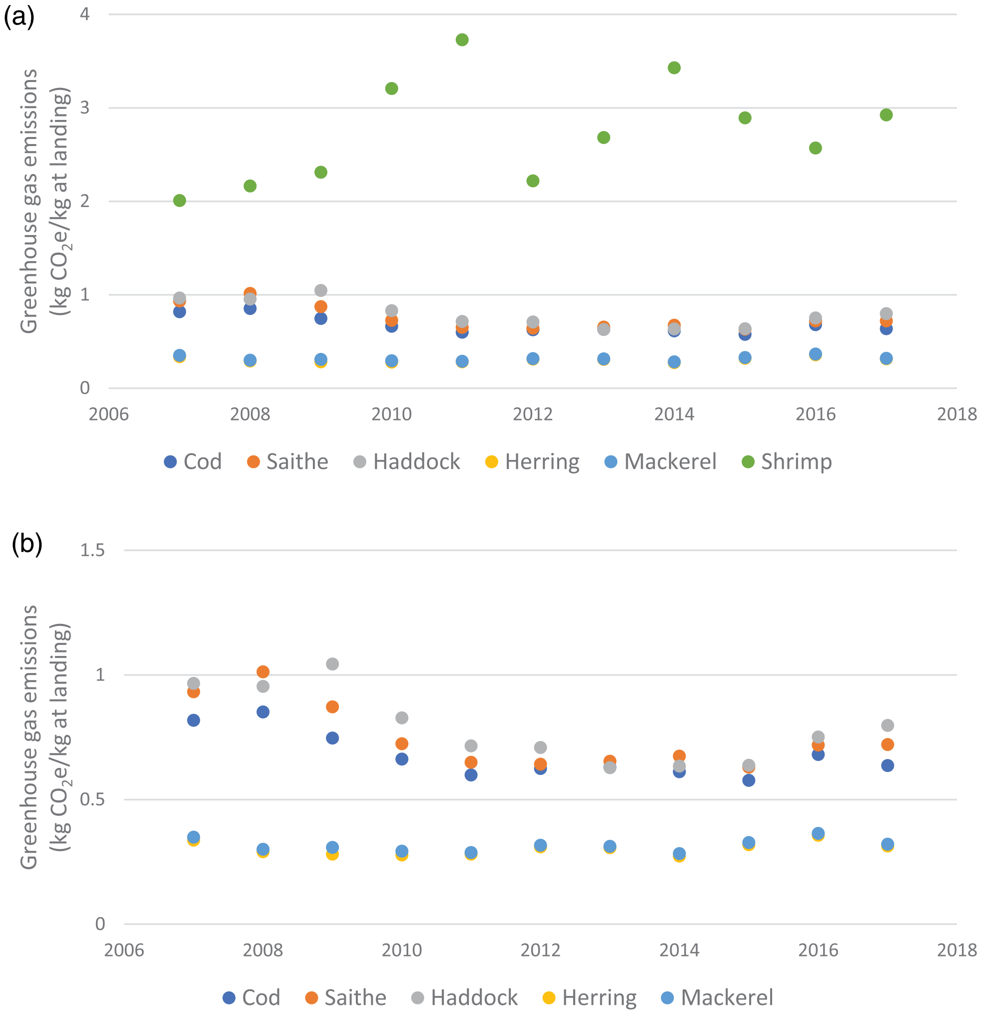

FIGURE 4 Development of estimated total GHGs, using proposed method for Norwegian fisheries 2007–2017, (a) with and (b) without shrimp. Data found in Supporting Information S3

et al., 2019). It is important to recognize that there are methodological differences between the studies reviewed by Philis et al. (2019) with regard to for example system boundaries and impact assessment methods.: The higher result of this study over previous ones is explained by the inclusion of Land Use Change emissions, the accounting for micro-ingredients and the increased inclusion of these relatively emission intensive feed inputs together with a slightly higher feed conversion ratio. The higher feed use is caused by increasing disease and parasite challenges, causing slower growth and higher mortality- and the need for treatment with biological, chemical or mechanical methods.

Except the uncertainties around the fuel use in fisheries mentioned above, there are many other sources of uncertainty. For salmon, one of the largest sources of uncertainty is the modeling of LUC, mandated by recent standards (e.g., ISO, 2020; Zampori & Pant, 2019), with models differing widely in results. A discussion in relation to the use of soy is whether certified soy should be considered free from LUC, described in detail in Winther et al. (2020). The use of database data for farming of agricultural feed inputs is another source of uncertainty as agricultural efficiency can vary both spatially and temporally. We have used the data that best match the information on feed sources obtained. The data concerning the micro-ingredients is linked to high uncertainty as their emissions were estimated using literature values. Still, we could show that these ingredients, although representing a small proportion of the feed, can contribute unproportionally to emissions.

The simplified approach gives a quick picture of the performance of the production system, see Supporting Information S2 for an instruction for how to apply it to capture fisheries and salmon farming. The differentiated upscaling factors that could be extracted by comparing the simplified with the comprehensive assessment for 2017 are a refinement over previous generalized factors (Parker et al., 2018). It seems logical that non-fuel emissions represent a lower proportion in fuel intensive fisheries than in fuel efficient ones and taking this into account can lead to more accurate estimates, although this can certainly be further developed.

A similar approach to estimate GHG emissions from key drivers has been developed for the Monterey Bay Aquarium initiative "Seafood Watch" (https://www.seafoodwatch.org/) which gives seafood consumer advice related to seafood based on similar principles as seafood certification, that

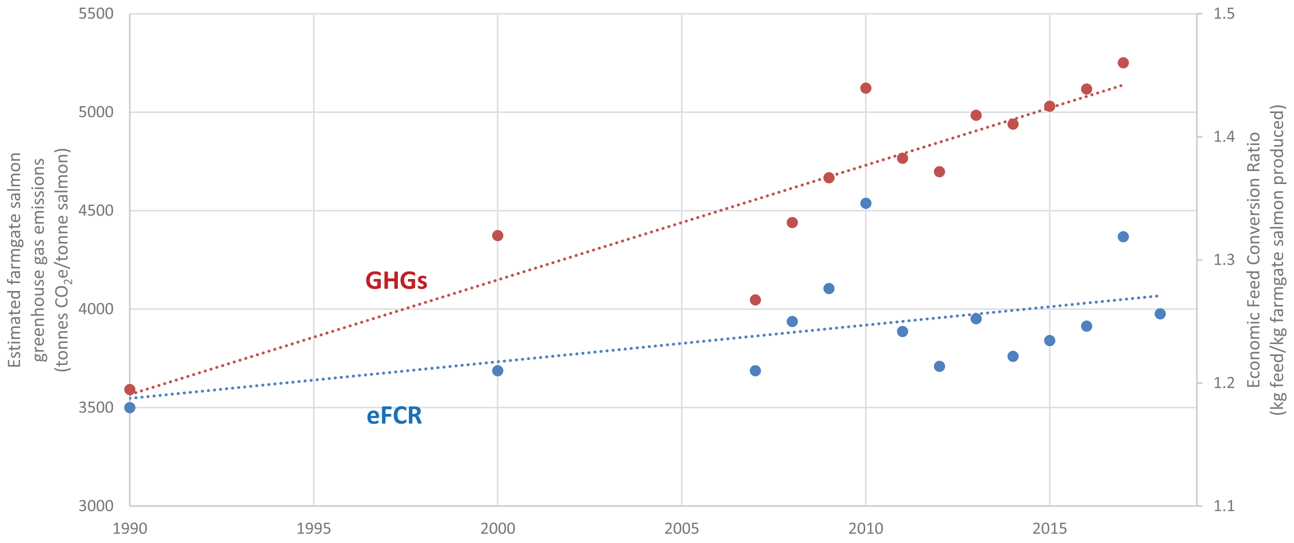

FIGURE 5 Development of estimated total GHGs of farmed Norwegian salmon 1990–2017, using official eFCR data from the Fisheries Directorate. Feed composition in terms of the six major groups: fish meals and oils, vegetable proteins, oils and starches and micro-ingredients was found in Winther et al. (2009, 2020) for 2007 and 2017 and from Aas et al. (2019) for 1990, 2000, 2010, 2012, 2013, and 2016, and was linearly interpolated between years, using the upscaling factor and assuming the same composition of each the six feed groups as in 2017. Note that both *y*-axes are truncated. Data found in Supporting Information S3

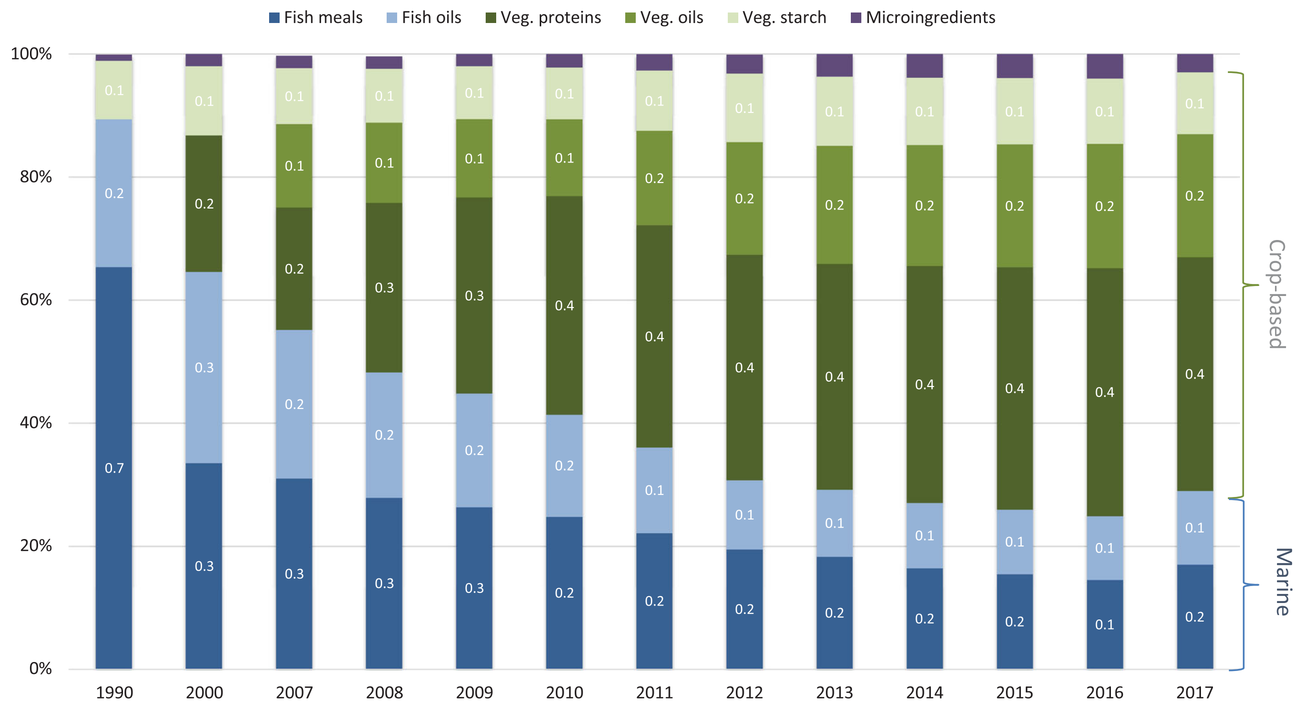

FIGURE 6 Composition Norwegian salmon feed in major feed components (modified from Aas et al., 2019, complemented with data from Winther et al. (2009, 2020). Data found in Supporting Information S3

is, based on criteria related to ecological sustainability and management. The approach suggested then was based on three feed input categories only (marine-, crop- and animal-derived) and based on literature data on GHG intensity (e.g., Pelletier et al., 2009; McGrath et al., 2015). However, it has not yet been implemented in the overall assessments of the Seafood Watch.

How useful is this suggested approach and for which purposes? It can be used to monitor performance of a fishery or fish farm from year to year, with the aim of understanding better the dynamics between different parameters, how they interact and how that influences the GHG performance of the product. It cannot give exact values of product GHGs that can be communicated externally to compare against other products, though. It is important to recognize that the post-harvest supply chain can have considerable impact, in particular when it entails airfreighting, and is excluded entirely from the simplified approach, for reasons explained earlier. Another question is how specific the validity of this approach is to the Norwegian production systems for which it was developed? Considering that the technologies used here, industrial large and small-scale fishing methods and netpen salmon aquaculture, are used in many other regions around the world and technology/fleet segment was a more important determinant of fuel use and greenhouse gas emissions than for example, stock biomass, we expect that the approach should be applicable to systems using similar technologies, but not for very different technologies such as non-motorized fisheries or recirculating or non-fed aquaculture systems. The product-based estimates can also be used to provide a rough picture of the contribution of a producing sector to national level emissions, in order to follow up against climate and other sustainability goals. Scaled up to national production, the Norwegian salmon farming industry was in 2017 responsible for almost seven million tonnes of GHGs. The growth of a sector like aquaculture can of course outbalance emission reductions on the product-level, but it is important to consider emissions from a sector in a holistic perspective.

The choice of how to model electricity production, assuming Norwegian hydropower or the more fossil-based European average grid, did not alter results significantly. This implies that the main drivers in this type of production system remain main drivers also if using other energy sources. But what happens if the feed and fuel emissions are reduced to the point where other inputs become relatively more important for total emissions, through major technological breakthroughs or patient continuous improvement processes? If and when a major reduction is seen using the simplified approach, it is recommended to again make a more comprehensive assessment to establish new upscaling factors and identify potential main drivers that need to be included in the simplified approach. Major shifts in composition within the six feed input groups from the data presented in Winther et al. (2020), in particular with regard to key emission drivers such as soy and animal by-products, should also be checked and if needed adjusted for. Altogether, the more regular monitoring of GHG performance of seafood production systems will lead to improved understanding in the sector and perhaps most importantly increased data availability on critical parameters, which has strongly hampered this type of assessment to date.

ACKNOWLEDGMENTS

The authors would like to thank various parts of the Norwegian seafood industry for contributing data and the advisory board and external reviewers for asking relevant questions and giving useful feedback which improved the study. Shradda Mehta, Maitri Thakur, Louisa Borthwick, and Malin Axel-Nilsson assisted with the data inventory. Three reviewers helped us improve the manuscript by asking good questions.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Friederike Ziegler https://orcid.org/0000-0003-1995-2338

REFERENCES

Aas, T. S., Ytrestøyl, T., & Åsgård, T. (2019). Utilization of feed resources in the production of Atlantic salmon (*Salmo salar*) in Norway: An update for 2016. *Aquaculture Reports*, *15*(2019), 100216.

Avadí, A., & Fréon, P. (2013). LCA of fisheries: A review for fisheries scientists and managers. *Fisheries Research*, *143*, 21–38.

BSI (2012). *PAS 2050–2:2012 Assessment of life cycle greenhouse gas emissions. Supplemental requirements for the application of PAS 2050:2011 to seafood and other aquatic food products*. British Standard Institute.

Costello, C., Cao, L., Gelcich, A. (Eds.) (2019). The future of food from the sea. https://oceanpanel.org/sites/default/files/2019-11/19_HLP_BP1%20Paper.pdf

Costello, C., Cao, L., Gelcich, S., Cisneros-Mata, M. A., Free, C. M., Froehlich, H. E., Golden, C. D., Ishimura, G., Maier, J., Macadam-Somer, I., Mangin, T., Melnychuk, M. C., Miyahara, M., de Moor, C. L., Naylor, R., Nøstbakken, L., Ojea, E., O'Reilly, E., Parma, A. M., … Lubchenco, J. The future of food from the sea. *Nature*, *588*, 95–100.

Directorate of Fisheries (2020). Forbruk av fôr fordelt på år 2005–2020 (in Norwegian) [Feed use for years 2005-2020]. https://www.fiskeridir.no/Akvakultur/Tall-og-analyse/Biomassestatistikk/Biomassestatistikk-etter-fylke

FAO (2020). *The state of world fisheries and aquaculture 2020. Sustainability in action*. Food and Agriculture Organization of the United Nations.

Hallström, E., Bergman, K., Mifflin, K., Parker R., Tyedmers P., Troell M., & Ziegler F. (2019). Combined climate and nutritional performance of seafood. *J Clean Prod*, (230), 402–411.

Hilborn, R., Banobi, J., Hall, S. J., Pucylowski, T., & Walsworth, T. E. (2018). The environmental cost of animal source foods. *Front. Ecol. Environ.*, *16*(6), 329-335

Hoegh-Guldberg, O. (Ed.). (2019). *The ocean as a solution to climate change: Five opportunities for Action*. https://oceanpanel.org/sites/default/files/2019-10/HLP_Report_Ocean_Solution_Climate_Change_final.pdf

Hognes, E. S., & Jensen, J. I. (2017). Drivstofforbruk og klimaregnskap for den norske fiskeflåten Utviklingen fra 2001 til 2015 (in Norwegian) [Fuel use and greenhouse gas accounting for the Norwegian fishing fleet. The development from 2001-2015]. https://www.fhf.no/prosjekter/prosjektbasen/901248/?fileurl=https://fhfno.sharepoint.com/sites/pdb/Publisertedokumenter/255585Fagrapport%20Drivstofforbruk%20og%20klimaregnskap%20for%20den%20norske%20fiskefl%C3%A5ten.pdf.PDF&filename=Sluttrapport:%20Drivstofforbruk%20og%20klimaregnskap%20for%20den%20norske%20fiskefl%C3%A5ten

ISO (2006a). *ISO 14040. Environmental management – life cycle assessment – principles and framework*. International Standards Organization.

ISO (2006b). *ISO 14044. Environmental management – life cycle assessment – requirements and management*. International Standards Organization.

ISO (2020). ISO 22948. Carbon footprint for seafood—Product category rules (CFP-PCR) for finfish International Standards Organization.

Jafarzadeh, S., Ellingsen H., & Aanondsen S. A. (2016). Energy efficiency of Norwegian fisheries from 2003 to 2012. *Journal of Cleaner Production*, *112* (Part 5), 3616–3630.

McGrath, K. P., Pelletier, N. L., & Tyedmers, P. H. (2015). Life cycle assessment of a novel closed-containment salmon aquaculture technology. *Environmental Science & Technology*, *49*, 5628–5636.

Paradis, S., Goni, M., Masque, P., Duran, R., Arjona-Camas, M., Palanques, A., & Puig, P. (2020). Persistense of biogeochemical alterations of deep-sea sediments by bottom trawling. *Geophysical Research Letter*, *48*(2), e2020GL091279. https://doi.org/10.1029/2020GL091279

Parker, R. W. R. (2012). *Review of life cycle assessments research on products derived from fisheries and aquaculture: A review for Seafish as part of the collective action to address GHG in seafood*. Sea Fish Industry Authority.

Parker, R. W. R. (2018). Implications of high animal by-product feed inputs in life cycle assessments of farmed Atlantic salmon. *I J LCA*, *23*:982-994

Parker, R. W. R., Blanchard, J. L., Gardner, C., Green, B. S., Hartmann, K., Tyedmers, P. H., & Watson, R. A. (2018). Fuel use and greenhouse gas emissions of world fisheries. *Nature Clim. Change*, *8*, 333–337.

Pelletier, N., Tyedmers, P., Sonesson, U., Scholz, A., Ziegler, F., Flysjö, A., Kruse, S., Cancino, B., & Silverman, H., (2009). Not all salmon are created equal: Life cycle assessment (LCA) of global salmon farming systems. *Environmental Science and Technology*, *43*(23), 8730-8736.

Philis, G., Ziegler, F., Gansel, L. C., Dverdal Jansen, M., Gracey, E. O., & Stene, A., (2019). Comparing life cycle assessment (LCA) of salmonid aquaculture production systems: Status and perspectives. *Sustainability*, *11*, 2517.

Philis, G., Ziegler, F., Dverdal Jansen, M., Gansel, L. C., Hornborg, S., Hansen Aas, G., & Stene, A. (in press). Quantifying environmental impacts of cleaner fish used as sea lice treatments in salmon aquaculture with Life Cycle Assessment (LCA). https://doi.org/10.1111/jiec.13118

Philis, G., Ziegler, F., Snåre, M. W., Dverdal Jansen, M., Gansel, L. C., & Stene, A. (in prep). Quantifying environmental impacts of mechanical, chemical and total sea lice treatments in salmon aquaculture with Life Cycle Assessment (LCA). Manuscript submitted for publication.

Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science*, *360*, 987–992.

Sala, E., Mayorga, J., Bradley, D., Cabral R. B., Atwood T. B., Auber A., Cheung W., Costello C., Ferretti F., Friedlander A. M., Gaines S. D., Garilao C., Goodell W., Halpern B. S., Hinson A., Kaschner K., Kesner-Reyes K., Leprieur F., McGowan J., …, & Lubchenco J., (2021). Protecting the global ocean for biodiversity, food and climate. *Nature*. *592*(7854), 397–402. https://doi.org/10.1038/s41586-021-03371-z

Scarborough, P., Appleby, P., Mizdrak, A., Briggs, A. M., Travis, R., Bradbury, K., & Key, T. (2014). Dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in the UK. *Climatic Change*, *125*, 179e192.

Standards Norway (2013). *Carbon footprint for seafood —Product category rules (CFP-PCR)/Klimaspor for sjømat—Produktkategoriregler (CFP-PCR)*, Standards Norway.

Tilman, D., & Clark, M. (2014). Global diets link environmental sustainability and human health. *Nature*, *515*, 518e522. https://doi.org/10.1038/nature13959

Winther, U., Ziegler, F., Skontorp Hognes, E., Emanuelsson, A., Sund, V., & Ellingsen, H., (2009). Carbon footprint and energy use of Norwegian seafood products (Report No. SFH80 A096068). SINTEF Fisheries and Aquaculture.

Winther, U., Skontorp Hognes, E., Jafarzadeh, S., & Ziegler, F. (2020). Greenhouse gas emissions of Norwegian seafood products in 2017 (Report No. 2019:01505). SINTEF Ocean AS.

Zampori, L., & Pant, R. (2019). *Suggestions for updating the Product Environmental Footprint (PEF) method*. Publications Office of the European Union.

Ziegler, F., Winther, U., Skontorp Hognes, E., Emanuelsson, A., Sund, V., & Ellingsen, H., (2013). The carbon footprint of Norwegian seafood products on the global seafood market. *Journal of Industrial Ecology*, *17*(1), 103–116

Ziegler, F., Groen, E. A., Hornborg, S., Bokkers, E. A. M., Karlsen, K. M., & de Boer, I. J. M. (2018). Assessing broad life cycle impacts of daily onboard decision-making, annual strategic planning and fisheries management in a northeast Atlantic trawl fishery. *International Journal of Life Cycle Assessment*, *23*(7), 1357–1367.

Ziegler, F., Hornborg, S., Green, B. S., Eigaard, O. R., Farmery, A., Hammar, L., Hartmann, K., Molander, S., Parker, W. R., Skontorp Hognes, E., Vázquez-Rowe, I., & Smith, A. D. M. (2016). Expanding the concept of sustainable seafood using life cycle assessment. *Fish and Fisheries*, *17*(4), 1073–1093.

Ziegler, F., Hornborg, S., Valentinsson, D., Skontorp Hognes, E., & Eigaard, O. R. (2016). Same stock, different management: Quantifying the sustainability of three Skagerrak shrimp fisheries from a product perspective. *ICES Journal of Marine Science*, *73*(7), 1806–1814.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Ziegler F, Jafarzadeh S, Hognes ES, & Winther, U. Greenhouse gas emissions of Norwegian seafoods: From comprehensive to simplified assessment. *J Ind Ecol*. 2021;1—12. https://doi.org/10.1111/jiec.13150