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Greenhouse gas emissions of Norwegian seafood products in 2017

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Report

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ABSTRACT

Greenhouse gas emissions have been quantified for 21 Norwegian seafood products, most of which currently represent important components of Norwegian seafood export regarding volume and value. The products come from salmon aquaculture and from capture fisheries for cod, saithe, haddock, herring, mackerel, shrimp and king crab. In general, products from pelagic fisheries were found to have the lowest greenhouse gas emissions, while salmon and crustacean products had the highest greenhouse gas emissions. Emissions of products from demersal fisheries were found to be in a range between those of pelagic and salmon products. Due to differences in methods used and available data, the results presented in this report is not directly comparable to results presented in a study published in 2009. The present study is carried out in a collaboration between SINTEF Ocean AS, Asplan Viak AS and RISE Research Institutes of Sweden.

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Abbreviations

Acronym/Unit	Explanation
BUIM	By-product utilization in market
CF	Carbon Footprint
CEF	Constant Emissions Factor
CFC	Chlorofluorocarbons
CO_2e / CO2e	Carbon dioxide equivalents
dLUC	Direct Land Use Change
eFCR / EFCR	Economic Feed Conversion Ratio
EPS	Expandable Polystyrene
FAO	Food and Agriculture Organisation of the United Nations
FCR	Feed Conversion Ratio
GHG	Greenhouse gas emissions
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbons
HFC	Hydrofluorocarbons
iLUC	Indirect Land Use Change
IPCC	Intergovernmental Panel on Climate Change
kWh	kilowatt hour
LCA	Life cycle assessment
LNG	Liquefied natural gas
LUC	Land Use Change
LW	Liveweight
Lwe	Live weight equivalent, a measure used to convert landed weight in fisheries to whole fish weight
Median	The middle number in a sorted, ascending or descending, list of numbers
Mt	Million metric ton, 1,000,000,000 kg
NOK	Norwegian kroner
NTM	Network for Transport Measures
PEF	Product Environmental Footprint
PEFCR	Product Environmental Category Rules
RAS	Recirculating aquaculture system
SPC	Soy Protein Concentrate
SSB	Statistics Norway
Ton	Metric ton, 1,000 kg
VEF	Variable Emissions Factor
w%	Percentage of mass
WFE, wfe	Whole Fish Equivalent used for salmon. The weight of the fish after starving and bleeding

Summary in Norwegian

Klimagassutslipp er beregnet for 21 norske sjømatprodukter, de fleste representerer viktige produkter i norsk sjømateksport med hensyn til volum og verdi. Produktene kommer fra oppdrett av laks og fra fiske etter torsk, sei, hyse, sild, makrell, reker og kongekrabbe. Etter slakting og landing blir fisken foredlet til en rekke ferske, frosne, runde, sløyde eller fileterte produkter, som blir transportert til sine respektive markeder. Det at den samme metodiske tilnærmingen brukes til å vurdere et stort antall verdikjeder, fra fiske/oppdrett til grossist, gir mulighet for sammenligning mellom produktene. Resultatene illustrerer effekten av arter, transportmodus og avstand og produktform, både hver for seg og kombinert. På grunn av forskjeller i metoder som er benyttet og tilgjengelige data, er resultatene som er presentert i denne rapporten ikke direkte sammenlignbare med resultatene presentert i en studie publisert i 2009 [1].

Generelt sett har produkter fra pelagiske fiskerier de laveste klimagassutslippene, mens produkter fra laks og skalldyr har de høyeste klimagassutslippene (Figur 1). Utslipp fra produkter av torskefisk ble funnet å ligge i et område mellom utslipp fra pelagiske produkter og lakseprodukter. Selv om resultatene som presenteres i denne rapporten ikke er direkte sammenlignbare med resultatene i rapporten fra 2009 referert til ovenfor, kan det konkluderes med at klimagassutslippene fra produktene fra fiskeri (fiske etter torskefisk mer enn pelagisk) har blitt redusert i løpet av det siste ti år. En av hovedårsakene til denne utviklingen er utfasing av kjølemedier med et høyt klimautslippspotensial. På den annen side har klimagassutslippene fra lakseprodukter økt. Hovedsakelig fordi bidrag fra endring av arealbruk og mikroingredienser er inkludert i beregningene. Også økt dødelighet og redusert vekst på grunn av lakselus og sykdommer har bidratt til økningen. Disse utfordringene har resultert i økt fôrforbruk, økt behov for behandling med bruk av service- og brønnbåter og produksjon av legemidler og rensefisk som benyttes til behandling av lakselus.

Tiltak for å redusere klimagassutslipp er identifisert og potensial for reduksjon er kvantifisert. For oppdrett av laks foreslås de følgende tiltakene for reduksjon av klimagassutslippene:

- Forbedre fôreffektiviteten (redusere økonomisk fôrfaktor)
- Endre sammensetningen av fôret
- Sikre full bruk av biprodukter langs hele distribusjonskjeden
- Minimere transportbehovet (for eksempel unngå unødvendig transport for foredling og transport av biprodukter)
- Finne alternativer til flytransport av laks og generelt skifte til transportmåter og produktformer som gir lavere utslipp av klimagasser
- Øke energieffektiviteten og bytte til fornybare energikilder

Sammenlignet med utslippene av klimagasser der fersk laksefilet blir eksportert til Paris med lastebil og ferge med våre basis forutsetninger, reduseres utslippene med 42% i et tilfelle der forbedringer i økonomisk fôrfaktor, opprinnelse av soya, biproduktutnyttelse, energibruk i forskjellige trinn i produksjonskjeden og belastningen med returfrakt er innarbeidet.

For fiskeriene foreslås de følgene tiltakene for reduksjon av klimagassutslippene:

- Forbedre drivstoffeffektiviteten til fiskefartøyer
- Bytte til alternative drivstoff, for eksempel hydrogen og flytende naturgass
- Bruke kuldemedier med lavt klimagassutslipp og forbedre drivstoffeffektiviteten til kjøling ombord
- Sikre full bruk av biprodukter langs hele produksjonskjeden

- Minimere transportbehovet (unngå for eksempel unødvendig transport for foredling og transport av biprodukter)
- Skifte til mer klimaeffektive transportformer

Hvis all torsk ble fanget av fartøyene som i dag fisker med høyest drivstoffeffektivitet i hvert flåtesegment, med samme bidrag fra hvert flåtesegment, kan karbonavtrykket samlet i hele distribusjonskjeden for fersk torskefilet levert til Paris bli nær halvert. Biproduktutnyttelsen er allerede relativt høy, men full utnyttelse ville, når det gjelder hyse levert til London, ytterligere redusert utslippene i hele distribusjonskjeden med 10-15%. Forskjellen i klimapåvirkning av produktene mellom full og ingen utnyttelse av biprodukter er en faktor på 3.

For å kunne vurdere trender over tid i utslipp av klimagasser, er det utviklet en forenklet metode for beregning av klimagassutslipp av norske sjømatprodukter ved landing og levering til slakteanlegg, der endringer i metoder og ulik tilgang til data forsøkes redusert til et minimum. For produksjon av laks foreslås de følgende parameterne brukt som basis i beregningene:

- Økonomisk fôrfaktor
- Sammensetningen av fôret med hensyn til viktige fôrtyper/fôrgrupper
- Servicebåt- og brønnbåtaktivitet

For fiskeriene vil trender over tid være tett knyttet til utviklingen av drivstoffeffektiviteten i fiskeriene, siden drivstofforbruk dominerer utslippene fra fiskeri (mer enn 80%). Endringer i drivstoffintensiteten fangst av ulike arter (L drivstoff/kg fangst i levende vekt) kan derfor brukes til å indikere endringer i klimaavtrykket til norske fiskerier over tid. Den forenklede metoden for fiskeri bygger derfor kun på drivstoffeffektivitet i fisket av hver art, som avhenger av drivstoffeffektiviteten av hvert flåtesegment som fisker på den aktuelle arten og dens andel av den totale fangsten.

Klimautslippet til norske sjømatprodukter er presentert relativt til europeiske landbaserte kjøttprodukter, der utslippet til europeisk storfe er satt til 1 (Figur 2). Resultatene viser at svin har 31% av utslippet til storfe, og kylling om lag halvparten av det (16%). Reker er det sjømatproduktet som har det høyeste klimautslippet ved landing, 24% av utslippet til storfe. Norsk oppdrettslaks har et utslipp ved levering til slakteanlegg som er 20% av storfe og både reker og laks ligger mellom kylling og svin. Endring av arealbruk (Land use change – LUC) er ikke inkludert i beregningene i denne sammenligningen da det ikke var mulig å harmonisere metodene for sammenligning mellom sjømatproduktene og produktene fra landbruk. Laks og kylling er de to produktene som i størst grad er avheng av soya som fôringrediens og det er utslippet til disse to som ville ha økt mest dersom direkte endring av arealbruk hadde blitt inkludert.

Når det gjelder tilgang til data til beregning av klimagassutslipp så har lite skjedd siden datainnsamlingen analysen gjennomført i 2009 [1], på tross av at rapporten den gangen ga klare indiksjoner på hvilke data som er sentrale å samle inn for å kunne gjennomføre en robust, datadrevet analyse for klimagassutslippene av norske sjømatprodukter. Det ville forenkle prosessen betydelig, både for den som skal gjennomføre LCA-analyser og for næringen selv, dersom de mest kritiske dataene ble samlet inn på en standardisert måte slik at de i det minste er tilgjengelige på forespørsel, eller ideelt sett gjort offentlig tilgjengelige. Våre anbefalinger basert på denne analysen er:

- Identifisere hvordan man kan endre fra soya fra land som utvider jordbruksarealet og dyrking av soya og i stedet for fase inn soya fra land der dyrkingen ikke forårsaker endringer i arealbruk – eller bytte til alternative fôringredienser.

- Vurdere nøye effekten i hele distribusjonskjeden av å bytte fôringredienser. Endring til ingredienser med lavere utslipp behøver ikke å redusere klimautslippet til produktet dersom for eksempel den økonomiske fôrfaktoren øker.

- Det er et stort behov for å forstå bedre rollen til mikroingredienser for klimautslippet til oppdrettet laks og annen dyreproduksjon.

- Identifisere måter som kan bidra til å forbedre drivstoffeffektiviteten i fiskeriene, enten gjennom utvikling av teknologi eller utvikling av policy. Forstå bedre årsakene til at noen fartøyer oppnår lave utslipp, og lære av disse.

- Overvåke bruken av HFC-kjølemedier i norske fiskerier og identifisere hvordan man redusere bruken ytterligere.

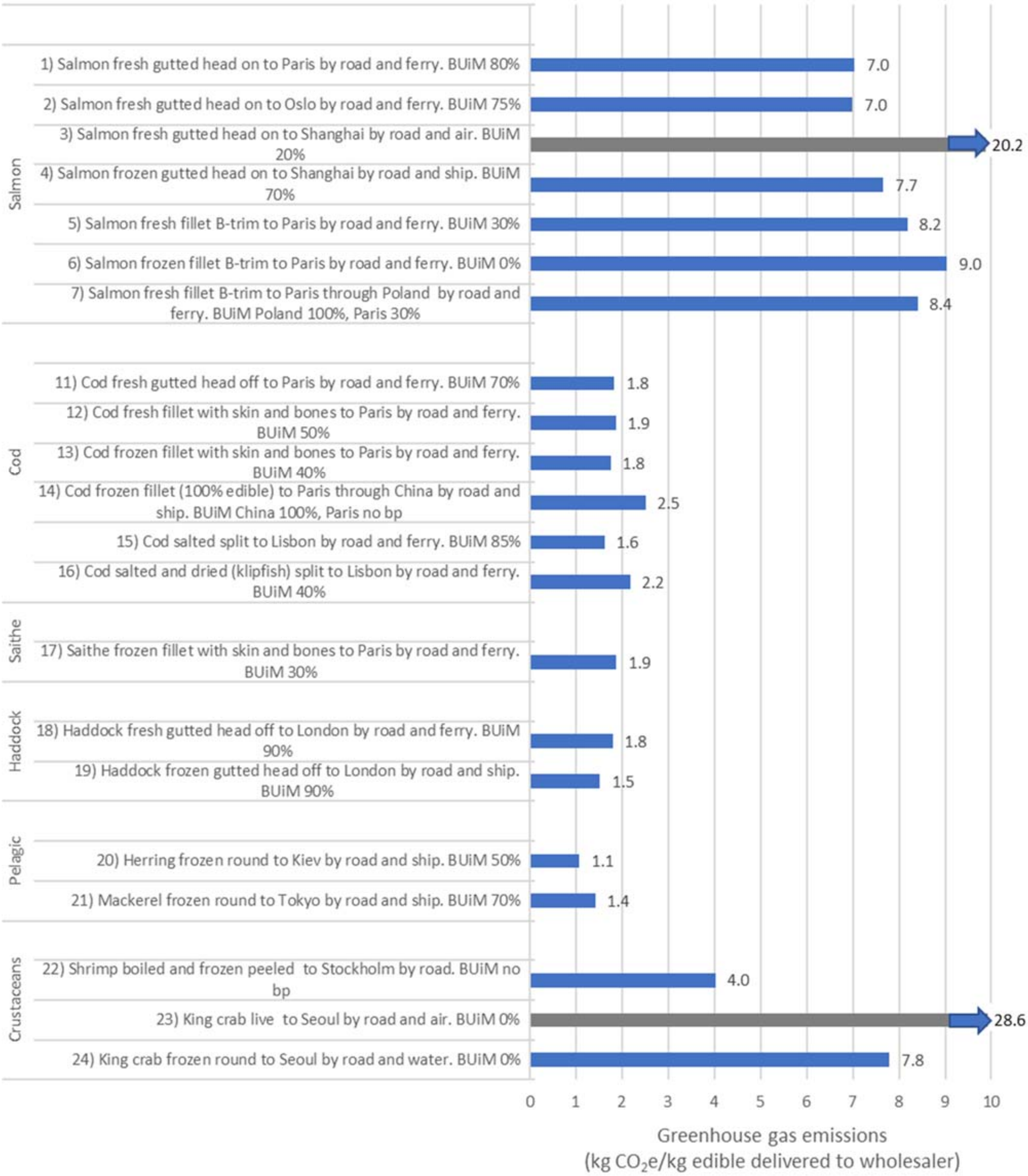
- Identifisere de viktigste data som bør overvåkes, registreres og lagres på en standardisert måte for å kunne følge utviklingen i klimautslippene over tid på en overordnet måte.

- Helt eller delvis fase ut flyfrakt i distribusjonskjeden for ferske norske sjømatprodukter.

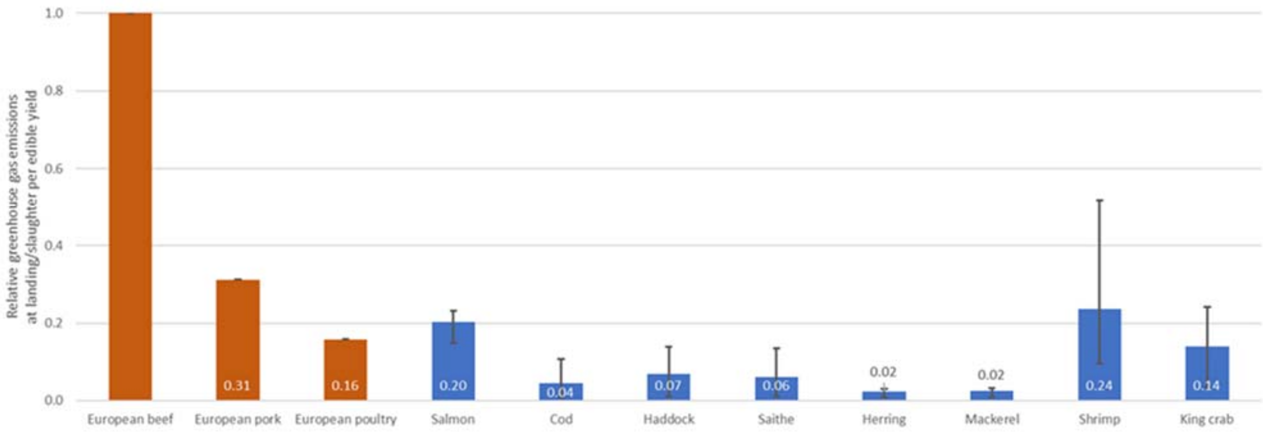
- Forbedre innsamling av data for bruk av biprodukter gjennom produksjons- og distribusjonskjeden.

- Stimulere til prosessering og foredling nært til der produksjonen og fangsten skjer og til å utvikle produkter med lang holdbarhet.

I denne rapporten har målet vært å presentere resultater for gjennomsnittlige norske sjømatprodukter i hver kategori. For produkter produsert ved bruk av forskjellige teknologier, betyr dette at gjennomsnittet er et vektet gjennomsnitt mellom disse teknologiene. For alle produktene vi presenterer resultater for, betyr det at resultatene er et aggregat av gode og dårlige utøvere og teknologier, og resultatene representerer derfor ingen enkeltprodusenter. Følgelig skal heller ingen produsenter bruke resultatene som presenteres i denne rapporten som deres nåværende klimaavtrykk eller klimaavtrykk fra 2017. Resultatene bør heller brukes som en benchmark som norske produsenter kan måle seg mot, og de foreslåtte forbedringstiltakene kan benyttes til å gjennomføre forbedringer.



Figur 1 Klimagassutslipp for alle produkter som er studert (kg CO_2e/kg spisbart produkt til grossist) BUiM = Bruk av biprodukter i markedet.



Figur 2 Klimautslipp av sjømat (blå søyler) ved landing/slakting vs. europeiske landbaserte kjøttprodukter (brune søyler), relativt til europeisk storfe. De svarte søylene for sjømat representerer minimum og maksimumsverdier med gjeldene produksjonspraksis. Tilsvarende estimater for minimum og maksimum, eller variasjon, er ikke tilgjengelig for landbaserte produkter i dataene som er benyttet.

Summary

Greenhouse gas emissions have been quantified for 21 Norwegian seafood products, most of which currently represent important components of Norwegian seafood export with regard to volume and value. The products come from salmon aquaculture and from capture fisheries for cod, saithe, haddock, herring, mackerel, shrimp and king crab. After slaughter and landing, the fish is processed into a variety of fresh, frozen, round, gutted or fillet products, which are transported to their respective markets. The fact that the same methodological approach is used to assess a large number of supply chains, from cradle-to-gate, allows for comparison between products. Results illustrate the effect of aspects, such as species, transport mode and distance and product form, both in isolation and combined. Due to differences in methods used and available data, the results presented in this report is not directly comparable to results presented in a study published in 2009 [1].

In general, products from pelagic fisheries were found to have the lowest greenhouse gas emissions, while salmon and crustacean products had the highest greenhouse gas emissions (Figure 1). Emissions of products from demersal fisheries were found to be in a range between those of pelagic and salmon products. Even though the results presented in this report are not directly comparable to the results in the 2009 report referred to above, it may be concluded that the greenhouse gas emissions of the products from capture fisheries (demersal more than pelagic) have been reduced during the last ten years. One of the main reasons behind this development is the phasing out of refrigerants with a high climate emission potential. The greenhouse gas emissions of salmon products have on the other hand increased, mainly due to including contribution from land use change and micro ingredients in the calculations. Reduced efficiency because of increased mortality and reduced growth due to salmon lice and diseases results in increased feed use and need for treatment with use of wellboats plus production of chemicals and cleaner fish used to treat salmon lice.

Options for reducing the greenhouse gas emissions are identified and reduction potentials are quantified. For salmon production, important improvement options are:

- Improving feed efficiency
- Changing feed composition
- Ensuring full by-product utilization along the entire seafood supply chain
- Minimizing the need for transportation (e.g. avoid unnecessary transport for processing and transport of by-products)
- Finding alternatives to airfreighting of salmon and generally shift to lower greenhouse gas transport modes and product forms
- Increasing energy efficiency and change to renewable energy carriers

Compared to the greenhouse gas emissions for a base case where fresh salmon fillets are exported to Paris by truck and ferry with the standard assumptions, the emissions are reduced by 42 % in a case where improvements in economic feed conversion rate, sourcing of soy, by-product utilization, energy intensity in various steps in the production chain and load of return freight are incorporated.

For capture fisheries, the following options for reducing the greenhouse gas emissions are identified:

- Improving the fuel efficiency of fishing vessels
- Switching to alternative fuels, such as hydrogen and liquified natural gas
- Using low greenhouse gas emission refrigerants and improving fuel efficiency of onboard refrigeration

- Ensuring full by-product utilization along the entire seafood supply chain
- Minimizing the need for transportation (e.g. avoid unnecessary transport for processing and transport of by-products)
- Shift to lower greenhouse gas transport modes and product forms

If all cod was caught by the vessels that today fish at the highest fuel efficiency in each fleet segment, with the same contribution of each fleet segment, the carbon footprint of the product supply chain of fresh cod fillets delivered to Paris could be reduced by half. By-product utilization is already relatively high, but full utilization would, in the case of haddock delivered to London further reduce supply chain emissions by 10-15%. The difference in greenhouse gas emissions of the product between full and no utilization of by-products is a factor of 3.

In order to be able to evaluate trends over time in greenhouse gas emissions, minimizing the influence of changes in methods and available data, a method for a simplified estimation of greenhouse gas emissions of Norwegian seafood products at landing and at farm gate is developed. For salmon aquaculture the following parameters are used as the basis:

- Economic feed factor (eFCR)
- Composition of the feed in terms of major feed types
- Service vessel and well boat activity

For capture fisheries, temporal trends in greenhouse gas emissions are tightly linked to the development of the fuel efficiency of the fisheries, since fuel use in fisheries dominates fisheries emissions (more than 80%). Changes in fuel use intensity of catching species (L fuel/kg liveweight catch) can therefore indicate changes in climate impact of Norwegian fisheries over time. The simplified method, therefore, only builds on the fuel efficiency in fishing each species, which depends on the fuel efficiency of each fleet fishing that species and its share in total landings.

Relative results of the comparison of Norwegian seafood products with European terrestrial animal-source foods are reported relative to the emissions of beef (Figure 2). Results show that pork has around 31% of the emissions of beef and poultry about half of that (16% of beef). Shrimp is the seafood product with the highest greenhouse gas emissions at landing, 24% of that of beef. Farmed Norwegian salmon has an emission intensity that is 20% of that of beef and both shrimp and salmon fall in between poultry and pork. It is important to note that although direct Land Use Change was included in the assessment of farmed salmon, for the sake of the comparison with terrestrial animal products it was excluded, as it was not possible to harmonize the methods for its assessment between seafood and livestock. Salmon and poultry are the species that to the greatest extent depend on soy as feed input and whose results would increase most if direct Land Use Change had been included.

In terms of data availability, little has changed since the data collection undertaken for the Winther et al. report 2009 [1], despite that that work gave clear indications on what type of data is central to collect in order to undertake a robust, data-driven analysis of the carbon footprint of seafood products in Norway. It would simplify the process considerably both for the LCA practitioner and the industry if the most critical data were collected in a standardised way so that they at least are available upon request, or ideally are made publicly available. Other recommendations based on this work:

- Identify means to shift away from soy originating in countries with expanding agriculture and soy farming, instead favouring soybeans farmed in countries where it does not cause land use change - or shift to alternative feed ingredients.

- Carefully evaluate the full supply chain effects of replacing feed ingredients. Shifting to lower input ingredients may not lower the carbon footprint of the product if e.g. the feed conversion ratio increases, or fish growth is reduced.

- Better understanding on the role of micro ingredients for the GHG of salmon and other animal production systems is urgently needed.

- Identify means to improve the fuel efficiency of fisheries through technology or policy. Better understand the reasons for vessels being best performers and learning from their behaviour.

- Monitor the use of HFC refrigerants in Norwegian fisheries and identify means for further reduction

- Per sector identify the most central data that need to be monitored and stored in a standardised way in order to be able to monitor performance from year to year in a simplified way

- Partially or fully shift supply chains away from airfreight

- Improve data collection on by-product utilization and supply chain product losses.

- Stimulate processing close to production and product forms with a long shelf-life

In this report, the aim was to present results for average Norwegian seafood products in each category. For products produced using various technologies, this means the average is a weighted average between these technologies. For all products, it means that results are an aggregate of good and poor performers and the results represent no one producer. Consequently, no producer should therefore use the results presented in this report as their current or 2017 carbon footprint. These should instead be used as benchmarks to rank Norwegian producers against, which is shown by the various improvement options demonstrated.

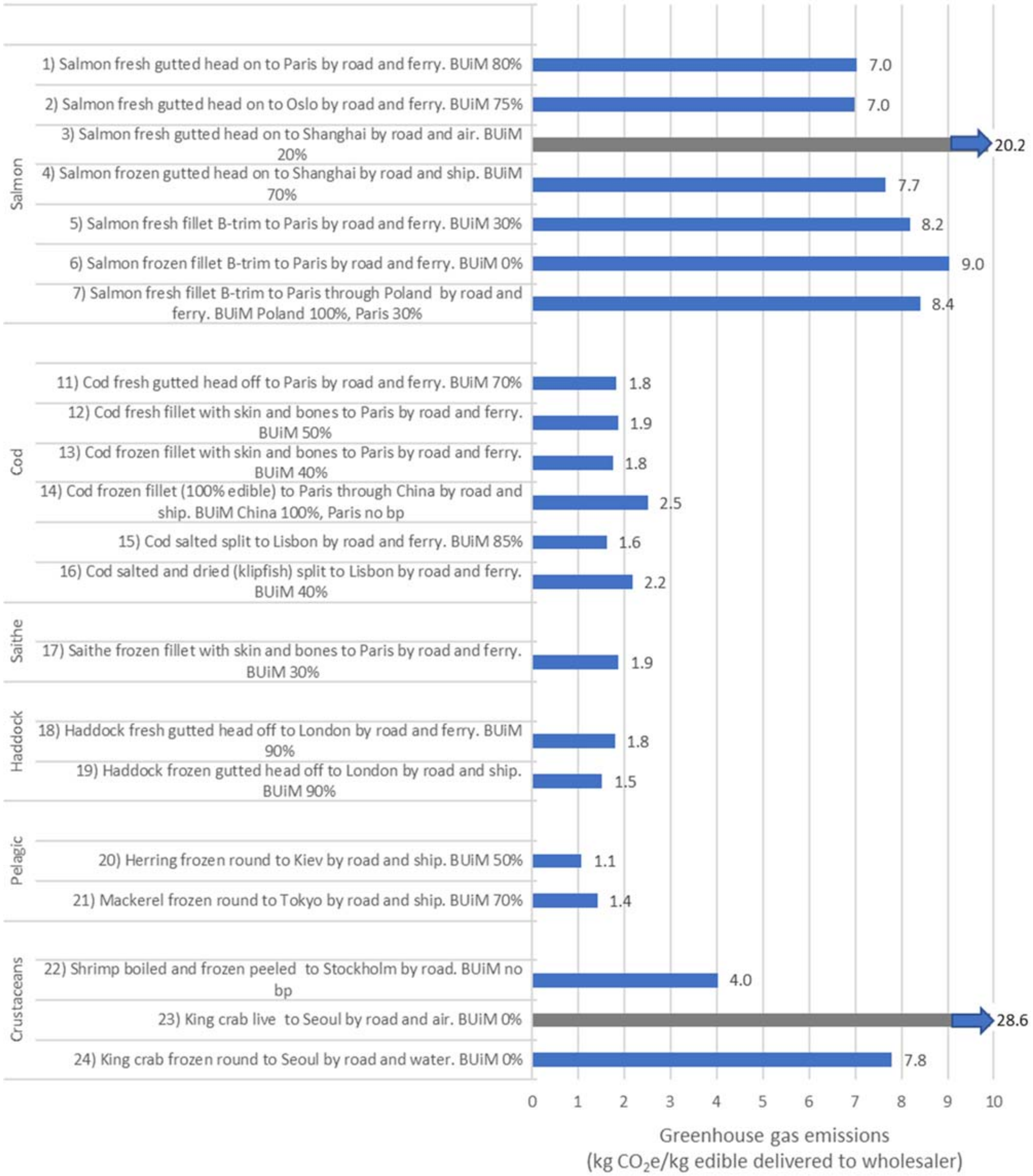


Figure 1 Greenhouse gas emissions of all studied products (kg CO_2e/kg edible product delivered to wholesaler) BUiM = By-product use in market.

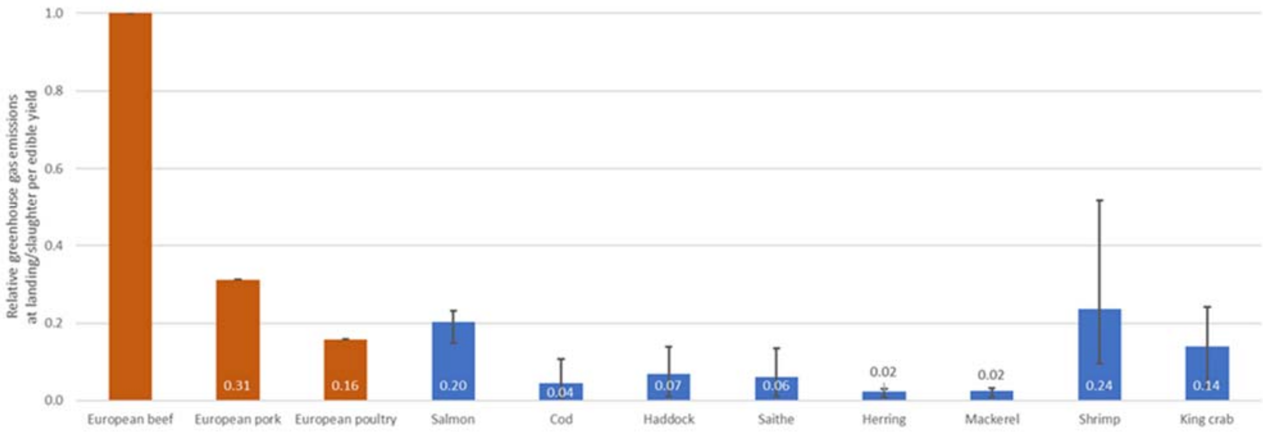


Figure 2 Relative greenhouse gas emissions of seafood (blue bars) at landing/slaughter vs. European terrestrial animal-source foods (brown bars), with average values in relation to European beef. Error bars for seafood represent min and max values under current production practise. Similar estimates for min/max or variability are not available for the terrestrial animal foods in the data used.

1 Introduction

1.1 Background

Climate change has become more and more evident over the last decade and is thoroughly documented in several reports from The Intergovernmental Panel on Climate Change (IPCC) [2,3]. Strong measures are needed to keep global warming below 1.5 degrees Celsius and the thorough documentation available makes it even more important that all industries contribute to reducing greenhouse gas (GHG) emissions. Recently, the ocean and ocean-based activities have been identified to have a major potential to contribute to solutions to climate change in a report from the High Level Panel for a Sustainable Ocean Economy [4]. In that report, fisheries, aquaculture and shifting towards more ocean-based diets is one of the five recommended actions for reducing carbon emissions, together holding the potential to reduce GHG emissions by 20% of what is required to reach climate goals (the other ones being renewable ocean-based energy, marine transportation, marine ecosystems and carbon storage in the seabed).

When it comes to the greenhouse gas emissions of the Norwegian seafood industry and Norwegian seafood products, an analysis of the carbon footprint of 22 Norwegian seafood products was carried out in 2009 [1]. A selection of these products was also compared with European terrestrial animal products. The conclusions from this work were that Norwegian seafood products were competitive from a carbon footprint and energy use perspective, both compared to other seafood products and compared to terrestrial animal products. Since then, several analyses of parts of the Norwegian seafood industry have been carried out. For fisheries, energy consumption, energy efficiency, refrigerant use and the resulting carbon footprint of the Norwegian fishing fleet and Norwegian fisheries have been studied [5,6]. For aquaculture, the focus has been on the feed, which is the single most important input contributing to the carbon footprint of salmon and salmon products [1,7,8]. Also, in other countries, environmental assessment of fisheries and aquaculture systems and the seafood products they produce is receiving increased attention; the number of seafood life cycle assessment (LCA) case studies performed has increased rapidly, and these are used in studies to compare across different foods [9] or aggregated to evaluate the sustainability of different diets [10]. Generally, seafood products come out favorably from this type of comparison, but there is a large span within seafood and overlap with other food groups. The large variability stems from the diversity in species, origins and production technologies. The growing interest in and volume of work in this field has also resulted in a need for methodological guidance and standardization to increase comparability across studies and products, resulting in a number of seafood specific standards (PAS 2050-2 [11] , PEFCR feed for food producing animals [12]) and data collection guidelines [13].

Since the analysis carried out in 2009, changes have taken place in both the Norwegian fisheries and in the Norwegian aquaculture industry, which may have an impact on the GHG emissions of the industry. The most important fish stocks for the Norwegian fishing fleet have developed differently. The stocks and catches of cod and haddock have had a positive trend since 2007, while the stock and catches of saithe has had a somewhat declining trend [14,15] . Looking at the pelagic species, the herring stock and catches are smaller in 2017 compared to 2007, while the mackerel stock and catches have increased. The Norwegian fishing fleet has in parallel undergone a renewal and modernization. The number of active fishing vessels has decreased somewhat since 2007 and older boats are replaced by modern vessels. In addition, quotas per vessel are larger in 2017 than in 2007 [16]. The use of refrigerants in refrigeration and freezer systems on board previously contributed significantly to the climate footprint of the fishing fleet. Now, over the last years, there has been a change to more climate-friendly refrigerants, due to regulations[17]. Now, these regulations also target refrigerants with high global warming potential.

Production of salmon and rainbow trout dominate the Norwegian aquaculture industry. The sales of these two species were 1,303,352 ton in 2017, up from 821,799 ton in 2007[18]. Since 2012, sales of these two species have been relatively stable around 1.3 million ton. Over the past ten years, production has in general shifted to operating in larger cages at sites approved for larger production, with more advanced equipment, so that larger quantities of fish can be farmed per site[1]. In principle, all sites are equipped with a barge for storing feed and contain an operating center for the site. In addition, numerous operating boats serving the sites have been introduced. The challenges of salmon lice have led to the need for a great deal of treatment of the fish to keep the salmon lice numbers low. The non-medical treatment is often carried out in well boats or in boats specialized for lice treatment. As some methods for treatment are stressful for the fish, the increased treatment has led to an elevated mortality also of large fish [19]. In parallel, there has been electrification of many feed barges and vessels used for service and maintenance, stimulated by grants from the state agency Enova. The fish feed is the single factor that contributes most to the carbon footprint of farmed fish [1,7]. In the last ten years, there has been a shift in the fish diets towards a more crop-based diet and currently salmon feed typically consists of about 70% of crop-based raw materials [20].

Fresh Norwegian fish has become a success in many markets, including Asia and the US, especially as regards salmon used in sushi and sashimi. This has led to a large increase in airfreight of fresh seafood from Norway in recent years [21].

Since the last major summary analysis of the climate footprint of Norwegian seafood products was published in 2009 based on data for 2007 [1], and it becomes more important for the seafood companies to document their carbon footprint, the industry has expressed interest in having a new and updated analysis undertaken, which is the background of the work presented in the present report.

1.2 Scope and organization of the project

According to the project proposal and description (exact wording), the original aim of the work was to:

"*Carry out a comparative analysis of selected products from Norwegian fisheries and aquaculture and European agriculture to obtain figures for energy consumption and GHG emissions. The results were to be comparable with figures from the 2009 analysis. The analysis should, by using comparable methods based on national and international standards, provide a basis for seeing how selected seafood products perform compared to selected agricultural products and how different seafood products perform compared to each other. The analysis should also be able to show where in the value chain energy consumption and GHG emissions are largest and where the largest opportunities/potentials for improvement are found. Proposals for measures and potential effects of the measures shall be presented*"

The aim and objectives of the work presented in this report are further specified in chapter 2.

FHF – Norwegian Seafood Research Fund has financed the present analysis. The work was carried out in a collaboration between SINTEF Ocean AS, Asplan-Viak AS and RISE Research Institutes of Sweden during the period December 2018 to February 2020. Representatives from the CICERO Centre for International Climate Research, NIBIO, Bellona and Future in Our Hands have served as a Project advisory group. FHF has participated in the meetings with the Project advisory group. Professor Peter Tyedmers, Dalhousie University, Canada, has served as the project external reviewer.

[1] For a description of the Norwegian salmon aquaculture industry, see e.g. White paper to the Norwegian Parliament Meld. St. 16 (2014-2015).

2 Overview of methods

In this section, overall methodological choices are explained, while more detailed choices and assumptions related to individual supply chains are explained in chapter 3.

Please note that every environmental assessment is a result of methodological choices and the quality of the available data. Responsible use and understanding of the results presented in this report is dependent on an understanding of the importance of these aspects and a reference to[2] where they are explained (in the present report). This study is done with the goal of quantifying impacts of average Norwegian seafood supply chains to be compared with each other, over time, and with terrestrial animal foods, which leads to certain method choices and assumptions that would not have been taken if a specific supply chain from one producer had been modelled. No producer can therefore say that the results are valid for their specific product and results presented are more to be seen as a benchmark against which to evaluate own performance. In particular, the results of the 2009 report cannot be directly compared with the ones presented here and the comparison over time is instead done using the approach presented here.

2.1 Goal and scope

The main goal of this work is to quantify GHG emissions of the most important Norwegian seafood export products from both fisheries and aquaculture in 2017, delivered to their typical markets (Table 2-1). Additional goals are to 1) compare GHG emissions over time and to 2) develop a simplified method suitable for GHG monitoring over time and 3) to identify improvement options and quantify their potential. The seafood products studies are also 4) to be put in perspective of alternative animal-source foods from agriculture in terms of GHG emissions.

Table 2-1 Norwegian seafood products studied defined by central parameters in the greenhouse gas emission assessment of seafood: species, product form, production method, transport mode and market. The functional unit is 1 kg of edible seafood at the wholesaler. Three products were later taken out from this original list due to lack of data, see footnotes.

No.	Product	Market/Destination	Transport mode	Production method
1	Salmon, fresh head-on gutted	Paris	Truck	Aquaculture (net-pen)
2	Salmon, fresh head-on gutted	Oslo	Truck	Aquaculture (net-pen)
3	Salmon, fresh head-on gutted	Shanghai	Air	Aquaculture (net-pen)
4	Salmon, frozen head-on gutted	Shanghai	Rail/Ship	Aquaculture (net-pen)
5	Salmon, fresh fillet (B trim)	Paris	Truck	Aquaculture (net-pen)
6	Salmon, frozen fillet (B trim)	Paris	Truck	Aquaculture (net-pen)
7	Salmon, fresh fillet (B trim)	Paris via Poland[1] (for processing)	Truck	Aquaculture (net-pen)

[2] Preferred reference: Winther et al. 2020 Greenhouse gas emissions of Norwegian seafood products in 2017 SINTEF Ocean report 2019:01505

8	Blue mussels, fresh[2]	Paris	Truck	Aquaculture (longline)
9	Blue mussels, fresh[2]	Oslo	Truck	Aquaculture (longline)
10	Trout, fresh head-on gutted[2]	Paris	Truck	Aquaculture (net-pen)
11	Cod, fresh head-off gutted	Paris	Truck	Capture fisheries (all gears)
12	Cod, fresh fillet with skin and bones	Paris	Truck	Capture fisheries (all gears)
13	Cod, frozen fillet with skin and bones	Paris	Truck	Capture fisheries (all gears)
14	Cod, frozen fillet all edible	Paris via China (for processing)	Ship	Capture fisheries (all gears)
15	Cod, salted head-off gutted, split	Lisbon	Truck	Capture fisheries (all gears)
16	Cod, salted and dried head-off gutted, split	Lisbon	Truck	Capture fisheries (all gears)
17	Saithe, frozen fillet with skin and bones	Paris	Truck	Capture fisheries (all gears)
18	Haddock, fresh head-off gutted	London	Truck	Capture fisheries (all gears)
19	Haddock, frozen head-off gutted	London	Truck	Capture fisheries (all gears)
20	Herring, round frozen	Kiev	Ship + truck	Capture fisheries (all gears)
21	Mackerel, round frozen	Tokyo	Ship	Capture fisheries (all gears)
22	Shrimp, peeled frozen[1]	Stockholm	Truck	Capture fisheries (demersal trawl)
23	King crab, live[1]	Seoul	Air	Capture fisheries (trap)
24	King crab, round frozen[1]	Seoul	Ship	Capture fisheries (trap)

[1]not in previous assessment
[2]product had to be excluded after data collection was finalized due to lack of data of sufficient quality

The primary target group of this report is the seafood sector, where it is intended to increase knowledge and inspire improvement measures.

The products (defined as a combination of species, product form, production technology, transport mode and market destination) were defined in collaboration between researchers and industry experts, based on volume and value of Norwegian seafood export. Table A-9-1 presents a more detailed overview of the different products. Most products from the 2009 study [1] remained and some were added (Table 2-1), most notably three crustacean products produced from northern shrimp (*Pandalus borealis*) and red king crab (*Paralithodes camtschaticus*). The main method choices from the 2009 study also remained, because these were still considered to be most appropriate.

One of the goals of this work was to analyze whether performance has improved over time for the products included in both assessments. Minor differences in methodology and data collection[3] makes the results in the two reports not being directly comparable, as already mentioned. To overcome this and be able to compare between the assessment years and also monitor performance over time more generally, a simplified method for GHG assessment for seafood products is developed, based on the full 2017 results. The method developed and implemented here is a novel, simplified basis for comparing major drivers of GHG emissions and is defined based on the principle that it should cover the main sources of emissions, in particular those that vary much between years. For the comparison over time, only the production phase is considered, i.e. the products are followed to the dock (landing/harvest). For products from aquaculture, feed composition and FCR (Feed Conversion Ratio) and the level of "other costs" in relation to 2017 is used to estimate the temporal trend. For capture fisheries, the development of fuel use using the approach used for 2017 is used as the basis for temporal trends. Details are explained in chapter 6. These results will not give a full picture of the carbon footprint of all the products but give a good indication of the temporal trends of the performance of the Norwegian fisheries and aquaculture sector, which can be followed up in coming years.

2.2 Functional unit

The functional unit is one kg of edible seafood delivered to a wholesaler. Transport packaging is included, while product packaging is excluded to ensure comparability across products since some, but not all, are exported for further processing. The product form is hence the product form as delivered to a wholesaler or processor and in many cases includes non-edible parts. Results are consistently presented per kg edible product, using conversion factors for edible yield for each product.

2.3 System boundaries

Amongst aquaculture-based production systems, the boundaries for activities for which foreground data were collected started at the production (fishing, farming and manufacture) of the feed ingredients and other supply materials used on farms. Fisheries-based supply chains start with the production of supply materials for the fishery like fuel, gear, vessel and refrigerants. All products are assessed to the wholesaler gate. Here wholesaler gate can be both retail to final consumer and industry where the product is an input to further processing or wholesaler. The assessment includes infrastructure, e.g. construction of fish farm equipment and fishing vessel and gear.

2.4 Allocation

Throughout the analyses, where an activity gives rise to two or more by-products that are subsequently utilized somewhere else in the economy, allocation of inputs and impacts up to the point of by-product generation is done in proportion to the mass of the by-products generated. Examples of such situations are the joint landing of several species in fisheries, processing where fish or crustaceans are filleted or peeled and production of feed ingredients, e.g. processing of rape seed into rape seed oil and meal. This basis of

[3] Changes between the 2009 report and the present one: IPCC 2013 indicators were used, European electricity production mix was used instead of Norwegian for electricity used in Norway, fuel use in fishing was estimated in a different way, edible yield data was different, cod was exported at headed and gutted not only to China, estimations on by-product use abroad were included in the calculations, direct Land Use Change GHG emissions, production of micro-ingredients, fishing gear and vessel and aquaculture service/maintenance vessel activity was included (but not in 2009).

allocation is widely used in seafood and food systems LCA research, is recommended by standards over other approaches (e.g. economic value) and mirrors the allocation practice applied in the 2009 report analyzing GHG emissions of Norwegian seafood products in 2007 [1]. When using this strategy, whether or not by-products are further utilized becomes very important. It is important to recognize that when they are, this effectively lowers the impacts of the main product and all by-products that are further utilized are assigned the same impacts *per kg*. This means, for example, that when the product is exported as round or head-on gutted, results are converted to edible/utilized using a yield factor and information on the extent of utilization of by-products in the market - and a higher by-product utilization rate results in a lower footprint of the product. Lack of robust data to support the inclusion of this aspect is an issue and needs more consideration.

The rationale for choosing mass over economic value as the basis for allocation is that, despite lower economic value per ton of biomass associated with some by-products, profit margins can be higher for the supply chain utilizing the by-products than the main product, which makes it difficult to say which one is the main product actually driving the production, a common motivation of value-based allocation. An advantage of biophysical allocation methods is also that they are stable over time and since temporal comparison is one of the goals of this study, it seems even more justified to choose a method for by-product allocation that is not influenced by relative economic values. Normally, the importance of this choice would have been analyzed in a sensitivity analysis, as it can have a major influence on results. However, it was decided that for seafood, including the systems analyzed here, it has already been shown how alternative allocation methods change the outcome (including in the 2009 report) and as collecting data to do an economic allocation scenario would have required a non-trivial effort, it was decided to instead this effort on evaluating the importance of various improvement options and focusing the sensitivity analyses on that.

In the ISO standard for LCA [22], the EU's Product Environmental Footprint (PEF) method [23], the PAS 2050-2 standard for greenhouse gas emission accounting of seafood [24] and the GHG protocol [25], physical allocation like mass-allocation is ranked above economic allocation in their allocation decision hierarchy – where the prioritized recommendation is to avoid allocation altogether, thus mass-based allocation is only used where needed. Other standards give different recommendations, the PAS 2050:2011[26], e.g. recommends economic allocation when allocation cannot be avoided or system expansion used. Even though the PEF method rank mass allocation above economic, it is worth noting that the PEFCR Feed for animal production, recommends economic allocation [12].

2.5 Data collection

In terms of foreground data collection, the general strategy has been to work "top-down", i.e. to the extent possible using national production data for the 10 species originally included. Either the dominant production technology was selected for a species (e.g. net-pen farming of salmon) or production technologies were weighted in proportion to their contribution to the annual production volume of a species (e.g. fleet segments fishing for cod). This means that all salmon products build on a common process for average 2017 Norwegian salmon farming, and all cod products build on an average 2017 Norwegian cod fishery. In reality, the fisheries deliver their catches to different supply chains, or at least in different proportions, but this type of data was impossible to obtain. This is one of the reasons why no one producer can say that the results apply to their specific supply chain and product.

When a "top-down" approach could not be applied e.g. because of a lack of national statistics or other source of aggregate production data, data from individual companies was used to fill these gaps. A triangulation approach was then used, where interviews with industry experts and companies together with literature was used to validate any assumptions or data. Data collection focused on 2017 data when that was available, otherwise data for the most recent year available was used. In a few cases where data for several years was available and highly variable between years, an average between years was used.

2.6 Impact assessment, modelling and background data

For impact assessment of GHG emissions, the 2013 version of the IPCC impact indicators was used [27]. The model was built in the LCA software SimaPro Developer MultiUser version 9.0.0.48 using background data drawn from Agri-footprint [28] (mass allocation) for feed input production and ecoinvent v 3.5 [29] (cut off by classification) for transports, energy production, fuels, materials, chemicals and infrastructure and from the database Network for Transport Measures (NTM) [30] for airfreight and ferry transports, as these were found more suitable than data found in ecoinvent. Agri-footprint, ecoinvent and NTM are three commercial Life Cycle Inventory databases, the former two were accessed through SimaPro licenses and NTM under a license to RISE Research Institutes of Sweden. Land use change (LUC) is modelled as in Agri-footprint using the Blonk Consultants LUC tool [31], also under a license to RISE.

2.7 Greenhouse gas emissions from Land Use Change

Land use change influences the carbon flux between land and atmosphere. For some changes the flux of carbon to the atmosphere can increase and/or the uptake of carbon can be reduced, causing climate change [32]. The Intergovernmental Panel on Climate Change (IPCC) special report on climate change and land [3] states that:

- One quarter to one third of land's potential net primary production is used for food, feed, fiber, timber and energy. About a quarter of the Earth's ice-free land area is subject to human-induced degradation.
- Soil erosion from agricultural fields is estimated to be currently 10 to more than 100 times higher than the soil formation rate. Climate change exacerbates land degradation, particularly in low-lying coastal areas, river deltas, drylands and in permafrost areas.
- Agriculture, Forestry and Other Land Use (AFOLU) activities accounted for 23% of total net anthropogenic emissions of GHGs. If emissions associated with pre- and post-production activities in the global food system are included, the emissions are estimated to be 21-37% of total net anthropogenic GHG emissions.

Several LCA and GHG standards, e.g. the EU's Product Environmental Footprint (PEF) method [23] require the accounting of direct[4] Land Use Change (dLUC) in GHG assessments including agricultural products. The GHG Protocol, one of the recommended standards for reporting to the Carbon Disclosure Project (CDP) [33], that most of the big Norwegian seafood companies report to, also require that land use climate impact is reported in scope 3 reporting[34,35]

In this work, dLUC is included for the cultivation of feed ingredients (for salmon feed) using the Direct Land Use Change Assessment Tool of Blonk Consultants [31]. Very roughly the tool uses data on expansion of agricultural land in each country and when an expansion has taken place during the past 20 years, a timeframe defined by IPCC, and allocates the land use change proportionally to the crops whose production has increased most. This means that in every country where expansion of agricultural land has taken place over the past 20 years, there will be dLUC GHG emissions, and this includes several European countries. The tool differentiates between different types of former land use and in cases where either the country of

[4] The more indirect Land Use Change (iLUC), caused by the indirect displacement of agriculture of one crop into *new* agricultural land by the expansion of another crop on *existing* agricultural land is even more difficult to quantify than dLUC in a robust way and is therefore not required.

production or the former land use is unknown, the tool can produce a more general weighted average value of dLUC.caused GHG emissions for a crop. Agricultural production data from the Food and Agriculture Organization of the United Nations (FAO) statistics combined with data on relative crop land expansions based on FAOSTAT is used [36]. IPCC calculation rules, following the PAS 2050:2011 methodology and the option "calculation of an estimate of the GHG emissions from land use change for a crop grown in a given country if previous land use is not known" [37,38] were used. This estimate is based on several reference scenarios for previous land use over the past 20 years (land use change before than that is not accounted for). The method is presented in detail in the report "Direct Land Use Change Assessment Tool - Updated description version 2018" [31]. The methods used by the Agri-footprint database seems to be fully in accordance with the rules of the Product Environmental Category Rules (PEFCR) for feed for food producing animals [12] as this also requires the inclusion of carbon uptakes and emissions originating from carbon stock changes caused by land use change.

3 Data inventory methodology and results

3.1 Fisheries

Total Norwegian landings in 2017 were 2,423,321 liveweight ton [39]. Although all species are not landed as liveweight, the volume of species landed in gutted or otherwise processed form is converted to liveweight equivalents in these statistics.

3.1.1 Fuel use in fishing

This study covers seven species from capture fisheries, namely cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), saithe (*Pollachius virens*), herring (*Clupea harnegus*), mackerel (*Scomber scombrus*), shrimp and king crab. The operation of fishing vessels often represents the largest contribution to fuel consumption and GHG emissions in the value chain of seafood from capture fisheries, except when airborne transportation is involved [40–42]. Therefore, the data used to estimate fuel use in fishing is critical in estimating the GHG emissions of a product from capture fisheries.

This section describes in detail the data sources and methods used to quantify the fuel use intensity (i.e. L fuel/kg liveweight fish) of the Norwegian fisheries included. Norwegian fisheries are separated into various fleet segments (see section 3.1.1.2), and the fuel use intensity is first calculated per fleet segment in 2007 and 2017 using data sources and methods specified in the following sections. Then, fuel use intensity for catching each species is estimated using the share of the fleet segments in landing each species in 2007 and 2017.

In Norway, the fleet segments are mainly distinguished by the fishing areas (coastal versus ocean-going), fishing gears (e.g. purse seiners and trawlers) and main type of fishery and target species (demersal versus pelagic). However, it is important to note that in addition to distance to fishing grounds, fishing gear and target species, there are many other factors, such as vessel size, fishermen's behaviour, fish stock biomass, quota allocation, fuel price and fuel and emission taxes that affect the fuel consumption and emissions of fishing vessels [43] . Readers are urged to keep this point in mind when interpreting or using the results.

3.1.1.1 Data Sources

The Norwegian Directorate of Fisheries provided data on a subset of Norwegian fishing vessels from 2007 to 2017 as requested for use in this study [44]. The data includes fleet segment, fuel consumption, fuel type, catch and gears of individual vessels among other things. It is based on annual profitability surveys of Norwegian fisheries, which survey a sample representing specific fishing vessels in each year (population hereafter). Before 2009, the population included the so-called year-round operating fishing vessels longer than 8 meters. To be considered year-round operating, a vessel had to land fish during at least 7 months a year, with a certain minimum catch income and have an owner who was not retired or disabled. Since 2009, there is no longer a limit on the vessel length and months of operation to be included in the population. The income threshold to be included in the population remains and depends on vessel size and fish price in the year of interest. In 2007, the defined income thresholds for vessels below 10 meters, 10–12.9 meters, 13–14.9 meters and above 15 meters were 310,400, 558,800, 682,800 and 869,200 Norwegian kroner (NOK), respectively. In 2017, the defined income thresholds for vessels below 10 meters, 10–10.9 meters, 11–14.9 meters and above 15 meters were 514,000, 855,000, 1,287,000 and 2,572,000 NOK, respectively. Therefore, different criteria were imposed for including vessels in the population and grouping them in 2007 and 2017, and the studied populations were smaller than the whole Norwegian fishing fleet (Table 3-1).

As mentioned, the Norwegian Directorate of Fisheries surveys only a subset of vessels in the population (sample hereafter; Table 3-1). The sampling procedure has three steps: first, vessels are grouped based on their operation and length. Then, the income of each group relative to the total income determines the number of vessels to be drawn from each group; therefore, more samples are drawn from groups whose landings result in higher income. Finally, the samples are drawn using simple random sampling without replacement [45]. Not all sample vessels are contacted to participate in the survey (e.g. due to change of ownership) and not all the contacted vessels are included in the analysis (e.g. some shipowners did not reply to the survey). As a result, the final number of vessels considered in the survey is lower than the sample [45,46] (respondents in Table 3-1).

As mentioned earlier, the Norwegian Directorate of Fisheries made several changes in 2009 that affected population of profitability surveys. In addition, the Norwegian Directorate of Fisheries reduced the sample size in 2009 onwards (Table 3-1). Consequently, the values (e.g. annual fuel consumption and catch) reported by individual respondents has a larger effect on the results (e.g. fuel use intensity) in 2017 than 2007. This is especially relevant for results at the vessel group level, for groups with small samples. For vessel groups with larger samples or for overall evaluations on all respondents, the reduction in the sample size has less significance. The reduction in the sample size makes the profitability surveys more vulnerable to dropouts and, therefore, it is very important that the selected vessels respond the surveys [45]. Readers are urged to note that a smaller and higher income earning subset of the Norwegian fishing fleet has formed the basis for estimating the fuel use intensity of the fleet segments and, consequently, species in 2017 compared to 2007.

Table 3-1 The size of the Norwegian fishing fleet and population and sample size of the annual profitability surveys of the Norwegian Directorate of Fisheries (based on [45][46]).

Year	Norwegian fishing vessels	Active vessels [a]	Population of profitability surveys	Sample size in profitability surveys	Respondents to profitability surveys (response rate)
2007	7,039	5,744	1,709	741	624 (84%)
2017	6,134	5,397	2,060	390	324 (83%)

[a] Vessels registered with a catch income in the Norwegian Directorate of Fisheries' Register of Landings

Using data provided by the Norwegian Directorate of Fisheries, fuel use intensity of individual vessels and, consequently, fuel use intensity of fleet segments are estimated. Although all species are not landed as liveweight, the volume of species landed in gutted or otherwise processed form is converted to liveweight equivalents in these statistics, and subsequently used for estimating fuel use intensity at landing per liveweight of each species.

In order to estimate the fuel use intensity for catching specific fish species, the outcomes are linked to catch of survey populations in 2007 and 2017 [45,46]. It should be noted that the data used for estimating the fuel use intensity of vessels and fleet segments include fuel consumption and catch of a subset of survey populations (e.g. maximum 324 vessels[5] in 2017), whereas the catch data in the so-called G tables of profitability surveys [45,46] covers the catch of the whole survey populations (e.g. 2,060 vessels in 2017).

3.1.1.2 Fleet segments

In the datasets provided by the Norwegian Directorate of Fisheries [44], vessels are grouped in nine fleet segments. The data covers 2007–2017. However, for two fleet segments, data is available in shorter periods as shown below in brackets:

1. Coastal conventional vessels
2. Ocean-going conventional vessels

[5] Some vessels will not be included in the analysis e.g. because they did not provide data on fuel consumption.

3. Coastal seiners
4. Purse seiners
5. Pelagic trawlers
6. Ocean-going crab vessels (2015–2017)
7. Coastal shrimp trawlers
8. Ocean-going shrimp trawlers (2007–2008, thereafter merged with cod trawlers)
9. Cod trawlers

Coastal conventional vessels mainly catch cod or similar species (e.g. haddock) using conventional gears, such as gillnet. These vessels can also catch pelagic species (e.g. herring) with seine gear, but this is not their main activity. Conversely, coastal seiners mainly fish pelagic species, such as herring with seine gear. However, they can also catch cod or similar species using conventional gears, but this is not their main activity. Since many Norwegian coastal vessels fish both cod and pelagic species, some vessels may be part of coastal conventional vessels one year and part of coastal seiners the other year. This depends on the most important fishery for the vessel in each year. In other words, one could find the same vessel in the dataset for conventional coastal vessels and coastal seiners, but not in the same year. Ocean-going conventional vessels are mainly auto liners that catch cod and similar species (e.g. haddock and ling (*Molva molva*)). Purse seiners mainly use purse seine gear to catch herring. These vessels may use trawl and conventional gears in addition to seine. For instance, some purse seiners have the license to use pelagic trawl to fish blue whiting (*Micromesistius poutassou)*. Pelagic trawlers may use different gears, such as pelagic trawl, bottom trawl and purse seine. They land various species, such as blue whiting, herring and sandeels (*Ammodytes sp.*). Ocean-going crab vessels use traps/pots and trawl and mainly catch snow crab (*Chionoecetes opilio*). Coastal and ocean-going shrimp trawlers mainly use shrimp trawl and bottom trawl to land shrimp. As mentioned, since 2009, ocean-going shrimp trawlers are merged with cod trawlers. Therefore, the cod trawler group consists of vessels that use bottom trawl to catch cod, shrimp and similar species.

In addition to the general methodology described above, some additional steps were required to model the fuel use intensity of fishing the two crustacean species. As in other fisheries, crustacean species are one out of several species targeted by the vessels during a year. Both shrimp and king crab are fished all year round, but in specific fishing trips, whose fuel use intensity can be markedly different from other trips due to a different fishing method and/or lower catch per unit of effort in crustacean fisheries. As a result, it is difficult to use annual fuel consumption data of vessels engaged in these highly different fisheries (in terms of fuel use per kg landed) to represent either of them well [43]. The segment ocean-going crab vessels mainly catches snow crab, which is not a species of interest in this study. Therefore, this fleet was not used to model fishing of king crab. Conventional vessels do catch king crab, but crab represents a very small proportion of catches and the fuel use intensity of these vessels can therefore not be used to represent king crab fishing. Instead, king crab license holders identified through the Norwegian Directorate of Fisheries (n=30) were contacted one by one and asked about their annual fishing pattern, quotas held for king crab, landings and fuel use during the most recent years. The data used is the median of four king crab fishers out of approximately 30 license holders contacted by phone, many of which were not reached. Despite the low number of fishers providing data, the data was not unusually variable and is considered being of sufficient quality for a preliminary analysis of the king crab fishery, however, it should be kept in mind in interpreting results that the data come from only four fishers.

Characterizing fuel use intensity in shrimp fishing is even more complicated, as catching shrimp is relatively fuel intensive compared to fish trawling (per kg of landing) but is partly done by the same fleet segment [47]. Efforts were done to collect data directly from shrimp trawlers in the same way as crab vessels but failed. Since 2009, ocean-going shrimp trawlers are merged into the cod trawler segment, a segment that in 2017 caught approximately half of the total Norwegian shrimp landings (based on the landing composition of the profitability survey's population), but for which shrimp landings only represented approximately 5% of the segment's total landings (based on the landing composition of the survey respondents). To address this challenge of representativity, *we kept all cod trawlers without shrimp catch in the cod trawler fleet segment, while moving data from cod trawlers with shrimp catch (irrespective of the amount) to the ocean-going shrimp trawler*s in 2007 and 2017. Cod trawlers are used for estimating the fuel use intensity for catching all species *except for shrimp*. Due to the highly mixed catches of the ocean-going shrimp trawler group, it was decided that this segment could not be used to model the fuel use intensity of catching shrimp, as its fuel use is still too dominated by (much more fuel efficient) fish landings. As shown in Figure 3-1, many of these vessels have very little shrimp catch compared to their total catch (with a minimum value of 0.001% shrimp catch). Had we chosen a threshold for separating cod trawlers and ocean-going shrimp trawlers, for instance 25% shrimp catch, only four vessels in 2007 and two vessels in 2017 from this fleet segment would be considered for estimating the fuel use intensity for catching shrimp. Therefore, *we excluded ocean-going shrimp trawlers from this study altogether* (Figure 3-1).

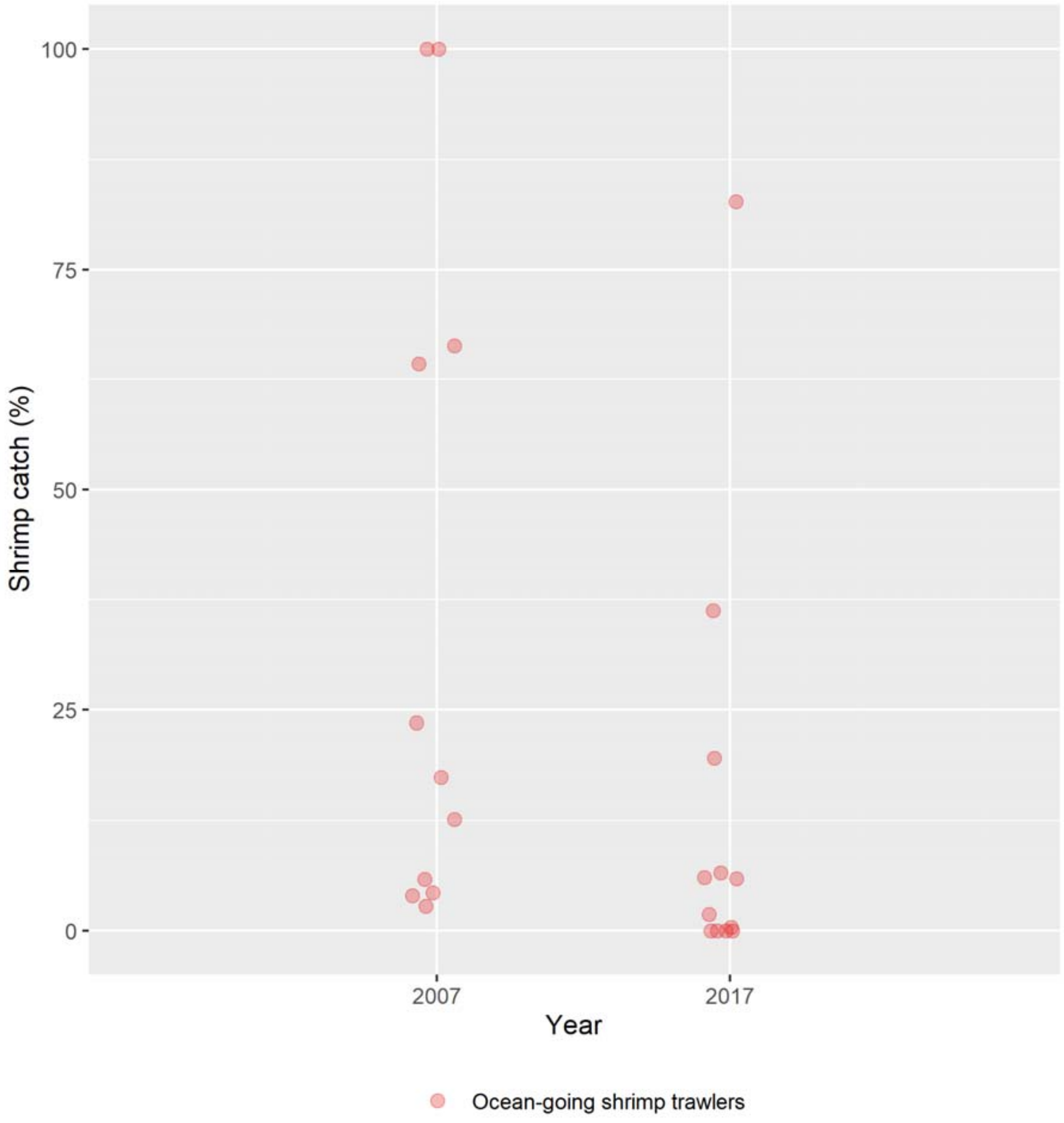


Figure 3-1 Share of shrimp catch in total catch of individual ocean-going shrimp trawlers

For the smaller coastal shrimp trawlers, a threshold was applied to separate shrimp from other catches. We separated vessels for whose annual landings were composed of >=25% shrimp from the rest, to estimate the fuel use intensity of catching shrimp and other species, respectively, by this segment. No vessel in the coastal shrimp trawlers segment had less than 25% shrimp catch in 2017. In other words, no coastal shrimp trawler is considered in evaluating the fuel use intensity of catching species other than shrimp in 2017. With a higher threshold, for instance 60%, still only one coastal shrimp trawler would be considered for species other than shrimp in 2017 (Figure 3-2.). Since, the results for a fleet cannot be based on only one vessel, we chose 25% threshold and did not consider any coastal shrimp trawlers while studying other species in 2017. This does not affect the results significantly, since coastal shrimp trawlers have a trivial share in total landings of other species. For example, coastal shrimp trawlers contributed less than 0.3% of total cod landings of the survey population in 2017 (own calculation based on [45]).

Figure 3-2. highlights an important difference between the coastal shrimp trawlers fleet segment in 2007 and 2017: this fleet segment mainly includes shrimp specialist vessels in 2017. This may be due to the changes in population definition made by the Norwegian Directorate of Fisheries in 2009 (see chapter 3.1.1.1), regarding which vessels with higher income are considered in the survey population of 2017 compared to 2007. Higher value of shrimp relative to finfish may be the reason for having vessels with higher shrimp share in the population, and consequently the sample, in 2017 compared to 2007. This may affect the results of this study and lead to underestimation of fuel use intensity of shrimp in 2007.

The conclusion regarding the fuel use intensity of shrimp fishing is that *only the data from the coastal shrimp trawler fleet segment was used, because these trawlers have the "cleanest" shrimp catches* (although they also have considerable amounts of whitefish). We believe that the fuel use intensity of smaller trawlers can also broadly represent the larger ocean-going shrimp trawlers because previous studies have not shown a major difference in fuel efficiency between large and small trawlers fishing offshore or more coastal [47,48]. Larger vessels do use more fuel per hour and travel further for their fishing, but this is more or less offset by larger catch rates and the small shrimp trawlers therefore better represent the landings of the large ones than the annual average fuel use of the large ones.

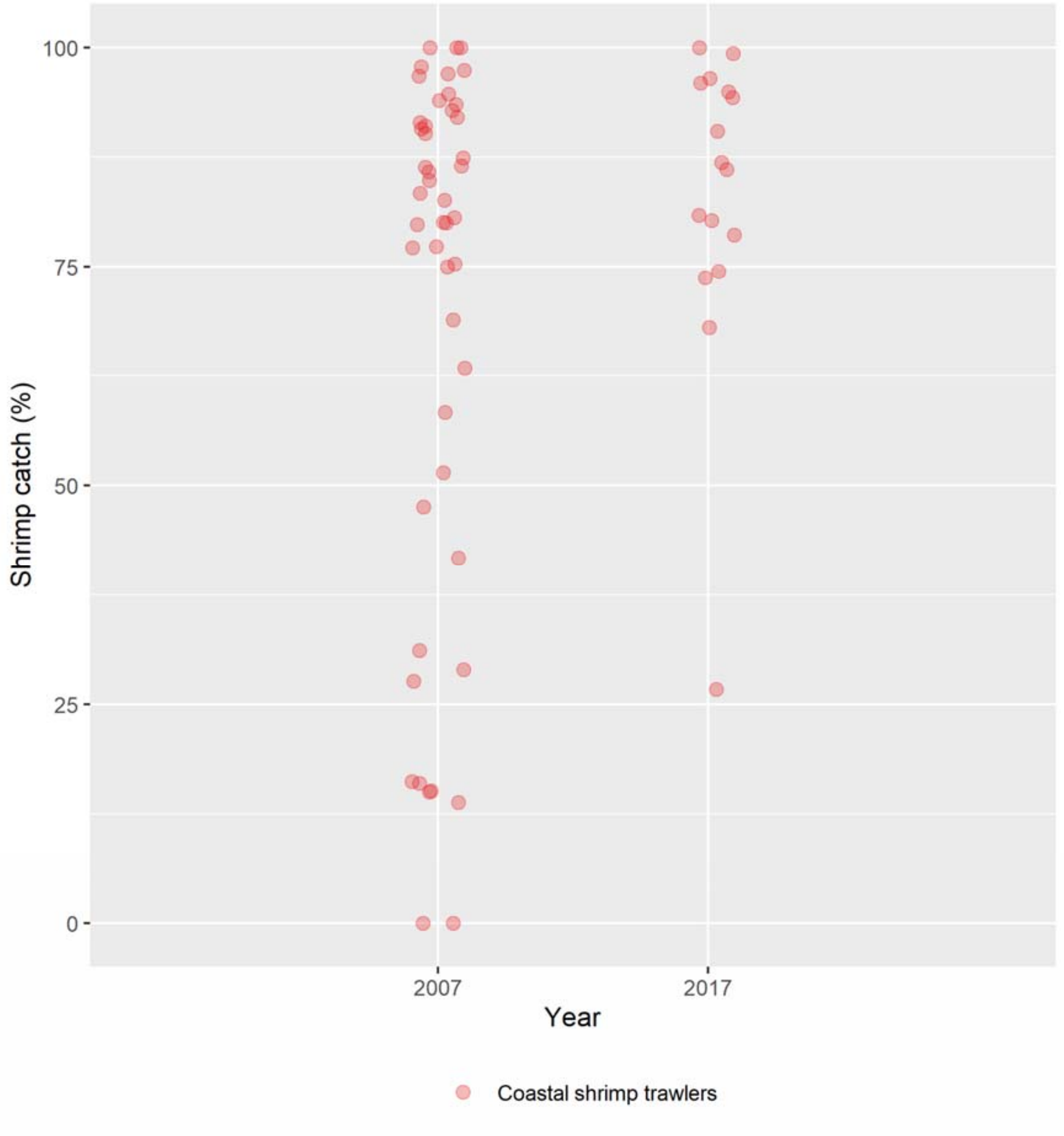


Figure 3-2. Share of shrimp catch in total catch of individual coastal shrimp trawlers

As a result, this study covers the following eight fleet segments. All these fleet segments exist in 2007 and 2017, except for coastal shrimp trawlers with less than 25% shrimp catch, which only exist in 2007 (Figure 3-2.):

1. Coastal conventional vessels
2. Ocean-going conventional vessels
3. Coastal seiners
4. Purse seiners
5. Pelagic trawlers
6. Coastal shrimp trawlers with 25% shrimp catch or more (used for estimating fuel use intensity of catching shrimp)

7. Coastal shrimp trawlers with less than 25% shrimp catch (used for estimating fuel use intensity of catching species other than shrimp)
8. Cod trawlers (used for estimating fuel use intensity of catching species other than shrimp)

By excluding ocean-going crab vessels and ocean-going shrimp trawlers, the population and respondents of interest are reduced from the values shown in Table 3-1 to the corresponding values shown in Table 3-2.

3.1.1.3 Fuel types

In the datasets provided by the Norwegian Directorate of Fisheries [44], vessels consume various types of fuel, the percentage of which is shown in Figure 3-3. for 2017. Marine gas/diesel oil and marine special distillate are the main fuel types used. Carbon dioxide emissions of the latter are slightly higher than the former (2.8 versus 2.6 kg CO_2e/L [1]). Marine special distillate is converted to marine gas/diesel using the ratio 2.8/2.6 [1,45].

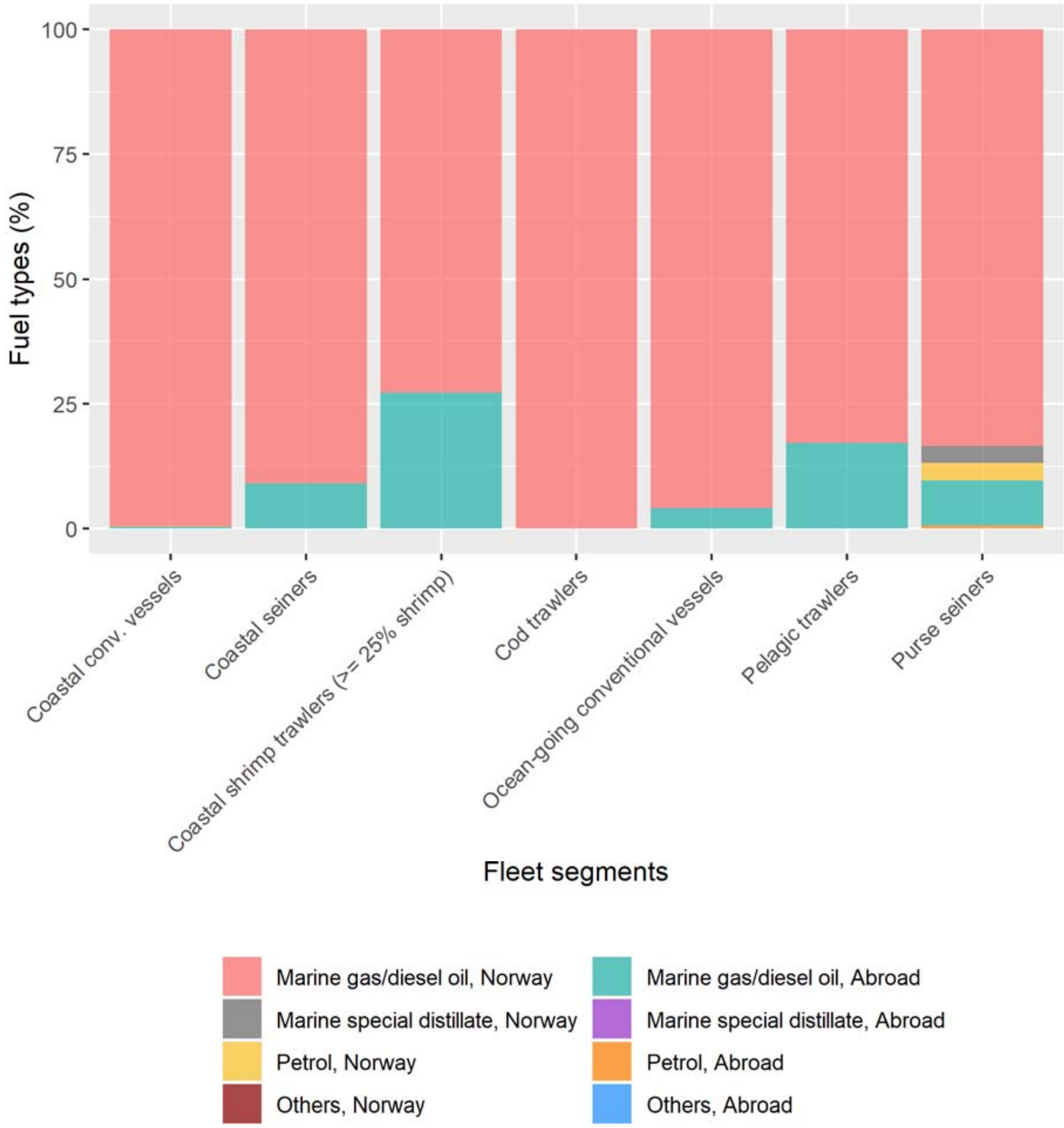


Figure 3-3. Shares of various fuel types used by the Norwegian fishing vessels in the 2017 (based on the respondents to the profitability survey in 2017 [44]**)**

In the data provided by the Norwegian Directorate of Fisheries [44], not all vessels have fuel information. Since this study investigates the fuel use intensity for catching various fish species, vessels with no fuel information are excluded from this study (Table 3-2).

Approximately 28%, 73% and 97% of active fishing vessels (Table 3-1) below 11 meters, 11–27.9 meters and above 28 meters long were included in the profitability survey of 2017, respectively [45] . Approximately 16%, 45%, 66%, 70% and 93% of active fishing vessels of 8–9.9 meters, 10–14.9 meters, 15–20.9 meters, 21–27.9 meters and above 28 meters were included in the profitability survey of 2007, respectively. In 2007, active vessels below 8 meters were not covered (i.e. 1,226 active vessels) [45] . Therefore, the profitability surveys include most of larger vessels, such as cod and pelagic trawlers.

Table 3-2. Number of vessels used in this study to estimate the fuel use intensity (L fuel/kg liveweight catch) of the fleet segments of interest.

Fleet segment	Respondents to profitability surveys[a]		Respondents to profitability surveys providing fuel data[b]		Respondents to profitability surveys providing fuel data and without filleting[b]	
	2007	**2017**	**2007**	**2017**	**2007**	**2017**
Coastal conventional vessels	359	168	266	128	265	126
Ocean-going conventional vessels	24	13	17	13	14	10
Coastal seiners	70	31	54	27	54	26
Purse seiners	61	56	45	52	43	52
Pelagic trawlers	21	8	15	8	15	7
Coastal shrimp trawlers with 25% shrimp catch or more	40	16	23	13	23	10
Coastal shrimp trawlers with less than 25% shrimp catch	7	0	3	0	3	0
Cod trawlers	31	15	24	14	14	14
Total	613	307	447	255	431	245

[a] Ocean-going shrimp trawlers (11 vessels in 2007 and 12 vessels in 2017) and ocean-going crab vessels (five vessels in 2017) are excluded when estimating the fuel use intensity of fleet segments.
[b] Ocean-going shrimp trawlers (10 vessels in 2007 and 11 vessels in 2017 providing fuel data) and ocean-going crab vessels (five vessels in 2017 with fuel data) are excluded when estimating the fuel use intensity of fleet segments as explained in text.

3.1.1.4 Product type

The datasets provided by the Norwegian Directorate of Fisheries [44] divide the catch in different product types, such as round fish, head, trimmings and fillet. To avoid possibly accounting for fish filleting twice (both onboard fishing vessels and then onshore), data from vessels reporting landings of filleted catch are excluded. This results in a further decrease of vessels in 2007 and 2017 (Table 3-2).

3.1.1.5 Fuel use intensity of fleet segments

Based on the catch and fuel data, the fuel use intensity of individual vessels is estimated. Tukey's boxplots in Figure 3-4 display the distribution of fuel use intensity of vessels in various fleet segments in 2007 and 2017. The boxes represent the lower quartile (Q1), median and upper quartile (Q3) of values. The whiskers represent the lowest datum within the 1.5 interquartile range (i.e. 1.5 (Q3 − Q1)) of Q1 and the highest datum within the 1.5 interquartile range of Q3. Figure 3-4 also displays outliers and the average value for the fleet segments.

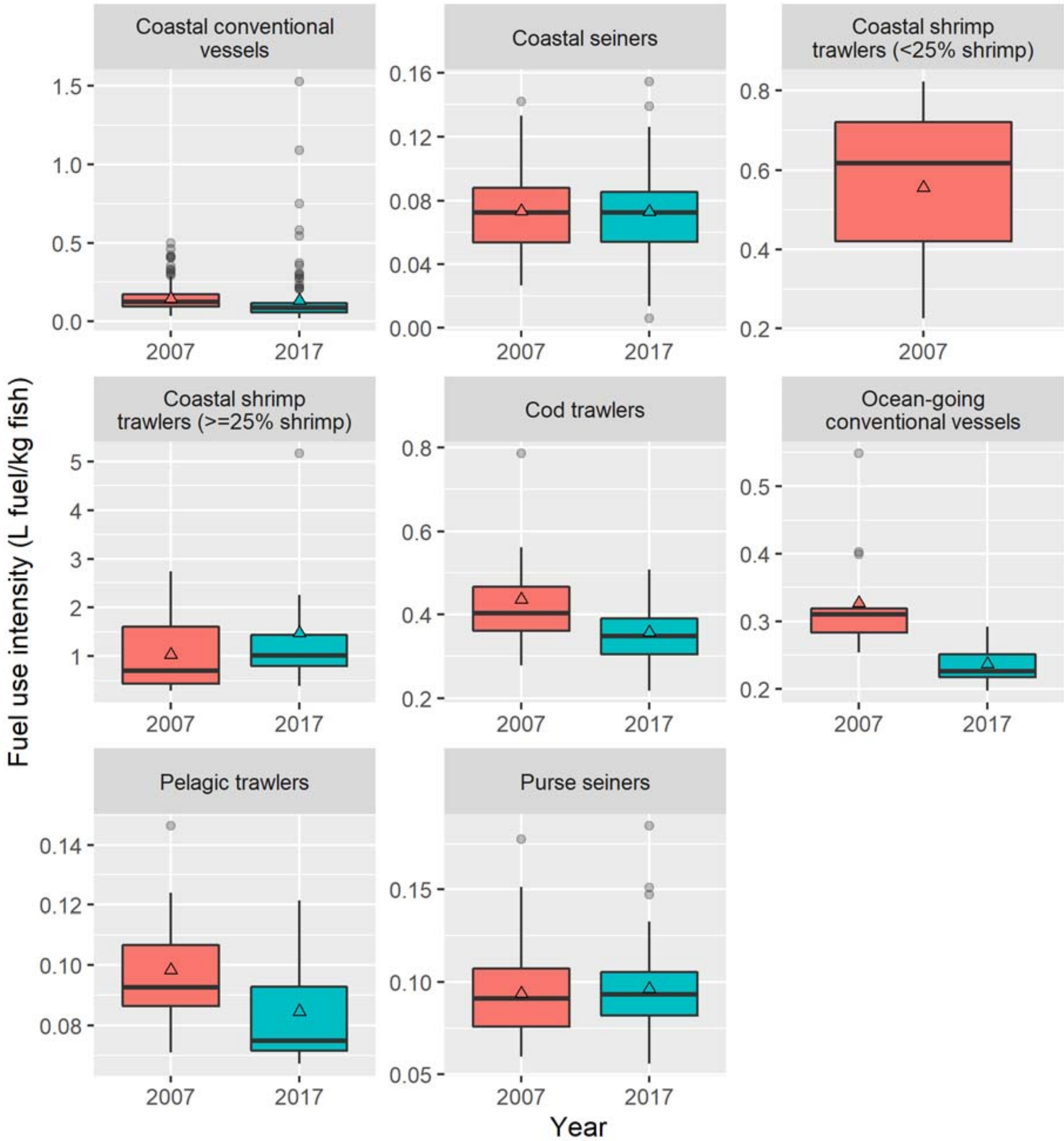


Figure 3-4. Fuel use intensity (L fuel/kg liveweight fish) of Norwegian fishing vessels in 2007 and 2017. The boxes represent the 1st and 3rd quartiles, with the median. The whiskers follow Tukey's method. The grey dots are outliers and the triangles show the average value for the fleet segments.

3.1.1.6 Fuel use intensity of species

To estimate the fuel use intensity for catching specific fish species, the fuel use intensities of fleet segments are linked to catch of survey populations in 2007 and 2017 [45,46] using Equation 3-1. In each year and for each species, the fuel use intensity of each fleet segment is multiplied by its share of the total catch of that species by the survey population, with the exceptions mentioned above. The sum of these values represents the fuel use intensity for catching the species in the year of interest. It should be noted that the fuel use intensity of the fleet segment is based on fuel consumption and catch data of a subset of vessels (e.g. 245 vessels in 2017; Table 3-2), whereas the total catch represents the catch of survey populations (e.g. 2,060 vessels in 2017; Table 3-1). We considered the total catch of survey populations instead of samples in order to have a better representation of Norwegian landings and the fleet segments participating in catching them. The catch composition of samples has some differences to the catch composition of survey populations. However, we chose the latter to have a better representation of the Norwegian fisheries.

Figure 3-5 illustrates the share of various fleet segments in the total catch of survey populations in 2007 and 2017. For sample vessels, the catch composition of individual vessels is available and, as mentioned, we kept all cod trawlers without shrimp catch in the cod trawler fleet segment, while moving data from cod trawlers with shrimp catch (irrespective of the amount) to the ocean-going shrimp trawler group. Similarly, we used 25% shrimp catch as a threshold to separate coastal shrimp trawlers in two groups. However, the survey population catch data is aggregated for different fleet segments defined by the Norwegian Directorate of Fisheries (and not the fleet segments we defined). Therefore, one cannot separate the catch of population between cod trawlers and ocean-going shrimp trawlers. Similarly, one cannot separate the catch of population between the two sub-groups of coastal shrimp trawlers. To separate catch between cod trawlers and ocean-going shrimp trawlers, all shrimp catch of the population was allocated to the latter. Since cod trawlers are used for estimating the fuel use intensity for catching all species except for shrimp, we assumed that this fleet segment lands all species except for shrimp that are caught by cod trawlers and ocean-going shrimp trawlers. For coastal shrimp trawlers, all shrimp catch of the population was allocated to coastal shrimp trawlers with >=25% shrimp since this fleet segment is used for estimating fuel use intensity of catching shrimp. The rest of species are allocated to coastal shrimp trawlers with <25% shrimp (Figure 3-5).

Table 3-3 presents the fuel use intensity and catch composition that was used in the calculation of the CF of each species. The median was used as the default fuel use intensity for each fleet segment (Base scenario). Using Equation 3-1, one can combine fuel use intensity of fleets segments (Figure 3-4 and Table 3-3) and survey population catch data (Figure 3-5) to find fuel use intensity for catching various species. Table 3-4 shows the fuel use intensity of various species using the median value for the fuel use intensity of fleet segments (Figure 3-4 and Table 3-3).

$$\boldsymbol{FUI_{S,Y}} = \frac{\sum_1^N (\boldsymbol{FUI_{F,Y}} \times \boldsymbol{C_{S,F,Y}})}{\sum_1^N \boldsymbol{C_{S,F,Y}}}$$

Equation 3-1

FUI: Fuel use intensity (L fuel/kg liveweight catch) of fleet segment
C: Catch of survey population (kg liveweight catch)
S: Species of interest
Y: Year of interest
F: Fleet segment
N: Number of fleet segments

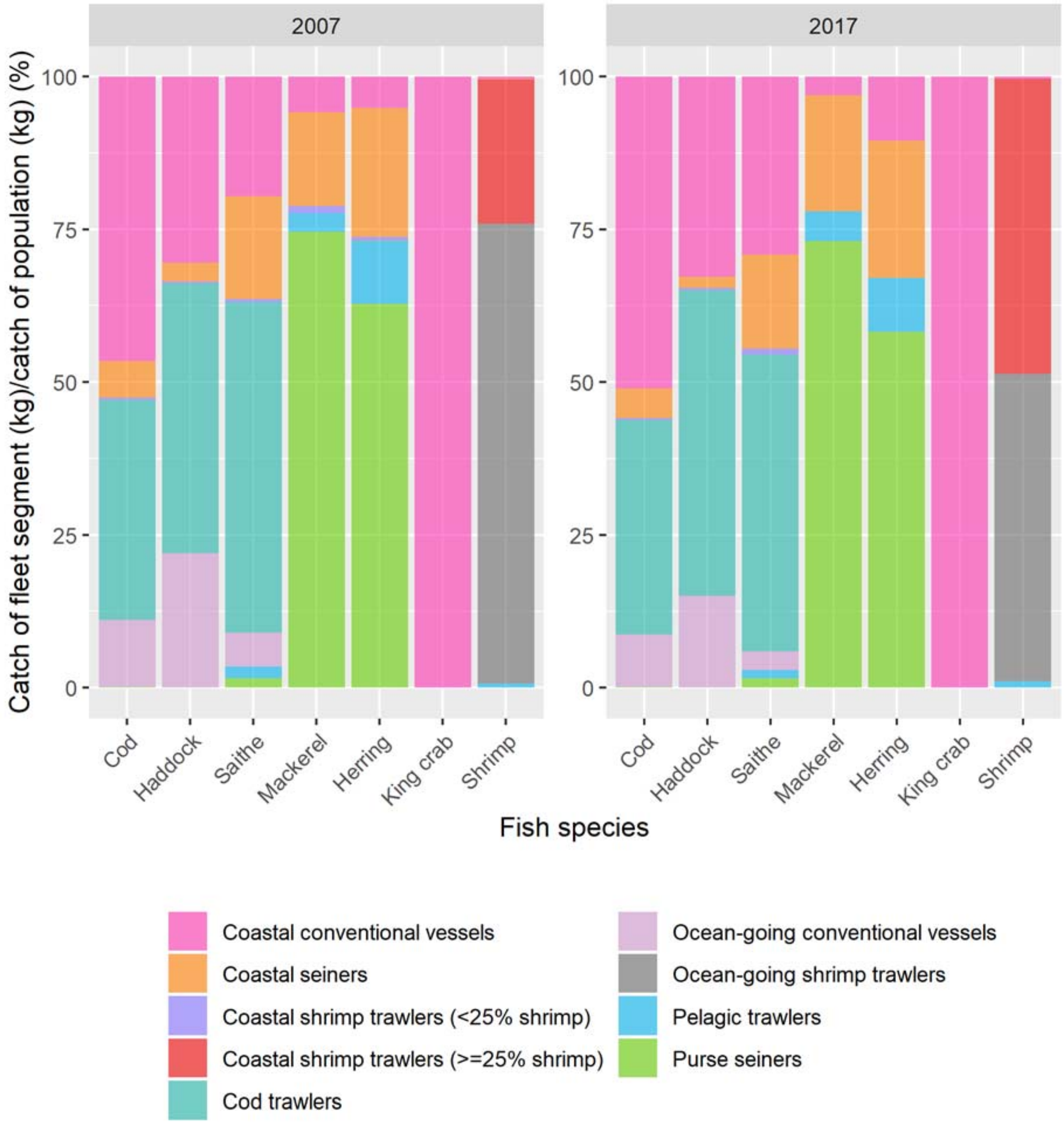


Figure 3-5. Share of various fleet segments in the total catch of survey populations in 2007 and 2017 (based on [45,46] **)**

Table 3-3 Fuel use intensity (L fuel/kg liveweight catch) of fleet segments and catch composition for 2017 used to calculate carbon footprint of fisheries.

Fleet segment	Fuel use intensity (L fuel/kg liveweight catch)				Species [c] (% landed by each fleet segment)					
	Min [a]	Median (base scenario)	Average	Max [b]	Cod	Haddock	Saithe	Mackerel	Herring	Shrimp
Coastal conventional vessels	0.02	0.09	0.13	0.17	51.0	32.7	29.1	3.0	10.5	0.0
Ocean-going conventional vessels	0.20	0.23	0.24	0.29	8.6	15.0	3.1	0.0	0.0	0.0
Cod trawlers	0.22	0.35	0.36	0.51	35.2	49.9	48.5	0.0	0.0	NA
Coastal shrimp trawlers with 25% shrimp catch or more	0.39	1.01	1.48	2.25	NA	NA	NA	NA	NA	100.0 [d]
Coastal seiners	0.01	0.07	0.07	0.13	4.8	1.9	15.5	19.0	22.5	0.0
Purse seiners	0.06	0.09	0.10	0.13	0.1	0.0	1.6	73.1	58.3	0.0
Pelagic trawlers	0.07	0.07	0.08	0.12	0.0	0.0	1.3	4.9	8.8	0.0

[a] The lowest datum within 1.5 interquartile range (1.5*(Q3-Q1)) of Q1. Q1 and Q3 are lower and upper quartiles, respectively.
[b] The highest datum within 1.5 interquartile range of Q3 (upper quartile)
[c] King crab was treated separately: Conventional vessels do catch king crab, but crab represents a very small proportion of catches and the fuel use intensity of these vessels can therefore not be used to represent king crab fishing. Instead, king crab license holders identified through the Norwegian Directorate of Fisheries (n=30) were contacted and asked about their annual landings and fuel use, among others, during the most recent years. The data used is the median of four king crab fishers, who responded. This is further explained in the text. Minimum, median and maximum fuel use intensity of king crab were 0.167, 0.841 and 1.405 L fuel/kg liveweight catch, respectively.
[d] In reality, shrimp are landed by coastal and ocean-going shrimp trawlers, but due to the highly mixed landings in all segments except for coastal shrimp trawlers landing more than 25%, these are used to represent all shrimp fishing. Their fuel use intensity was considered more representative also of the other shrimp-landing segments than the median fuel use intensity across all landings in these segments. This is an exception only made for shrimp and is further explained in the text.

Table 3-4 Fuel use intensity (L fuel/kg liveweight catch) of various species based on median fuel use intensity of Norwegian fleet segments and survey population catch.

Year	Cod	Haddock	Saithe	Mackerel	Herring	Shrimp	King crab [a]
2007	0.244	0.288	0.278	0.096	0.093	0.696	-
2017	0.189	0.237	0.215	0.088	0.086	1.013	0.841

[a] estimated through a fisher survey, not based on the profitability surveys like the other species

3.1.2 Refrigerant use in fishing

In the study building on data from 2007 [1], refrigerants turned out to give a substantial contribution (up to 30%) to the GHG emissions of some Norwegian seafood products from capture fisheries, in particular from demersal fisheries cod, saithe and haddock. It was estimated that the Norwegian fishery industry emitted 200 ton of R22, with a global warming potential (GWP) of 1,810 kg CO_2e/kg [1].

The use of refrigerants has changed rapidly during the last years, mostly because of international regulations aiming to phase out refrigerants with ozone depletion potential (incl. R22) and/or high GWP, including R22 and many hydrofluorocarbons (HFCs) which were introduced to replace R22.

When Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs) (e.g. R22) were first banned, ammonia and carbon dioxide started to be used on new vessels. However, to convert an existing refrigeration system to these both ozone- and climate-neutral refrigerants, the whole refrigeration system needs to be exchanged at considerable costs. Carbon dioxide is today the most common refrigerant in Norwegian fisheries today [6], but some vessels use so called “drop in” refrigerants to replace R22, which does not require replacing the entire refrigeration system. These drop in refrigerants are HFCs with a lower ozone depletion potential that CFCs and HCFCs, *but often have an even higher GWP than R22*. The only official data on how much HFCs that are sold to the Norwegian fishing fleet are data on national emission to air per sector at Statistics Norway (SSB). SSB estimated that the Norwegian fishing fleet emitted 464 kg HFCs in 2015 [6].

Hognes and Jensen [6] performed a survey by interviewing 146 fishing vessel owners about what refrigerants they used. They could not answer how much was emitted on a yearly basis, but from that survey it seemed likely that a considerable share of vessels use drop in refrigerants, however, the sample size is small. Interviews of vendors and service companies for refrigeration systems revealed that while carbon dioxide and ammonia are the dominating refrigerants, several said that some Norwegian vessels probably source refrigerants outside of Norway, volumes which are not captured by SSB numbers.

Emissions of HFCs from Norwegian fisheries were estimated based on the data found in the report by Hognes and Jensen [6]. Only data for vessel groups where more than 25% of the active vessels were asked was used. This gave an estimate on the number of vessels that still use climate-intensive refrigerants. To estimate the volume of refrigerants used in the Norwegian fishing fleet, the estimate on the numbers of vessels was combined with assumptions on the load of refrigerant in each vessel for the different vessel groups. Table 3-5 presents these data and assumptions made.

For all groups it is assumed that 20% of the refrigerant is emitted per year. This assumption is based on information from people working with refrigeration systems and emission rates for transport refrigeration systems (see chapter 3.5.2). The result of this estimate is that the annual HFC emission from Norwegian fisheries is more than 16 ton. This is considerably more than the data reported by SSB, i.e. 464 kg.

Table 3-5 Data used to estimate HFC emissions in Norwegian fisheries in 2017.

Vessel group[1]	Estimate vessels using drop in refrigerants (HFCs)	Number of active vessels in group	Share of active vessels that replied survey	Mass of refrigerant in each system (kg)	Estimate HFC emission (10% emission rate) (kg)	Catch of vessel group (ton)	HFC emission rate (kg HFC/ton landed)
Conventional high sea	36 %	33	52 %	2,000	4,794	2,397	0.027
Demersal trawlers	18 %	63	43 %	2,000	4,432	2,216	0.007
Coastal purse seine	54 %	66	26 %	400	2,823	1,411	0.008
Pelagic trawl	50 %	27	59 %	400	1,067	534	0.003
Sum					**6,558**		

[1]Note: Not the same fleet segments that were used to model the fuel use intensity

3.1.3 Bait use in fishing

Some fisheries use bait, usually some kind of small, pelagic fish, as a supply material and amounts used can in extreme cases exceed the volume of fish landed, when bait use can become an important parameter [49]. Bait is included based on data from personal communication with Mustad Longline (Table 3-6). Two fisheries have input of bait: Conventional coastal and conventional high sea, and their bait use is modelled with data on coastal longliner and high sea longliner. Bait can be sourced from numerous different sources, even produced artificially. In this work it is assumed that bait is sourced from Norwegian pelagic fisheries.

Table 3-6 Data and assumptions made related to the provisioning and use of bait.

Parameter	Data
Bait per hook (g)	25
Catch rate coastal longliner (kg lwe landed/hook)	0.7 (range 0.3 – 1.5)
Catch rate high sea autoliner (kg lwe landed/hook)	0.4 (range 0.2 – 0.6)
Fuel use in bait fishing (L fuel/kg lwe landed)	0.09 (ref chapter 3.1.1.6)
Chilled storing of frozen bait (days)	60 (assumption)

3.1.4 Fishing gear and fishing vessel

Construction of the fishing vessel is usually not a major climate aspect in fisheries; therefore the construction of fishing vessels is included in a simplified way using data on the light ship weight of demersal trawlers. This is used as a proxy for all fisheries. The light ship weight of demersal trawlers was calculated as dead weight minus displacement of trawlers produced by the shipyard Ulstein, based on data on their webpage [50], giving a light weight of 2,770-4,700 ton of demersal trawlers. A light weight of 3,500 ton was used and assumed to be composed of 10% chrome steel and 90% low alloyed steel. This composition was based on data on the material composition of the demersal trawler Hermes [51].

To calculate the impact per unit of fish landed from construction of the fishing vessel, the annual landing of demersal trawlers of 8,722 ton of fish per year per vessel (Table G15 in the annual profitability survey of Norwegian fisheries [45]) was combined with the assumption that the vessel operates for 30 years. Maintenance of the vessels is not included in this work.

Input of fishing gear was estimated based on data from Deshpande et al., 2019 [52]. They estimate that commercial fishing in Norway contributes to around 380 ton/year of marine plastic pollution from lost fishing gears and parts, and that 4,000 ton/year of plastic waste is collected from fishing gears. Combining this with an annual catch of around 2.4 million ton (all Norwegian fisheries), this equals a plastic input rate of 1.83 kg plastic per ton round weight fish landed.

The data provided by Deshapande et al. [52], that was available at the time of this analysis, did not include metals. But it refers to gear retrieval survey by the Directorate of Fisheries where equal (weight) amounts of plastic and metals were retrieved. Since good data on the metal input was not found, it was simply assumed that it is equal to that of plastics.

Key data for the inclusion of construction of fishing vessel and fishing gear is presented in Table 3-7.

Table 3-7 Data and assumptions used to model vessel and gear construction.

Parameter	Data
Lifetime fishing vessel (years)	30 (assumption)
Light ship weight of demersal trawler (ton)	3,500 [50].
Annual catch of demersal trawler (ton)	8,722 [45]
Demersal trawler material composition (%)	10% chrome steel and 90% low alloyed steel [51]
Input fishing vessel (ton of light weight ship/ton fish landed)	3,500/(8,722*30) = 0.0134
Plastic (fishing gear lost at sea) (ton/year)	380 [52]
Plastic (fishing gear) collected as waste (ton/year)	4,000 [52]
Annual catch of Norwegian fisheries (million ton)	2.4
Plastic/metal use (ton of material/ton fish landed round weight)	(380+4,000)/2,400,000 = 1.83e-3

3.2 Salmon aquaculture

The production of salmon and trout in Norway in 2017 was 1,236,354 ton and 66,999 ton, respectively [53] for a total of 1.3 million ton of whole fish equivalents. 93% of the salmon and 73% of the trout was exported.

The production is done by using 1,377 licenses (1,157 licenses for grow-out and 220 licenses for juvenile production) [54]. These licenses are distributed on 986 on approved locations, but based on information from the Directorate of Fisheries only 779 locations were used, with a total of around 5,500 cages [55]. In a study of potential GHG reductions by electrification, Bellona and ABB state that 578 locations were in active use in 2017.

The Norwegian salmon and trout grow out is done by 173 farming companies, but the 10 biggest companies sold 68% of the total salmon and trout production [54].

The production of salmonids (salmon and trout) in 2017 was slaughtered in a total of 58 approved facilities, the average mass of fish slaughtered per facility was around 22,500 ton per year in 2017 [54].

3.2.1 Juvenile production and input

Juvenile production has, just like gear and vessel construction, not been identified as an important hotspot in previous assessments of farmed fish, but it was still included in a simplified way using available data combined with expert assumptions in order to get an assessment as complete as possible. The juvenile (or smolt) production is included as a Recirculating Aquaculture System (RAS) production with an **electricity use of 10 kWh/kg juveniles produced** and an **economic feed factor of 1 kg feed per kg juveniles produced** [56]. The electricity intensity used is based on a combination of data from fish farmers and literature. In an analysis that considered potential effects of more land based aquaculture in RAS a group of experts estimated that energy use can be as low as 6-9 kWh/kg juveniles produced [56]. In this work the feed used in the hatchery was assumed to be equal to that of the salmon grow out (chapter 3.2.4). We are aware that the feed used for juveniles is not identical to that of the grow out, but in lack of more specific data, the grow out feed composition was used. Salmon juveniles can also be produced in flow through systems, these are typically more energy efficient since the water is not recirculated/pumped and cleaned as much as in a RAS.

The juvenile RAS plant also includes some use of diesel (0.033 L/kg juvenile produced, data from one producer) and input of chemicals [56] and construction of the plant. Construction of the plant is based on data from an article that compared RAS and open net pen salmon production [57].

The sludge output from the RAS plant is 1.5 kg sludge with 10% dry weight content per kg juvenile produced. It is then assumed that water is removed without the use of energy until a dry content of 20weight% is achieved and then that the remaining water is vaporized. The heat of vaporization of water is 2,260 kJ/kg, resulting in an energy use of the sludge treatment of **0.5 kWh electricity per kg sludge dried.**

The amount of juveniles used was calculated based on the annual smolt production and fish slaughtered in 2016 and 2017 and an assumption of the weight of an average juvenile. Table 3-8 presents the number of smolt/juveniles that was produced in 2016 and 2017 [58]. Based on the assumption that the average weight of the juvenile is 100 gr this gives the following juvenile input factor: (680 million juvenile*100 gr/juvenile)/2.6 million ton produced = **0.026 kg juvenile/kg salmon produced.**

Table 3-8 Data on the annual production of salmon and trout juveniles and grow out production [58]**.**

Year	2016	2017
Salmon smolt (million fish)	314.8	326.1
Rainbow trout (million fish)	19.6	19.8
Grow out production (salmon + trout) (million ton wfe)	1.3	1.3

3.2.2 Fish farm, service companies and well boats

Extensive efforts were made to gather data on these activities from the different companies performing them. That effort showed that some fish farming companies have data on the energy (fuel and electricity) bought by them, but not the energy used by their sub-contractors, such as service companies and well boats.

The service companies that were contacted were not able to document or willing to share data on their energy use. One fish farmer had documented the energy used by their service companies, that was used: 0.01 liter fuel per kg fish produced. A project report from NTNU also estimated this energy use with a result of 0.02 liter fuel per kg fish produced [59]. **Based on these two data points, an energy intensity of 0.015 liter fuel per kg fish produced was used for service vessels.**

On-farm energy use, i.e. energy used by mainly by generators providing electricity for feeding, light and other equipment was modelled using data from a Master's thesis from NTNU [60], based on data from 51 localities in the Trøndelag region for production cycles from 2016 to 2019. The study presented a range in energy use of 0.44 kWh per kg produced for non-electrified localities to 0.26 kWh per kg produced for electrified localities. 0.44 kWh fuel equals 0.04 liter of fuel. Interviews with three fish farmers gave a range of 0.02 to 0.03 liter fuel per kg produced. **It was decided to use data for localities that are not electrified and a fuel intensity of 0.04 liter fuel per kg produced is used for the fish farm.**

Well boat activities in the Norwegian aquaculture industry include transport of fish, but also operations such as lice treatment and grading. The number of well boats operating in the Norwegian aquaculture industry in 2017 was 76 vessels with an average age of 14 years and average deadweight of 1,600 ton [61] The aquaculture industry also uses 30-35 ships transporting feed [61].

A project carried out by DNV GL indicates a fuel intensity of 0.03 liter fuel per kg produced. We expect that this is an estimate that only covers the well boats moving and not all of their activities at the fish farm as it is based on satellite (AIS) data on movement. One fish farmer had collected data on the fuel use of well boats, that showed an intensity of 0.04 liter fuel per kg produced. A thesis from NTNU presented an estimate (based on one vessel) of 0.08 liter fuel per kg produced [59]. All of the major well boat companies were contacted and asked about their energy use. Two companies could provide their annual energy use, but not how much salmon they handled using this amount of fuel. We then related their joint fleet of 22 well boats to the total of 76 well boats operating in Norway in 2017 [46]. **This approach gave an estimate on the well**

boat fuel intensity of 0.08 liter fuel per kg produced which was the value was used to represent well boat activities.

The extensive efforts to gather energy data from fish farms, service vessels and well boats showed that all necessary data are in the systems of the different actors, it is just not collected/structured into an environmental management system and made available for research.

3.2.3 Fish farm equipment

The fish farm equipment is included using data from a report by Hognes and Skaar [55] that investigated waste handling of plastics and metals in the Norwegian salmon aquaculture industry. That report included interview with salmon producers of different sizes and situated in different regions, representing more than 40% of the Norwegian salmon industry (in terms of producing licenses). The biggest equipment suppliers were also included in the project. Table 3-9 presents data that was used.

Table 3-9 Data on material composition and intensity of salmon fish farm equipment.

Input/activity	**Data** (kg/kg LW produced)
Polypropylene plastic	0.011
Polyethylene plastic	0.011
Chromium steel	0.0019
Low alloyed steel	0.0045
Waste handling plastic:	0.022
Waste handling metals:	0.0065

3.2.4 Salmon feed composition

As mentioned earlier, the feed is the most important input in aquaculture systems and great care was therefore taken in obtaining high quality data on the feed composition and use of feed used in Norwegian salmon farming in 2017. Table 3-10 presents the composition, based on reported data from the three largest feed producers which was used to calculate a weighted average. The origin of the different raw materials is presented with more detail in the following chapters. Marine ingredients grouped as “reduction fishers” are ingredients from fisheries where the main purpose is to source feed ingredients (not for direct human consumption). Marine ingredients grouped as “co-products” are sourced from cut offs, intestines, bycatch etc. from fisheries where the main purpose is direct human consumption.

Table 3-10 Composition of feed formulated for farmed salmon in Norway in 2017 (data from three major feed producers).

Ingredient group	Ingredient	Scientific name of fish species	Volume (ton)	Proportion of feed (%)
Micro ingredients (3%)	Amino acids		4,763	0.35%
	Medicine		3	0.00%
	Micro ingredients - undefined		17,888	1.30%
	Phosphate		6,980	0.51%
	Pigments		218	0.02%
	Pigments natural		1,438	0.10%
	Pigments synthetic		227	0.02%
	Vitamins and minerals		4,493	0.33%
Crop-based oil (20%)	Rapeseed		274,695	20.03%
Crop-based protein (40%)	Faba beans		41,589	3.03%
	Guar		12,656	0.92%
	Horsebeans		2,823	0.21%
	Legume		37,903	2.76%
	Maize		14,674	1.07%
	Pea		13,192	0.96%
	Soy		281,824	20.55%
	Sunflower		18,687	1.36%
	Wheat		124,786	9.10%
Crop-based starch/carbohydrates (10%)	Pea		12,630	0.92%
	Tapioka		35	0.00%
	Wheat		124,123	9.05%
Fish meal - Reduction Fishery (12%)	Argentine / Silver Smelt	*Argentina sphyraena*	152	0.01%
	Blue Whiting	*Micromesistius poutassou*	77,888	5.68%
	Capelin	*Mallotus villosus*	6,909	0.50%
	Fish meal - Undefined	*Unknown*	139	0.01%
	Atlantic herring	*Clupea harengus*	5,846	0.43%
	Atlantic horse mackerel	*Trachurus trachurus*	75	0.01%
	Jack Mackerel	*Trachurus japonicus*	1	0.00%
	Krill	*Euphausia superba*	12,464	0.91%
	Mackerel	*Scomber scombrus*	727	0.05%
	Gulf menhaden	*Brevoortia patronus*	1,803	0.13%
	Peruvian Anchoveta	*Engraulis ringens*	15,501	1.13%
	European pilchard (Pilchard)	*Sardina pilchardus*	383	0.03%
	Norway pout	*Trisopterus esmarkii*	5,902	0.43%
	Sandeel	*Ammodytes sp.*	22,014	1.61%
	European pilchard (Sardine)	*Sardina pilchardus*	103	0.01%
	Silvery lightfish	*Maurolicus muelleri*	2	0.00%
	Sprat	*Sprattus sprattus*	9,166	0.67%

Fish meal - By-products (5%)	Capelin	*Mallotus villosus*	3,510	0.26%
	Fish meal - Undefined	*Unknown*	4,698	0.34%
	Atlantic herring	*Clupea harengus*	34,742	2.53%
	Atlantic horse mackerel	*Trachurus trachurus*	10	0.00%
	Atlantic mackerel	*Scomber scombrus*	7,616	0.56%
	Whitefish	*Gadus morhua (e.g.)*	11,676	0.85%
Fish oil - By-products (4%)	Capelin	*Mallotus villosus*	2,876	0.21%
	Fish oil - Undefined	*Unknown*	5,441	0.40%
	Atlantic herring	*Clupea harengus*	13,507	0.98%
	Atlantic herring	*Clupea harengus*	7,597	0.55%
	Atlantic horse mackerel	*Trachurus trachurus*	392	0.03%
	Atlantic mackerel	*Scomber scombrus*	9,594	0.70%
	Atlantic salmon	*Salmo salar*	6,873	0.50%
	Whitefish	*Gadus morhua (e.g.)*	2,902	0.21%
Fish oil - Reduction Fishery (8%)	Blue Whiting	*Micromesistius poutassou*	8,896	0.65%
	Capelin	*Mallotus villosus*	6,652	0.49%
	Fish oil - Undefined	*Unknown*	625	0.05%
	Atlantic herring	*Clupea harengus*	6,516	0.48%
	Atlantic horse mackerel	*Trachurus trachurus*	188	0.01%
	Atlantic mackerel	*Scomber scombrus*	1,178	0.09%
	Gulf menhaden	*Brevoortia patronus*	26,989	1.97%
	Peruvian Anchoveta	*Engraulis ringens*	18,348	1.34%
	Norway pout	*Trisopterus esmarkii*	2,337	0.17%
	Sandeel	*Ammodytes sp.*	10,783	0.79%
	Sardine	*Sardina pilchardus*	3,784	0.28%
	Sprat	*Sprattus sprattus*	18,649	1.36%
Algae oil (0.02%)	Algae oil		241	0.02%
	Total		**1,371,322**	**100%**

3.2.5 Feed use

The economic Feed Conversion Ratio (eFCR) is an especially important parameter in the carbon footprint of farmed fish (and other fed animal production systems) since the footprint of the feed often dominates the overall carbon footprint of the product [1,7,8,62]. The eFCR includes all feed that was used on a farm during a year per salmon slaughtered and sold. The eFCR for the Norwegian aquaculture industry in 2017 was 1.32 kg feed used per kg sold, calculated by the Norwegian Directorate of Fisheries based on their annual profitability survey of the Norwegian aquaculture industry [63]. In the profitability survey all companies with a production license for commercial production of salmon and trout participate. This includes companies of all sizes. For 2017, 118 companies with fish farming received the profitability questionnaire and of this 82 companies replied. Thus, the data used in this work is the average of 82 companies. These 82 companies cover 62.5 % of the Norwegian production licenses.

The Directorate of Fisheries calculate the eFCR in the following way:

$$\frac{feed\ in\ storage\ Jan\ 1 + feed\ bought - feed\ in\ storage\ Dec\ 31}{mass\ sold + frozen\ fish\ in\ storage + \frac{(biomass\ Dec\ 31 - mass\ of\ smolt\ released - biomass\ Jan\ 1)}{1.067}}$$

Equation 3-2

The denominator 1.067 converts from live fish to whole fish equivalents (which corresponds to the weight of fish that has been slaughtered and bled)

3.2.6 Marine ingredients

Marine ingredients are an essential part of salmon feeds, composed by fish meals and oils as well as fish protein concentrates made from whole fish (reduction fisheries) or processing trimmings (co-products), together constituting about 30% of the feed.

Figure 3-6 presents the carbon footprint of the marine ingredients as they enter the feed mill in Norway, including transportation to Norway. The carbon footprint of the marine ingredients includes fishing, reduction from round fish and co-products to meal and oil and transport of meal an oil to feed mill in Norway. Due to the allocation strategy used (mass-based), the carbon footprint for the meal/protein and the oil/lipid product of a species are equal. The way marine inputs were modelled in terms of fuel use and meal and oil yields is presented in Table 3-11. The reduction from round fish and co-products to meal and oil is presented in Table 3-12.

The reduction process (Table 3-12) is modelled based on data from LCA databases and literature. The electricity input, 26 kWh per ton into reduction, is an expert judgement based on a range from 14 kWh/ton (ecoinvent process for reduction of Peruvian Anchoveta[6]) to 38 kWh/ton used by the Agri-footprint database for generic fish oil/meal. A FAO technical paper presents a range of 25-35 kWh/ton [64]. The input of heat, 1,910 MJ per ton into reduction, is based on the data used by ecoinvent for oil/meal production from Anchoveta. A FAO technical paper presents a range of 1,230-2,255 MJ heat per ton reduced [64]. Construction of the plant was included using the ecoinvent process "Fishmeal plant {GLO}| market for fishmeal plant | Cut-off, U". Material inputs of plastic and waste handling is included also with data from ecoinvent process for reduction of Peruvian Anchoveta[7].

Algal oil was a part of Norwegian salmon feed in 2017, but only 0.02% of the total mass. Still some work was done to find the carbon footprint of this ingredient. That concluded that there is none (at least what we could find) publicly available information on the carbon footprint of algal oil for use in feed, despite the focus this ingredient has a promising sustainable alternative to e.g. fish oil [65]. The only information we could find was a poster from a poster presented at a SETAC conference indicating that algal oil have a CF higher than average fish oil [66]. This is also confirmed by feed producers that have access to unpublished information.

[6] Name of process: "fishmeal and fish oil production, 63-65% protein – PE"
[7] Name of process: "fishmeal and fish oil production, 63-65% protein – PE"

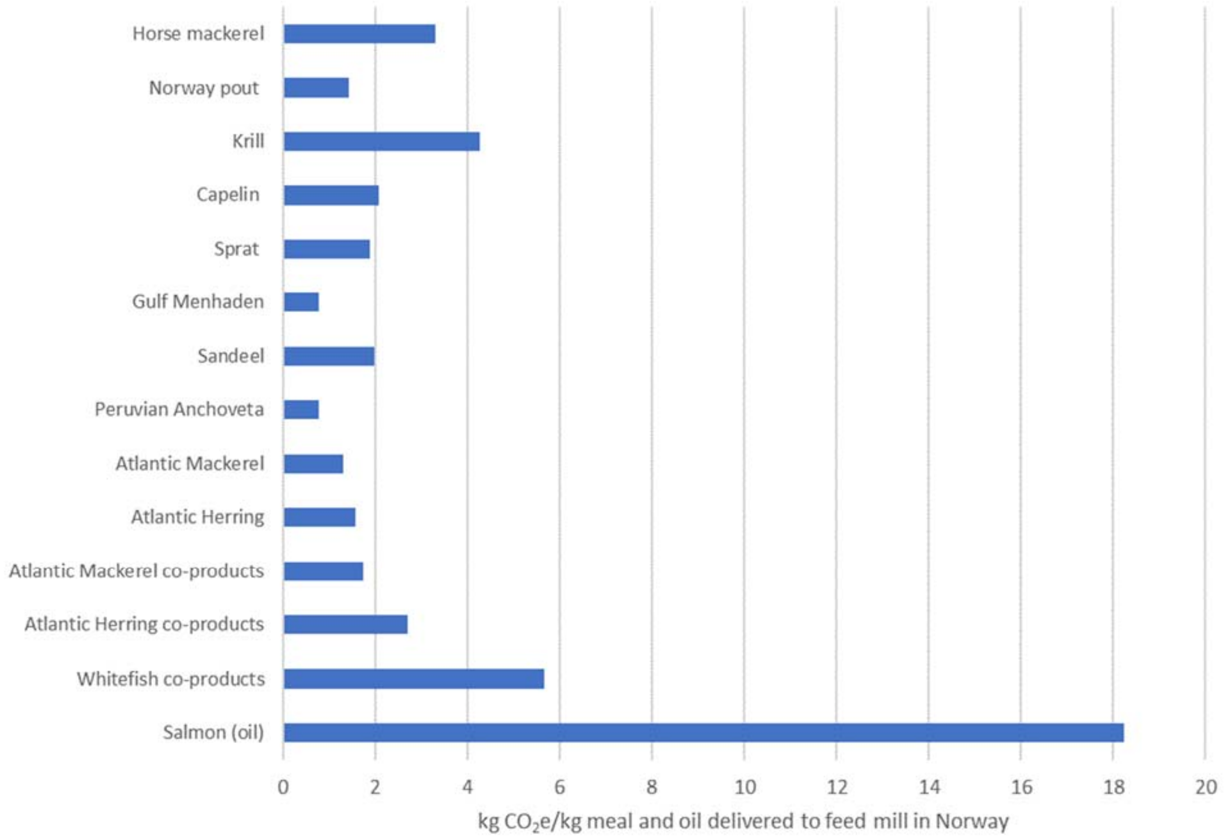


Figure 3-6 Greenhouse gas emissions of marine ingredients as delivered to feed mill in Norway, the value is the same for both meal and oil product since mass allocation is used.

Table 3-11 Fuel use and yield data used for marine feed inputs. Yield data from Cashion et al [67] and [68].

Species			Yield (kg out/100 kg in)	
Reduction fishery	**Share of feed, meal and oil (w%)**	**Description of how fishery is modelled and fuel intensity**	**Oil**	**Meal**
Blue whiting	6.33	Modelled with Norwegian purse seine fishery (fuel use in chapter 3.1.1)	19.70	1.90
Peruvian Anchoveta	2.47	0.018 l/kg [68]	24.00	5.00
Sandeel	2.39	Modelled as 55% pelagic trawl and 45% purse seine (fuel use for these fisheries in chapter 3.1.1)	19.70	4.24
Menhaden	2.10	Fuel sue from literature 0.037 l/kg [68]	21.00	16.00
Sprat	2.03	Modelled with Norwegian purse seine fishery (fuel use in chapter 3.1.1)	18.80	7.90
Capelin	0.99	Modelled with Norwegian purse seine fishery (fuel use in chapter 3.1.1)	16.50	7.70
Krill	0.91	Fuel use from literature: 0.141 l/kg [68]	16.00	0.08
Herring	0.90	Modelled with data for Norwegian herring (fuel use in chapter 3.1.1)	20.00	11.00
Norway pout	0.60	Modelled with data on pelagic trawl (fuel use in chapter 3.1.1)	20.4	11.5
Sardine	0.28	Included as sandeel	19.7	4.24
Mackerel	0.14	Modelled as Norwegian mackerel (fuel use in chapter 3.1.1)	19.4	18.6
Fish oil - Undefined	0.05	---	---	---
Pilchard	0.03	Included as Peruvian Anchoveta	---	---
Horse mackerel	0.02	0.270 l/kg [69]	23	7
Argentine / Silver Smelt	0.01	Included as Sandeel	---	---
Fish meal - Undefined	0.01	---	---	---
Co-products fishery				
Herring	3.52	Modelled with data for Norwegian herring (fuel use in chapter 3.1.1)	4	20
Mackerel	1.26	Modelled as Norwegian mackerel (fuel use in chapter 3.1.1)	18.6	19.4
Whitefish	1.06	Modelled as Norwegian cod landed (fuel use in chapter 3.1.1)	1.7	17
Salmon (oil)	0.50	Estimate based on yield and lipid content from Głowacz-Różyńska et. al [70]	14	17
Capelin	0.47	Included as herring co-products	---	---
Fish oil - Undefined	0.40	---	---	---
Fish meal - Undefined	0.34	---	---	---
Horse mackerel	0.03	Included as herring co-products	---	---

Table 3-12 Data used to model reduction of marine raw materials to meal and oil (references in text).

Activity and in-/outputs	Value
Electricity input (kWh/ton into reduction)	26
Heat from natural gas combustion (MJ/ton into reduction)	1,910
Polypropylene (kg/ton into reduction)	0.594
Extrusion, plastic film	0.594
Treatment of plastic waste in municipal incineration	1.19

3.2.7 Crop-based feed ingredients

To model crop-based feed ingredients, data from Agri-footprint was used [28]. The climate impact of Land use change climate impacts (LUC) is an important climate aspect of vegetable feed ingredients, especially those farmed on land that was formerly forest, see chapter 2.7 for a more comprehensive presentation of how LUC is included.

Table 3-14 presents the different crop-based ingredients that are used to model the salmon feed. It presents how much of the feed they compose, the name of the Agri-footprint process used to include it, a comment with some detail on the origin of the data in the Agri-footprint process and finally the CF of the ingredient and how much of this comes from LUC and dinitrogen monoxide (N_2O), a potent greenhouse gas emitted in agriculture.

3.2.8 Transportation of feed inputs

Transport of feed ingredients from market to Norway is included for all inputs. The transport distance are set based on simple assumptions. For the CF of the feed these transport in sum contributed with less than 4% of the feed CF at the point where it is delivered to the fish farmer.

Table 3-13 Transport of feed raw materials from production to feed mill in Norway.

Transport	Composition	GHGs (kg CO_2/ton ingredient at feed mill entry)
Vegetable ingredients from Europe	1440 km road and 135 km sea (ferry)	145
Marine ingredients from Europe	500 km road and 1 617 km by sea	59
Marine ingredients from South America	500 km by road and 13 425 km by sea	197
Marine ingredients from North America	500 km road and 8 906 km sea	146
Marine ingredients within Norway	500 km road	45

Table 3-14 Data used to model crop based ingredients and GHGs as delivered to feed mill in Norway.

					GHGs (kg CO_2e/kg)		
Raw material	**Group**	**Share of feed (w%)**	**Data used in Agri-footprint**	**Comment**	**Total**	**LUC**	**N20**
Faba beans	Protein	3.0	Broad bean. meal. at plant/NL Mass	Mix: France (50%) and Austria (50%)	2.79	1.01	0.18
Guar	Protein	0.9	This is included as Legumes (see Legumes)	---	---	---	---
Horsebeans	Protein	0.2	Included as Faba beans (ses Faba beans)	---	---	---	---
Legume	Protein	2.8	Soybean. at farm/IN Mass	Modelled using processing of Brazil SPC as proxy. Input used is soybeans from India	3.66	1.47	0.21
Maize	Protein	1.1	Maize gluten meal. consumption mix. at feed compound plant/NL Mass	Mix: Germany (20%), Netherlands (25%), US (35%) and France (20%).	1.13	0.04	0.20
Pea	Protein	1.0	Pea. protein-concentrate. at plant/RER Mass	Mix: France (81%) and Germany (19%)	0.81	0.02	0.15
Pea	Starch/carbo hydrates	0.9	Pea. starch (from protein-concentrate). at plant/RER Mass	Same as for pea protein (coproducts)	1.27	0.02	0.16
Rapeseed	Oil	20.0	Crude rapeseed oil. from crushing (solvent). at plant/DE Mass	Mix: Germany (63%), France (11%) and the rest a mix from the rest of Europe.	2.64	0.58	0.87
Soy	Protein	20.6	Soybean protein concentrate. from crushing (solvent. for protein concentrate). at plant/BR Mass	All soy produced in Brazil.	6.01	4.81	0.11
Sunflower	Protein	1.4	Sunflower seed meal. consumption mix. at feed compound plant/NL Mass	Mix: Argentina (80%). China (10%) and Ucrain (10%)	1.82	0.02	0.20
Wheat	Protein	9.1	Wheat gluten meal. consumption mix. at feed compound plant/NL Mass	Mix: Netherlands (80%). Belgium(10%) and Germany (10%)	2.98	0.04	0.52
Wheat	Starch/carbo hydrates	9.1	Wheat starch. dried. consumption mix. at feed compound plant/NL Mass	Same as wheat gluten (coproducts)	0.30	0.00	0.02

3.2.9 Micro ingredients

Micro ingredients are added to the feed in small amounts to fulfil certain nutritional/biological requirements of the fish, for example minerals, vitamins and pigments. The micro ingredients composed less than 3% of the weight of the salmon feed formulated in Norway in 2017 (Table 3-10), and were mainly composed of amino acids, phosphate, pigments and vitamins.

LCI data on these inputs are not readily available and considerable efforts were spent on obtaining data that could be used. A dialogue with feed producers confirmed that such data is difficult to find and/or when available is generally not well documented, of an unknown quality, and not publicly available.

A screening from 2014 [71] showed that micro ingredients can be an important source of GHG emissions in salmon aquaculture, which motivated the effort to search for data in this study. Five years later, the situation regarding data availability has not changed much.

Vitamins and minerals compose around 25% of the micro ingredients and were modelled using data from the Global Feed LCA Initiative database [72] (the data set "Total minerals, additives, vitamins, at plant/RER Mass S"). Transport was added, 50% 1,440 km on road and 50% 13,425 km by sea which resulted in a **vitamin and mineral carbon footprint of 1.33 kg CO_2e per kg delivered to a feed mill in Norway.** Almost all, 87% of this is production of the vitamins and minerals. As a reference, ecoinvent data on production of dimethyl malonate[8], a chemical used e.g. in the production of vitamins, pharmaceuticals and agrochemicals, has a CF of 5.5 kg CO_2e per kg**.**

Phosphate is included in feed by a range of different inorganic substances [73] , very often in the form of monocalcium phosphate or mono ammonium phosphate. Due to lack of LCI data for the production of these substances, we here modelled the phosphate inputs with data from the Agri-footprint data on the production of Triple superphosphate (80% $Ca(H_2PO_4)_2$)[9]. Transport was added, 50% 1,440 km on road and 50% 13,425 km by sea. **This gives the phosphate used a CF of 0.7 kg CO_2e per kg delivered to a feed mill in Norway.**

Amino acids are another important micro ingredient that is added to improve digestion and fish health. **The use of amino acids was modelled using a carbon footprint of 10.2 kg CO_2e per kg amino acid delivered to a feed mill in Norway.** Almost all of this, 97%, comes from the production of the amino acids. This value is a best estimation based on literature data and a dialogue with feed and amino acid producers. A report by Blonk consultants, for the company Novoenzymes [74], shows a range of 5.4 to 19.7 kg CO_2e per kg amino acid produced. Dialogue with a feed producer indicate that it is fair to assume that the range for amino acids is in the range 1-20 kg CO_2e/kg, and that European production are typically represented in the low end of the range, and Asian production in the higher end of the range. Transport was added, 50% 1,440 km on road and 50% 13,425 km by sea.

The input of pigments was included with data synthetic production of astaxanthin. Astaxanthin can be produced both synthetic and naturally, e.g. from the freshwater green algae *Haematococcus pluvialis*[10]. Publicly available data on the energy use and/or carbon footprint of astaxanthin production is very limited. A publication on the techno-economic assessment of astaxanthin produced from algae report an energy use of 1,148 MWh to produce 569 kg astaxanthin [75]. It is assumed that this is pure 100% astaxanthin. With an average European electricity grid mix (0.44 kg CO_2e/kWh) this result in a carbon footprint of: (1,148*1,000*0.44)/569 = 888 kg CO_2e per kg 100% synthetic astaxanthin.

It is further assumed that the pigment volume that is reported is a solution that contains 10% pigment, thus **the CF of the pigment as it enters the feed, as 10% astaxanthin, carries a CF of 89 kg CO_2e per kg**

[8] ecoinvent name: Dimethylmalonate {GLO}| market for | Cut-off, U
[9] Agri-footrint name: Triple superphosphate, as 80% Ca(H2PO4)2 (NPK 0-48-0), at regional storehouse/RER Mass
[10] https://en.wikipedia.org/wiki/Haematococcus_pluvialis

10% synthetic astaxanthin delivered to a feed mill in Norway. Transport was added, 50% 1440 km on road and 50% 13,425 km by sea. 99% of this from production of the pigment. A dialogue with a feed producer shows that they have data (not publicly available) in the range of 50 -190 kg CO_2e/kg 10w% astaxanthin.

Greenhouse gas emissions of feed inputs used in Norwegian salmon feed in 2017 are shown in Figure 3-7.

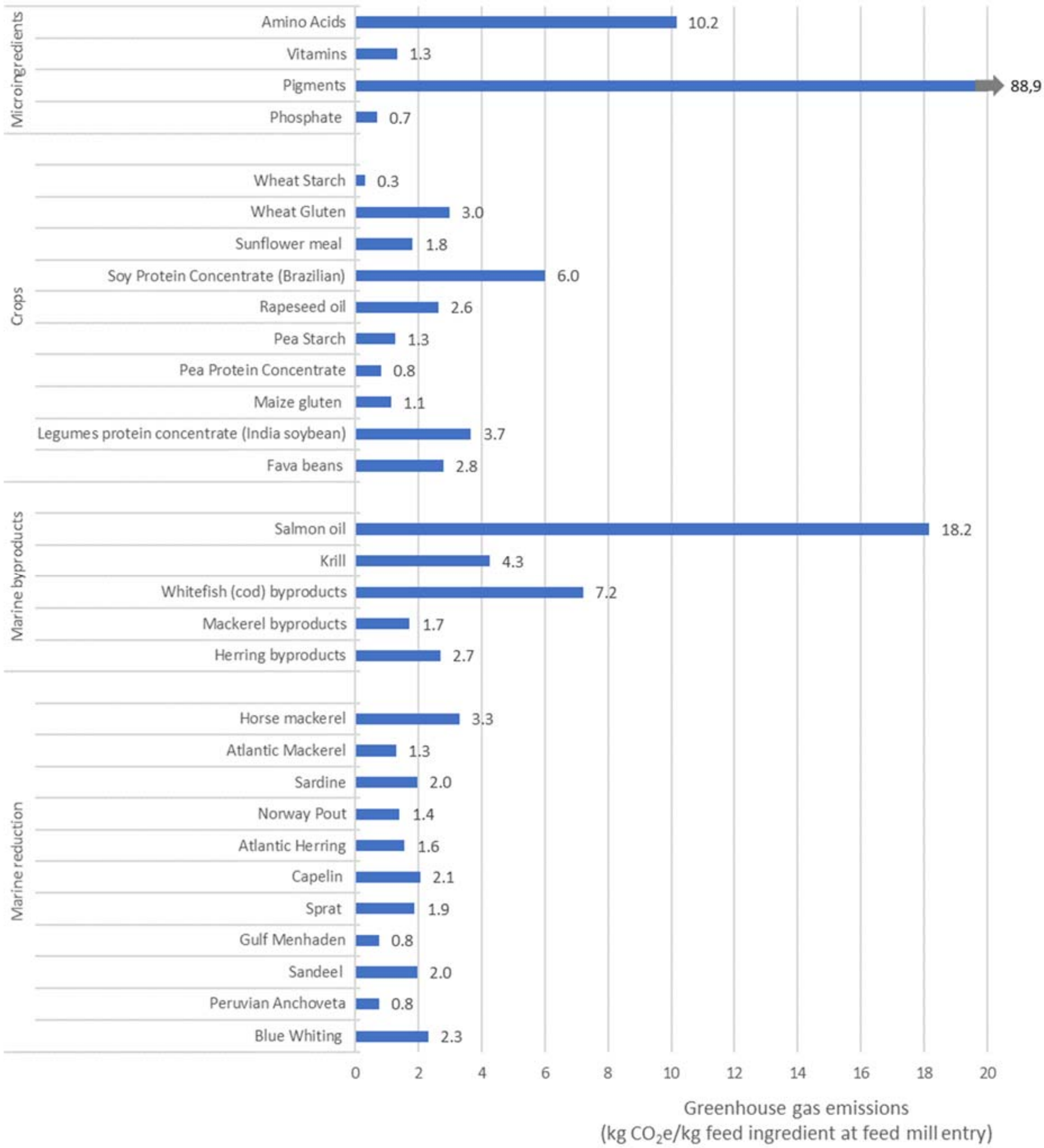


Figure 3-7 Greenhouse gas emissions per kg feed input for feed inputs used in Norwegian salmon feed in 2017.

3.2.10 Feed mill and feed transport

Data used for feed milling is based on data from two plants for two different feed producers. Table 3-15 present the energy use of the feed mills. Construction of the plant or the equipment is not included.

Transport of the feed is included with data from one feed transporter. It is assumed that each kg of feed is transported 500 km from the feed mill to the fish farm, this with a vessel that spends 0.0129 liter fuel per ton*km. The unloading of the feed is also included with an energy use of 0.4 liter fuel per ton feed unloaded.

Table 3-15 Data on the energy use and waste handling for a feed mill.

Input or activity	Value
Electricity (GJ/ton output)	0.524
Diesel (liter/ton output)	0.525
Heat from natural gas (GJ/ton output)	0.289
Liquefied Petrol Gas (LPG) (kg/ton output)	2.76
Mixed waste (plastic, cardboard, metals…) (kg/ton output)	8

3.2.11 Lice treatment

The energy that is used for handling of lice is already included in the total energy use of the fish farm, service vessels and well boats (chapter 3.2.2). Therefore, below only the production and use of the inputs of H_2O_2 and cleaner fish used to treat for salmon lice are presented.

In 2017, 54,575,000 cleaner fish were used, of these 30,862,000 were farmed, with the balance fished [76]. This input is included assuming that the farmed cleaner fish is produced in a plant similar to smolt production (chapter 3.2.1) and that the caught fish was landed by demersal coastal vessels. It was assumed that the cleaner fish was released into the cage at an average weight of 50 gr. A transport of 500 km by truck was included for both the fished and farmed cleaner fish.

The input of H_2O_2 in 2017 was 9,277 ton (100% concentration) according to BarentsWatch[11].

3.3 Mussel farming

It was not possible to get updated data for Norwegian mussel farming within the frames of this project, thus the carbon footprint of mussel products is not presented since it would involve assumptions on almost all parts of the system. However, blue mussels are associated with low energy input in the farming and harvesting of the product compared to other seafood products, mainly due to the fact that they do not require the input of manufactured feeds. The challenge for the carbon footprint of blue mussel is:

- yield, that is loss from products that are not suited for human consumption and
- transport efficiency. Since the yield from round live mussel to edible product is quite low the mass that needs to be transported is high compared to many other seafood products.

Blue mussels also present an interesting opportunity to increase the overall resource efficiency of salmon farming when it is grown on nutrients from fish farms.

[11] https://www.barentswatch.no/havbruk/kjop-av-legemidler

3.4 Processing

Processing refers to the transformation (e.g. filleting, freezing, boiling, peeling, salting, drying) of fish and crustaceans to seafood products. Preparation and processing are in this report used as synonyms.

3.4.1 Yield data

Data on edible yield is used for the conversion to the functional unit which is 1 kg edible seafood. Table 3-16, Table 3-17 and Table 3-18 presents the yield data that are used for the different products. These yields are based on the official conversion factors published by the Directorate og Fisheries [77], industry data and interviews with experts.

Table 3-16 Edible yields used for products originating in capture fisheries, except saltfish and klipfish (kg out/kg in).

Product conversion	Herring	Mackerel	Cod	Haddock	Saithe
Live to head on gutted	0.935	0.870	0.847	0.877	0.833
Live to head off gutted	0.820	0.769	0.667	0.714	0.741
Live to fillet with skin and bones	0.476	0.385	0.377	0.362	0.392
Live to edible (skin and boneless fillet)	0.410	0.385	0.308	0.317	0.333
Head on gutted to fillet			0.445		
Head off gutted to fillet			0.566	0.507	
Head on gutted to edible	0.439		0.363	0.362	0.400
Head off gutted to edible	0.500		0.462	0.444	0.450
Fillet to edible	0.861	1.000	0.815	0.876	0.850

Table 3-17 Edible yields used for salmon products (kg out/kg in).

Product conversion	Yield
Whole fish to head on gutted	0.833
Whole fish to head off gutted	0.741
Whole fish to A-trim fillet - no backbone and bellybone off.	0.633
Whole fish to B-trim fillet - no backbone. bellybone off. back fins off. collar bone off. belly fat off and belly fins off.	0.592
Whole fish to C-trim fillet - no backbone. bellybone off. back fins off. collar bone off. belly fat off. belly fins off and pinbones off	0.558
Whole fish to E-trim - skin and boneless fillet. Edible product.	0.450
A-trim fillet to edible	0.711
B-trim to edible	0.761
Head on gutted to B-trim	0.710
Head on gutted to edible	0.540

Table 3-18 Edible yields used for saltfish[1] and klipfish[2] products (kg out/kg in). Data from SINTEF Ocean.

Product conversion	Yield
Live fish to gutted head off	0.667
Head off gutted to split	0.882
Split to saltfish	0.700
Saltfish to klipfish	0.875
Klipfish to edible	0.850
Saltfish to edible	0.667

[1]Saltfish is product 15 "Cod salted split"
[2]Klipfish is product 16 "Cod salted and dried split"

The edible yield for the crustacean products was taken from FAO [78] and was 0.36 for northern shrimp. Shrimps are not only peeled but also boiled before being frozen and will lose some water, resulting in a lower yield, which was not accounted for. Despite extensive contacts with the major Norwegian producer of boiled, peeled shrimps it was not possible to get specific data on actual processing, i.e. boiling, peeling, freezing and packaging from the production plant. These processes therefore had to be approximated by other data for similar processes or by theoretical values (boiling) which was added as using the assumption that two L of water are boiled per kg fresh shrimp and that boiling water requires 418 kJ/kg water.

For king crab, two producers provided data on edible yield, stating it to be 0.33 kg/kg LW if only legs are used and double if also the crab meat in the body of the crab is used. In lack of detailed data on this matter,, it was assumed that half of the meat in the crab body was used and that the edible yield from LW of crabs hence was the average of 0.33 and 0.66 which is 0.49 (kg out/kg in).

3.4.1 Salmon processing

Salmon often undergoes several processing steps, the first one at a slaughter plant whose main product is head-on, gutted salmon, but which often also produces very minor quantities of fresh or frozen fillets (which were disregarded here). According to industry experts and available data, the freezing process itself represents a negligible part of the energy use of processing plants, it is rather the cold storage before and after processing that uses most energy and it is similar for cold and frozen storage, why processing of fresh and frozen fish was not distinguished in this study. Table 3-19 presents the energy inputs to such a plant. In addition to the energy use at the processing plant, waste handling was included with a generic process (chapter 3.4.5).

Table 3-19 Data used to model primary processing of salmon (slaughter).

Input	Data used	Comment
Electricity input (kWh/ton LW input)	107	Baris et al. present a range of 70-88 kWh/ton LW input [79]. Data from industry indicated up to 107 kWh/ton LW input, which was used
Fuel (L/ton LW input)	0.13	Data from industry (one plant)

3.4.2 Processing of whitefish

Whitefish is often landed in gutted (or headed and gutted) form and further processing most often means either filleting and/or freezing. There are 280 processing plants for whitefish in Norway[12]. According to industry experts and available data, the freezing process itself represents a negligible part of the energy use of processing plants, it is rather the cold storage before and after processing that uses most energy and it is similar for cold and frozen storage, why processing of fresh and frozen fish was not distinguished in this study. Processing of demersal fish was modelled using an energy use of 363 kWh/ton LW, based on data from one of the major whitefish companies with 10 plants that during 2016 to 2017 processed 170,000 ton of fish using 61.4 GWh of electricity. Compared to the energy intensity of salmon processing, this is considerably higher. One reason is that some demersal/whitefish plants only operate at parts of the year, one example from Myre[13] presented a plant with a capacity of 100 ton per day that was only utilized 25 % of the year. When parts of the energy use is caused by heating, ventilation etc., that is occurring even though there is no production, this will reduce the overall energy efficiency of the plant. Fuel consumption of 0.13 liter/ton was also included, based on information for a salmon slaughter plant, as it is assumed that also demersal processing uses some fuel. In addition to the energy use at the processing plant, waste handling was included with a generic process (chapter 3.4.5).

3.4.3 Processing of saltfish and klipfish

Data on the salting and drying processes of cod was collected from experts within SINTEF Ocean. For salting, 1 kg salt is used and drying of saltfish to klipfish uses 250 kWh/ton klipfish. It is assumed that the salting and drying is taking place within the same plant as the primary processing, so that no extra infrastructure or transportation between these steps is added.

3.4.4 Processing of pelagic fish

Herring and mackerel are normally landed round without any form of processing onboard. There are around 30 processing plants for pelagic fish in Norway[12]. Preparation here includes freezing of round herring and mackerel and is modelled with an electricity intensity of 216 kWh/ton LW, based on data from a report on energy use in the Norwegian pelagic industry and three plants [80]. A fuel consumption of 0.13 L/ton into processing is also included, based on information for a salmon slaughter plant, but it is assumed that also a pelagic processing plant uses some fuel. In addition to energy, the construction of the plant and waste handling is modelled using a generic process (chapter 3.4.5).

3.4.5 Loss of products and by-product utilization

Loss is included in the following ways for fished products: Losses in fisheries (discard) is included indirectly since the fuel intensities are calculated per unit of fish landed. Thus, fish that is not landed will reduce the fuel efficiency (compared to if it was landed and used). Further by-products from capture fisheries that are not utilized are included based on data from SINTEF and a survey of by-product utilization in the Norwegian seafood industry [81] , which concludes that in the whitefish industry 60% of by-products (generated at sea, like guts, and on land, like heads, backbones etc.) are utilized and in the pelagic industry utilization is 100%.

For salmon, loss/mortality in farming is included by using the *economic* FCR which includes all feed utilized at the farm as input and only the mass of fish that is actually sold, so that the FCR is higher than if the *biological* FCR had been used. This has a similar effect on the efficiency as discards in fisheries. After harvest, 91% of the by-products from salmon slaughter and processing in Norway is somehow utilized, based on a recent report analyzing rest raw material used in the Norwegian seafood sector [81].

[12] Link: https://www.pwc.no/no/publikasjoner/Sjomatbarometer_WEB_V01.pdf
[13] Link: https://www.fylkesmannen.no/contentassets/0abfa5947d804ff08a525afa6dad9435/ny-mappe/soknad-om-sarskilt-tillatelse-etter-forurensingslovens--11---myre-fiskeindustri-as.pdf

Loss during transport is not included, but the potential effect of such loss is illustrated for selected cases in chapter 5.4.

For by-product utilization in the market, i.e. in most cases after export, unpublished data was obtained from the data and analysis provider Kontali Analyse AS for all products except for king crab, where the rate therefore was assumed to be zero, which was confirmed by the producers/exporters.

3.4.6 Waste and infrastructure of processing plants

Material inputs (except the raw material/fish), waste handling and infrastructure is included for all processing plants based on data from one salmon slaughtering plant.

Table 3-20 Data used for material inputs, waste handling and infrastructure in processing per ton of fish processed.

Input	Comment and value
Building hall	Estimated based on information that a plant that is 15,000m^2 has an annual production of 90,000 ton and an expected lifetime of 30 years: 15,000/(90,000*30)= **0.0056 m^2/ton**
Fresh water input	6.1 m^3/ton
Soap	0.3 kg/ton
Detergent	380 gr/ton
Metals	0.23 kg/ton
Biowaste	185 kg/ton
Wood	0.25 kg/ton
Non sorted waste	2.21 kg/ton

3.4.7 Freezing of fish

Freezing of the frozen products is already included in the energy use of the processing plants (chapter 3.4.1, 3.4.2, 3.4.3, 3.4.4) and data and experts suggest that the main part of the energy in processing plants is used for cold storage, with minor differences if it is chilled or frozen storage and that the proportion used for the freezing process is negligible. Thus, no extra energy use is added to the frozen products in order to avoid double-counting. For salmon slaughter plants Baris et al. estimate that as much as 69% of the energy that is used is used by the refrigeration system [79].

3.4.8 Chilled storing

Chilled storing is included for the fish that is used for saltfish production (90 days) and for the bait (60 days). Other products are also stored but storing on the same location/plant as where the fish is prepared will be included in the annual total energy use of the processing plants.

Chilled storage of products is modelled by energy use and emission of refrigerant, assuming that the refrigerant 134a is used.

Table 3-21 presents key data for the chilled storing. With these data chilled storing contributes with a CF of 0,524 gr CO_2e per kg stored per day (kg CO_2e/kg*day).

Energy use in chilled and frozen storage show a wide range, 26-130 kWh/m3/year [82]. It is assumed that 75% of the storage volume is utilized, is operating 250 days per year and that fish is packed with a density of

20 kg fish in a box that is 0.045 m3 [83] (444 kg fish/m3), this gives an energy use in the range of 0.31 – 1.56 kWh/kg*day.

Refrigerant emissions from cold storage are included based on the assumption that a refrigeration system that is charged with 5 kg refrigerant can service a 40 feet container with a volume of 70 m3. Further an annual loss rate of 10% is assumed.

Table 3-21 Data used to model chilled storing.

Input/activity	Value
Operating days of storage (days)	250
Fish density (kg fish/m3)	20/0.045 = 444
Storage volume utilization (n/n)	0.75
Energy use in storage (kWh/year/m3)	78 (26-130)
Kilo specific energy use (kWh/kg*day)	78/0.75/444/250 = 9.4e-4
Refrigerant charge per volume of storage (kg/m3)	5/70 = 0.07
Refrigerant yearly emission rate (n/n)	0.1
Kilo and time specific refrigerant emission rate (kg refrigerant/kg fish*days)	5/70*0.1/444/250 = 6.4e-8

3.5 Transport to market

After processing, products are distributed to their typical markets by road, rail, sea and air, mostly abroad, but in some cases the market is domestic. Table A-9-1 (appendix A) presents the different transport methods and routes that are used for each product.

Table 3-22 presents the CFs of the transports that are used in the export of the products, more details on each transport is presented in the following chapters.

Table 3-22 Summary of CFs of transports used in the export of the fish products.

Transport	CF (kg CO_2e/t*km)
Road transport of fish (refrigeration not included). See chapter 3.5.1.	0.076
Road transport of other in- and outputs. See chapter 3.5.1	0.090
Ferry (roll on roll off ferry). See chapter 3.5.4.	0.060
Sea transport of frozen fish Norway to Europe. See chapter 3.5.4.	0.057
Sea transport of fish transoceanic. See chapter 3.5.4.	0.022
Air transport, range dependent of type of flight, distance and load utilization, see chapter 3.5.3	0.480 – 1.407

3.5.1 Road transport

Most transportation of Norwegian seafood products is done by road, either it is domestic or exported. Also for products that are airfreighted or shipped, parts of the distribution chain is done by truck (Table 2-1; Table A-9-1). Table 3-23 presents key parameters for the modelling of road transportation of fresh and frozen products. These data are based on information from fish exporting companies and the road transport operators. Transport are included with primary data because we consider it reasonable to assume that the load utilization of the outgoing transport is better than that of the average road transport.

The load utilization factor for trucks transporting fish is in general close to 100% when packaging is included. The fish export on road is done with Heavy Duty Vehicles (HDV) with a total weight of around 40 ton (payload and vehicle). The maximum cargo weight such vehicles can carry, the payload, is limited by EU law13F14 to 25 ton.

To include infrastructure (road wear) and production of the vehicle the ecoinvent process for a EUR5 heavy duty vehicle14F15 was adjusted to reflect the fuel use and load utilization factor presented in Table 3-24. This was used where the load utilization factor is not known as well as for the fish product transport, thus a more conservative and less efficient transport is used.

Fresh fish is transported in EPS boxes that can carry 20 kg of fish and approximately 5 kg of ice. Frozen fish is transported in cardboard boxes weighing 2 kg and carrying 25 kg of fish. These boxes are placed on Euro pallets, one truck can carry 33 pallets weighing 25 kg. Table 3-23 presents the total load for fresh and frozen fish transport on HDV road vehicle.

Table 3-24 presents the load utilization factor that are used, the fuel factor and the resulting fuel efficiency of this transport as liters of fuel per ton transported one km (L/t*km). The average utilization factor is calculated according to the recommendations of the PEF guide [23] and takes into account the difference in load utilization in both the outgoing and returning transport of the truck. This method assume that the distance of export and return is equal:

$$Average\ utilization\ factor = \frac{load\ utilization\ factor\ export + load\ utilization\ factor\ return}{2}$$

Equation 3-3

Table 3-23 Data used to calculate utilization of load capacity on trucks for transportation of fresh and frozen fish (based on pers. comm. with fish exporting companies and transport operators).

		Product/value	
Parameter	**Unit**	**Fresh**	**Frozen**
Fish per truck	kg	18,500	22,000[16]
Weight per box	kg	0.60	2.00
Fish per box	kg	20	25
Ice per box	kg	5	0
Euro pallets per vehicle	pieces	33	33
Weight/Euro pallet	kg	25	25
Total payload. Fish + ice + packaging	ton	24.50	25.03

[14] Council Directive 96/53/EC of 25 July 1996 laying down for certain road vehicles circulating within the Community the maximum authorized dimensions in national and international traffic and the maximum authorized weights in international traffic. ELI: http://data.europa.eu/eli/dir/1996/53/2015-05-26

[15] Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Cut-off, U

[16] Based on information from Lerøy they send as much as 23 ton of frozen fish per truck.

Table 3-24 Key parameters used in the modelling of truck transportation of seafood (based on pers. comm. with fish exporting companies and the road transport operators).

Parameter	Unit	Value
Fuel use HDV trucks	l/km	0.40
Max payload (by EU regulations)	ton	25
Average European utilization factor for HDV (PEF guide [23])	actual payload/max payload	0.64
Average utilization factor export	actual payload/max payload	1
Average load utilization factor, export and return	actual payload/max payload	0.82 (0.64+1)/2 = 0.82
Fuel use HDV trucks, average export and return	L fuel/ton*km	0.020 0.4/25/0.82 = 0.020

3.5.1.1 Transport time

The time needed for transportation is relevant as refrigeration is required on trucks transporting seafood and the fuel use needed for refrigeration as well as the leakage of refrigerants depends on the time refrigerated rather than on the distance. **The transport time is calculated from the distance assuming an average speed is 50 km/h.** Rest and working hours for drivers is regulated by law[17]. Truck drivers can drive for 9 hours, but also have to rest for 11 hours per day. Routes are often chosen to optimize time within these rules, which explains why ferry routes between Sweden and Denmark, Germany and Poland are often chosen over the direct connection over the bridge between Sweden and Denmark, as the former offer a couple of hours of rest for the driver in the way from Norway to continental Europe.

3.5.2 Refrigeration in transport

All transport modes except airfreight require refrigeration during transport. For shipping and rail freight, this is included in the ecoinvent data used. However for the type of road transport that is used for Norwegian seafood export this kind of data was not available in ecoinvent and emission of refrigerant and energy used for refrigeration was added using data from literature and manufacturers of this kind of equipment (Thermo King).

Energy used by the refrigeration system show a high degree of variation, a project report by Delft [84] present a range of 0,5 to ~3.75 liters fuel/hour, but concluded to use 2.5 liters fuel/hour and this is used in this assessment [84]. Producers of refrigeration systems claim consumption around 0.5 liters fuel/hour.

The leakage rate, how much of the refrigerant in the system that is emitted per year is set to 10%. This is based on interview with producers and confirmed by ecoinvent data that show a range of 10-37%. For Euro6 vehicles ecoinvent use a refrigerant emission rate of 10% and for Euro5 14%.

The total volume of refrigerant in each system is set to 7.6 kg, this based on data from Thermo King for the system they consider the most common today. This volume varies considerably, and 7.6 kg is a high volume in that range. ecoinvent use a volume of 4.5 kg refrigerant17F18.

The refrigerant that is used is R452A, a mix as presented in Table 3-25, this is also based on data from manufacturers of this kind of equipment.

[17] Link to Statens Vegvesen page on driving time and rest periods: https://www.vegvesen.no/en/vehicles/professional-transport/driving-time-and-rest-periods

[18] Link to ecoinvent: https://v34.ecoquery.Ecoinvent.org/Details/UPR/00FB2472-1578-4728-83CA-5D39E85A04EA/290C1F85-4CC4-4FA1-B0C8-2CB7F4276DCE

Table 3-25 Key data related to refrigeration systems on trucks (data from producers of refrigeration equipment e.g. Thermo King).

Parameter	Data
Type of refrigerant used	R452A. A mix of 30w% R123yf, 11w% R32 and 59w% R125A. This mix have a GWP of ~2140 kg CO_2e/kg refrigerant.
Volume of refrigerant in system	7.6 kg
Yearly leakage rate	10% (based on information from vendors and confirmed by ecoinvent data)
Yearly use of the refrigeration unit	1,500 hours
Refrigerant emission rate	(7.6*0.1)/1,500=0.00038 kg R452A emitted per hour
Refrigeration system fuel use	2.5 liter/hour [84]

3.5.3 Airfreight

Two of the products included are air freighted, live king crab to Seoul and fresh, gutted salmon to Shanghai. For calculations of GHG emissions from air transportation, the environmental calculation tool of the Network for Transport Measures (NTM), NTM Calc 4.0, was used [19] (advanced level which requires a login and license) in order to be able to model both dedicated cargo freight and belly freight (combined passenger and cargo freight). The ecoinvent database (used for other background data) only includes cargo airfreight and early on it was clear that some of the airfreighting of Norwegian seafood is done on belly freighters and that there would be questions about how that type of airfreight performs compared to cargo freight. Cargo flights of ecoinvent and NTM were compared and it was concluded that these were relatively similar and therefore assume that the use of different databases for air and road and sea transports does not affect a comparison between transport modes.

The NTM tool calculates the emissions from air transport using the sum of two factors: Constant emissions factor (CEF – use of fuel during take-off and landing) and Variable emissions factor (VEF - multiplied by the flown distance). The user of the tool adds weight of shipment, load factor and distance, the load factor for cargo and passengers are handled separately. A higher load factor makes use of fuel more efficiently, and affects the energy needs greatly. Goods can be transported on both passenger aircrafts (known as belly freighters) as well as on pure cargo flights. In the case of cargo transport on belly freighters, emissions are allocated by mass between passengers and cargo, where each passenger (including luggage) is assumed to account for 100 kg of weight. This is consistent with the general approach for allocation used in the project and reflects that cargo on a belly freighter is a part of the business of the airline and contributes to the profitability of the flight. This methodology for allocating emissions between passengers and cargo is also recommended by IATA/ICAO[20].

[19] https://www.transportmeasures.org/en/

[20] IATA recommended practice 1678: https://www.iata.org/whatwedo/cargo/sustainability/Pages/carbon-footprint.aspx

The fuel use per ton belly cargo is then calculated as:

$$Fuel\ use\ \left(\frac{L}{ton}\right) =$$

$$= \frac{total\ fuel\ use\ of\ flight}{passenger\ capacity * 0.1\ ton * passenger\ load\ factor +\ belly\ cargo\ capacity * cargo\ load\ factor}$$

Equation 3-4

The lower cargo capacity of belly freighters (around 14 ton) in relation to cargo flights (92 ton), leads to higher emissions per ton flown a certain distance on a passenger flight compared to a cargo flight using the same type of aircraft. It was not possible to obtain detailed load factors for the various airfreight legs involved in the supply chains studied and we chose to assume the highest possible load factors in each case. In addition, no flying from northern Norway to Oslo in the case of king crab (although this was indicated by one of the producers) and no low-load return flights from Asia was included.

While there are many alternative flight routes and these can also change depending on many factors, the scenarios selected for transportation of salmon and king crab by air reflect an average as described by various representatives for the seafood industry, airlines and the company running Norwegian airports, Avinor. Salmon is generally trucked to Oslo and then flown on cargo flights directly to Shanghai, while king crabs are flown in much smaller volumes on passenger flights that fly out from Oslo after trucking from northern Norway and make one stop on the way to Asia. As fuel use increased unproportionally during take-off and landing, the number of flight legs is more important than the mere distance for resulting airfreight emissions.

For the salmon a flight from Brussel to Oslo is included to include the positioning of the cargo airplanes. This inclusion is based on news cases regarding salmon transport by air [21]. The alternative to the airplane repositioning from Europe to Oslo, to pick up the salmon, is probably to transport the salmon to airports in Europe by road. The flight from Brussel to Gardermoen also included a load factor of 50%, meaning that it is actually not modelled as empty. The load factor of the flight from Oslo to Shanghai is 85%, that is the maximum for that distance as the NTM model takes into account the fuel that is necessary for that distance. It was decided to use such high load utilization based on the simple assumption that the producers will make sure to fill these flights as low utilization will probably be very expensive. However, the airfreight industry point at an average load utilization factor of less than 50%. Flight route and load utilization is explored more in the sensitivity analysis (chapter 5).

[21] https://fiskeribladet.no/nyheter/?artikkel=55295 and https://ilaks.no/laks-er-et-av-verdens-darligst-betalte-flyfraktprodukter/

Table 3-26 Data used for air transport, per kg cargo, used for salmon and king crab (source: NTM, by calculation model "shipment transport weight" and intercontinental flight).

Flight	Type of transport	Distance (Km)	Cargo load factor (%)	Passenger load factor (%)	Cargo carrier capacity (kg)	Fuel use (kg)	CF tank-to-wheel (kg CO_2e)
Oslo-Istanbul (king crab, product 23)	Passenger and cargo - Belly freighter. Cargo, range-based average	2,525	100	90	14,000	0.70	2.22
Istanbul-Seoul (king crab, product 23)	Passenger and cargo - Belly freighter. Cargo, range-based average	8,097	100	90	14,000	2.05	6.51
Oslo-Shanghai (Salmon, product 3)	Freight aircraft, range-based average	8,252	85	---	91,937	1.11	3.52
Brussel-Oslo (Salmon, product 3)	Freight aircraft, range-based average	1,200	50	---	---	0.33	1.04

3.5.4 Sea freight

A number of products are transported in frozen form to markets in Asia by ship: king crab, salmon, cod, herring and mackerel, in one case for processing, cod in China.

Shipping (except for ferries) was modelled using the ecoinvent data.
Sea transport from Norway to Europe was included using data from the ecoinvent process "Transport, freight, inland waterways, barge with reefer, freezing {GLO}| market for | Cut-off, U" that contribute with a CF of **0.057 kg CO2e/t*km**. Trans-oceanic sea transport was included with the ecoinvent process "Transport, freight, sea, transoceanic ship with reefer, cooling {GLO}| market for | Cut-off, U" that contribute with a CF of **0.022 kg CO2e/t*km**.

So called Roll on roll off (Roro) ferries were used as part of truck transports (e.g. for trucking from Sweden to Denmark and from Sweden to Poland) and data for this was taken from NTM. That RORO ferry transport contribute with CF of **0.060 kg CO2e/t*km**.

3.5.5 Transport packaging

Two types of transport packaging were modelled, for fresh fish an expandable polystyrene (EPS) box and for frozen fish a cardboard box with a plastic liner, based on information from producers and exporters. Data used is presented in Table 3-27.

Table 3-27 Key data used for transport packaging.

Data	EPS box	Cardboard box
Weight of box (kg)	0.600	2
Fish per box (kg)	20	25
Dimensions (mm)	800 x 400 x195	793 x 393 x 210

Data on the EPS box was extracted from an Environmental Product Declaration (EPD) of fresh fish transport with EPS box[22], presenting the carbon footprint, of "one delivery of 1,000 kg fish using sector average 20 kg EPS standard fish boxes to market in Norway/Europe". In the assessment the EPS box carries 22.5 kg of fresh fish, so the conversion factor to calculate the GHGs of one box is 1,000 kg/22.5 kg = 44.4.

The EPD presents the whole life cycle of the box, also potential benefits from material recycling. However, in this assessment, only the production of the box and the stages to the point where it is compressed and ready for material recycling is included. Thus, the potential benefits from material recycling are not included in our assessment, nor are emissions from incineration of used EPS boxes, if that is the end of life treatment. Resulting emissions with these assumptions, from production of polystyrene granulate, extrusion of EPS and molding of box, transport of empty box and compression of used boxes and transport of compressed boxes to end-of-life treatment is **3.2 kg CO_2e per EPS box.**

Data on size and weight of the cardboard box is retrieved from communication with producers of such packaging. Unfortunately, the cardboard box producers we contacted were not able to document the CF of their products through an EPD, or able to provide any other data such as energy use in their production. The production of the production of the cardboard box was then included using ecoinvent data.

3.6 Electricity and fuel inputs

Electricity used in the foreground system, or directly in the value chain of the seafood products, is modelled as average European grid mix with a carbon footprint of **0.44 kg CO_2e/kWh** with the ecoinvent data "Electricity, medium voltage {Europe without Switzerland}| market group for | Cut-off".
European electricity is used since use of electricity within Europe is linked physically, economically (e.g. through certificates of origin) and politically. One example of why electricity used in Norway should be considered as European electricity, is that only 14% of the electricity bought in Norway have Guarantees of Origin (GOs), thus renewable energy sources. The remaining should use the residue mix that NVE gives a CF of 0.52 kg CO_2e/kWh[23].

For processing in China, the electricity is modelled with the ecoinvent data "Electricity, medium voltage {CN}| market group for | Cut-off" that carries a carbon footprint of 1.00 kg CO_2e/kWh. The reason for using a country specific electricity mix for China is that it is different from European electricity production mix and that European and Chinese electricity production and consumption are not in any (known) way connected.

Production and distribution of diesel fuel used by the fishing vessels, vessels used in salmon aquaculture and road transport is included by the ecoinvent data "Diesel, low-sulfur {Europe without Switzerland}| market for | Cut-off,", the production of this diesel carries a carbon footprint of 0.54 kg CO_2e/kg diesel. Combustion of the diesel is modelled with emission factor from technical guidance documents to prepare national

[22] Link to EPS EPD: https://www.epd-norge.no/getfile.php/1310956-1566200454/EPDer/Emballasje/793_EPS-fiskekasse--20kg-standard--EPS-fish-box--20kg-standard_en.pdf
[23] Link to NVE page on Guarantees of Origin and residual CF: https://www.nve.no/energiforsyning/varedeklarasjon/nasjonal-varedeklarasjon-2018/

emission inventories by SSB [85]. **The complete process of producing, distributing and combusting diesel carries a carbon footprint of 3.2 kg CO_2e/L.**

For conversion from liter to kg of diesel, a density of 0.84 kg/l is used.

3.7 Waste treatment

Waste is in general included to the point where it is taken care of either through incineration or other end of life treatment. Products that are generated from the waste, such as energy and materials are not included, in other words no credits are given for material recycling. For materials that are recycled, the system is cut off at the stage where the product becomes an input to the material recycling system.

Two important waste flows in the foreground system are transport packaging and seafood that is not consumed or otherwise utilized, i.e. product losses.

Transport packaging. There are two types of transport packaging, EPS and cardboard. Both can be material recycled and incinerated with energy recovery. In this assessment both packages are included up to the stage where they are compressed and made ready for delivery to a waste management company.

Waste handling of fish that is not utilized is included with ecoinvent data for municipal waste treatment.

4 Results

4.1 Overall greenhouse gas emission results

The presentation of results starts with overall results for all products: first at landing/farmgate, then for the full supply chains. After that, details about drivers of greenhouse gas emissions are shown for salmon products and for the products from fisheries.

Figure 4-1 presents GHGs at landing (at slaughter for salmon) for the different species. The error bars indicate the range behind the average values used to calculate the default values for each product in terms of minimum and maximum levels, based on the available information. For the products from fisheries, the range reflects the variation in the fuel efficiency of the different vessels and vessel segments landing each species. For salmon, the range reflects the range in feed efficiency, feed composition and energy use. Note that these ranges do not represent optimized values, but the actual range based on the variation in selected important climate aspects of each product which shows that there are considerable differences and options for improvement by individual producers. The graph also shows clearly that emissions of salmon and crustaceans are considerably higher than demersal and in particular pelagic fish. As mentioned in chapter 3, trout had to be excluded as it was not possible to find any difference in the key parameters eFCR, feed composition or edible yield between salmon and trout so it would have been identical to salmon and blue mussels had to be excluded due to lack of data (products 8-10).

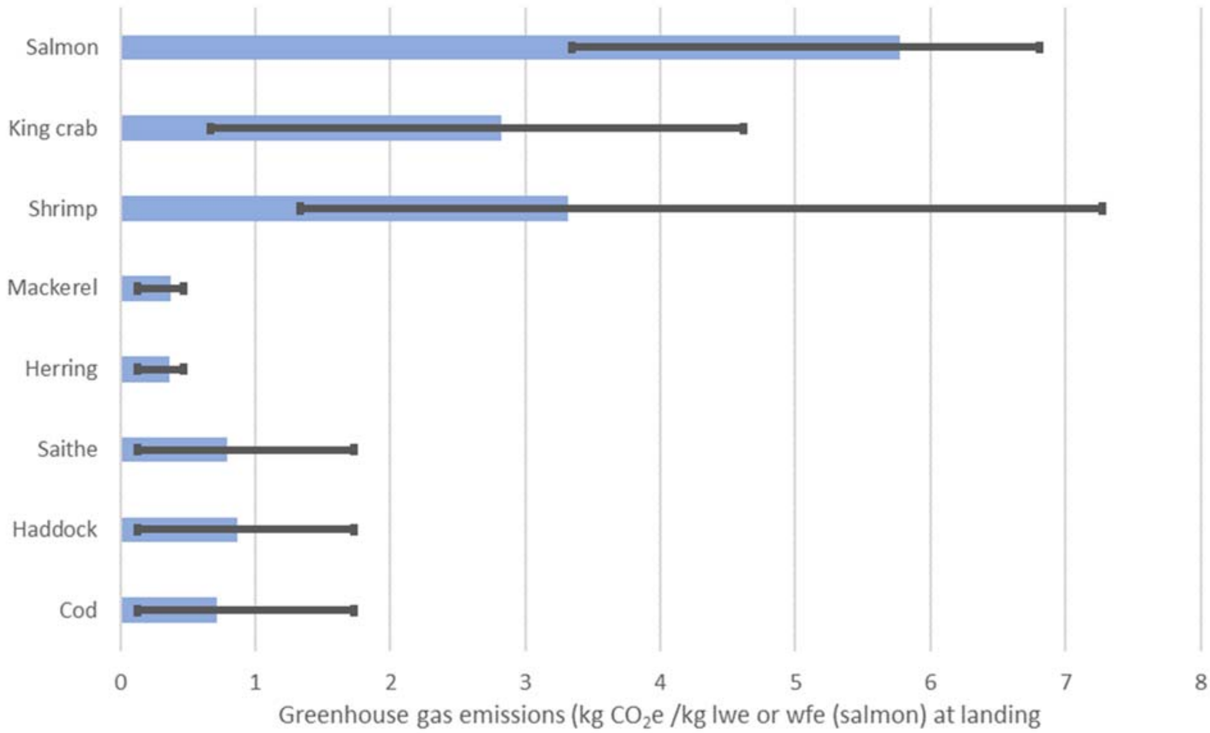


Figure 4-1 Greenhouse gas emissions at landing/slaughter for the studied species. Error bars show min and max values based on best and poorest current practice.

In Figure 4-2, total results for all supply chains are presented and some patterns can be identified. The first observation is that the two highest values are the two products that are airfreighted to markets, salmon (product 3) and king crab (product 23). Airfreighting is indeed the single largest contributor to total emissions for these products (Figure 4-3), representing 51 and 76% of total emissions, respectively. Note that king crab is flown as belly freight on passenger flights (with stopovers), while salmon is flown on dedicated cargo flights directly from Oslo to Shanghai.

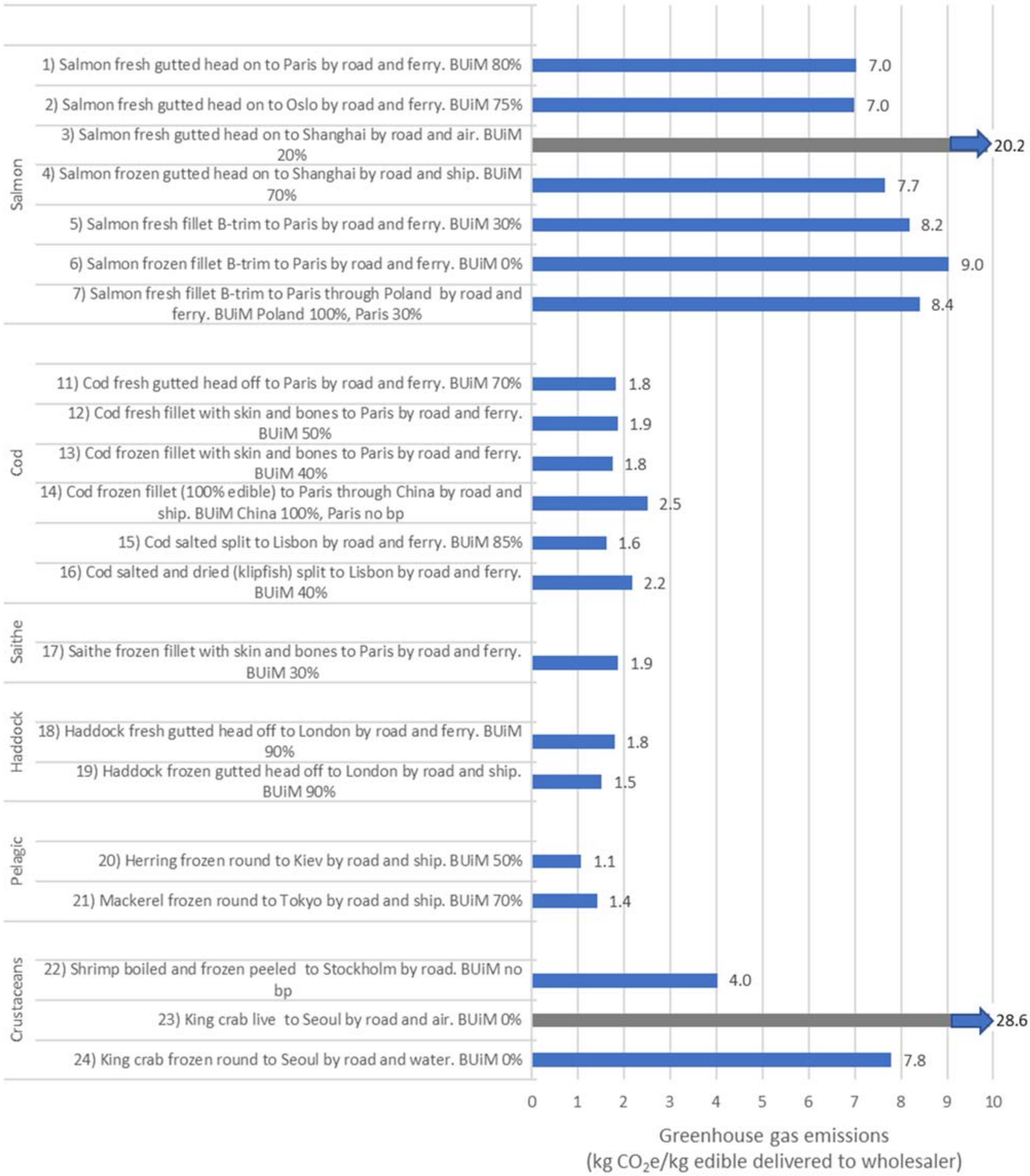


Figure 4-2 Greenhouse gas emissions of all studied products (kg CO_2e/kg edible product delivered to wholesaler) BUiM = By-product use in market.

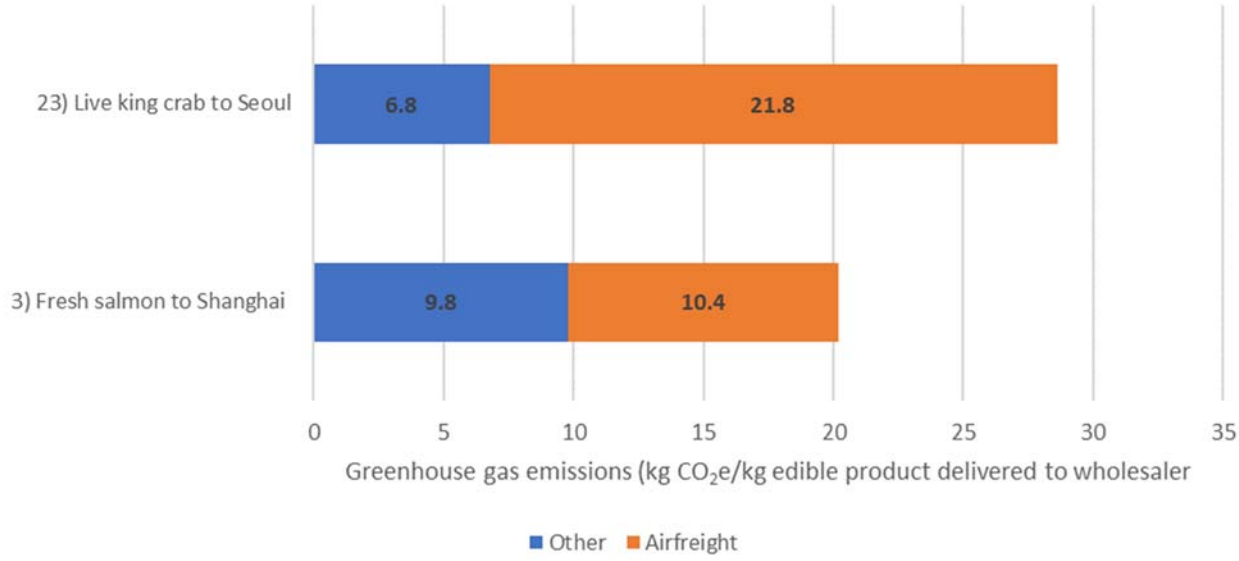


Figure 4-3 Greenhouse gas emissions of air freighted products.

4.2 Results for salmon products

Salmon products, except the airfreighted product, caused emissions of between 7-9 kg CO_2e/kg edible salmon in the market (Figure 4-4), depending on product form, packaging, transport mode and distance and perhaps most importantly, the extent of by-product utilization. The latter varies between 0 % (product 6, frozen to Paris) and 100 % (product 14, processed in China). When by-products are further utilized (e.g. to produce feed), these carry their share of the upstream environmental burden and therefore lower emissions of the edible product. If by-products are not used, all impacts are placed on the edible portion. Processing in Poland only adds very marginal emissions as evident in Figure 4-4 (compare products 5 and 7).

The result for farmgate salmon is 5.8 kg CO_2e/kg LW salmon produced in 2017 (Figure 4-1), of which 1.6 is due to LUC (i.e. 4.2 without LUC). Findings from previous salmon LCA studies about the importance of feed production are confirmed (Figure 4-4) and even reinforced when LUC is included. Climate impacts from land use change is today considered a scientific fact [3] and relevant standards for environmental assessment of feed require its inclusion [12]. Except for the airfreighted salmon product (where feed is of lower relative importance), feed represents between 75-83% of total GHG emissions of salmon delivered to the wholesaler. A detailed breakdown of the carbon footprint of the farmgate salmon is presented in Figure 4-5. The importance of LUC and the rest of the feed production is evident, but also that beyond feed, the remaining climate impact is distributed fairly evenly between a range of activities. It may appear as if salmon lice does not affect the GHGs of salmon very much (considering the bar that contains production of farm equipment, medicines and lice treatment (H_2O_2 and the farming of cleaner fish), but it is important to know that disease and parasites also affect other bars, perhaps most importantly the feed bars by increasing the eFCR through increased mortality (from either disease or stressful treatments) or reduced growth. In addition, the activity of service vessels and wellboats has increased, partly for the treatment of disease/parasites. The key message from this is that in order to reduce climate impact from salmon farming, all parts of the production system, including feed producers and sub-contractors, need to focus on changing to low-emission technologies and to sourcing of low-impact raw materials.

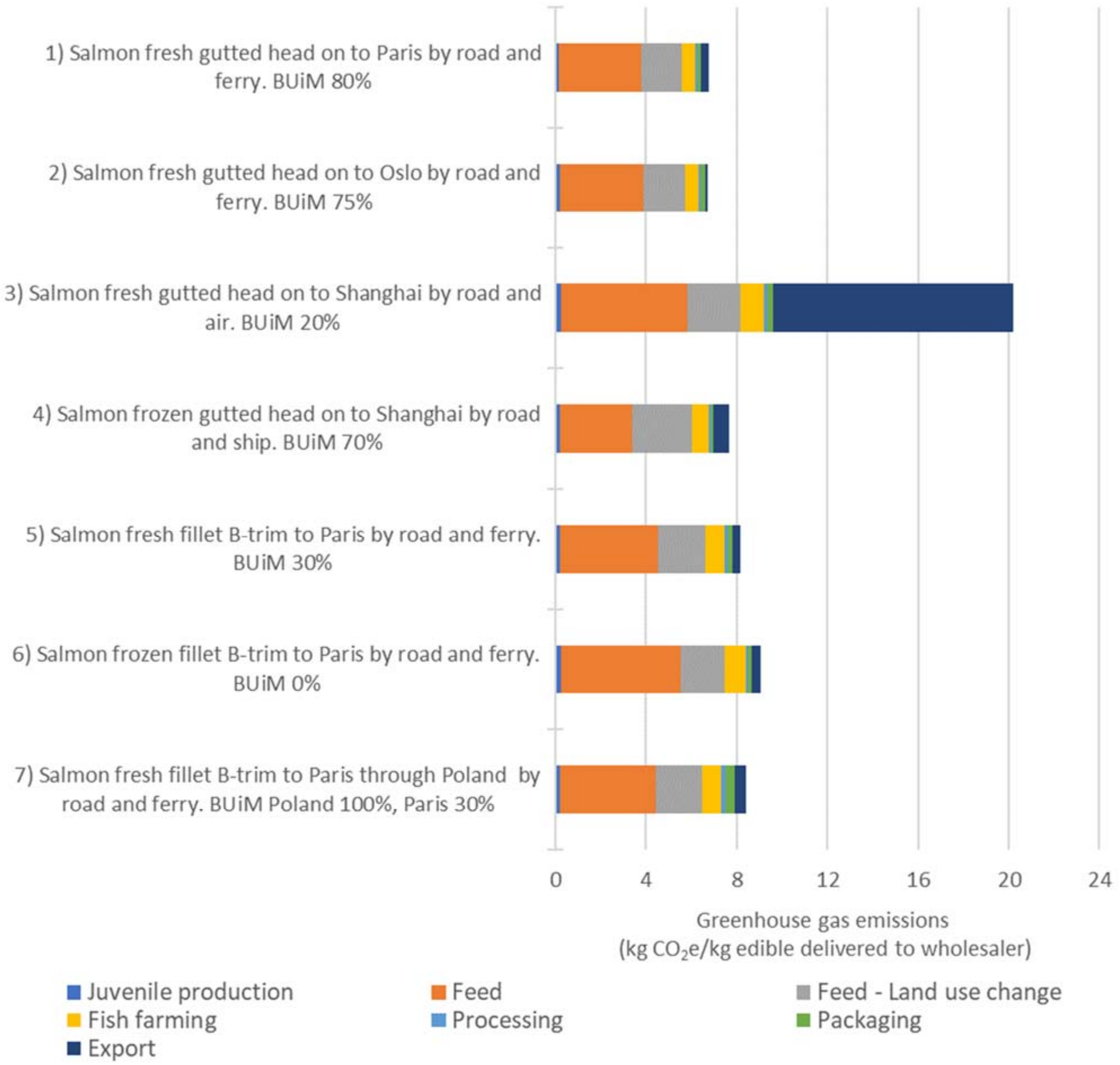


Figure 4-4 Greenhouse gas emissions of all salmon products (kgCO_2e/kg edible product at wholesaler) BUiM = By-product use in market.

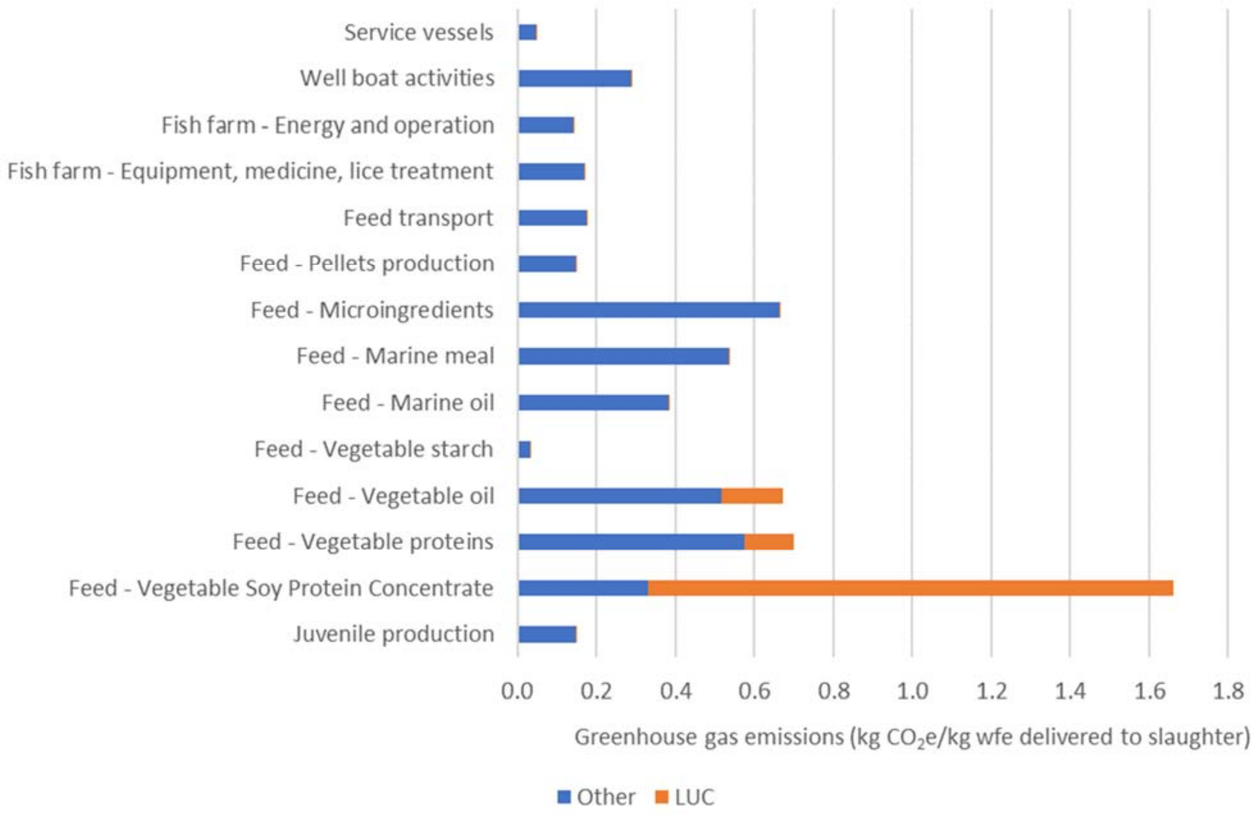


Figure 4-5 Detailed greenhouse gas emissions per kilo farmgate salmon of different activities and feed inputs, indicating the contribution from direct Land Use Change separately.

Looking a bit closer at the importance of the different feed inputs, some results stand out. Micro ingredients have to our knowledge not been included in published LCA studies of salmon (or other animal production systems). They represent a small proportion of the feed (3%), but a disproportionate contribution to GHGs, due to their relative GHG intensive production per kg of feed input (Figure 4-6). This graph shows that some inputs give a disproportionate contribution to the footprint in relation to the volumes used, namely micro ingredients and soy. Soy protein concentrate (SPC) has become an important input to the feed of farmed Norwegian salmon, used to replace fish meal in feeds as a protein ingredient. It represents a considerable part of the feed (21%), but almost twice as much of the carbon footprint. The relatively high footprint of SPC is due to expansion of cropland used for soy in Brazil connected to land use change, as described earlier. SPC was modelled using the Agri-footprint process "Soybean protein concentrate, from crushing (solvent, for protein concentrate), at plant/BR Mass". This process models soybeans farmed in Brazil that are transformed to SPC (56%), hulls (7.3%), molasses (16.4%) and oil (20.3%) in an extraction process using ethanol and energy. Impacts are allocated between the different outputs using mass allocation. More than 90% of the CF of the SPC arises from the growing of the soybeans, the remaining part is split between the ethanol and the energy (steam) input.

Micro ingredients are added to supply the nutritional needs of the fish and some of them (e.g. amino acids) are added for good digestion and fish health and are thought to contribute to lower the eFCR, which may outbalance the emissions caused by their production. However, we have no data available on the eFCR and fish losses in a hypothetical grow-out without the use of these micro ingredients and therefore at this point cannot evaluate this. We conclude that better understanding on the role of micro ingredients and data on their production is needed.

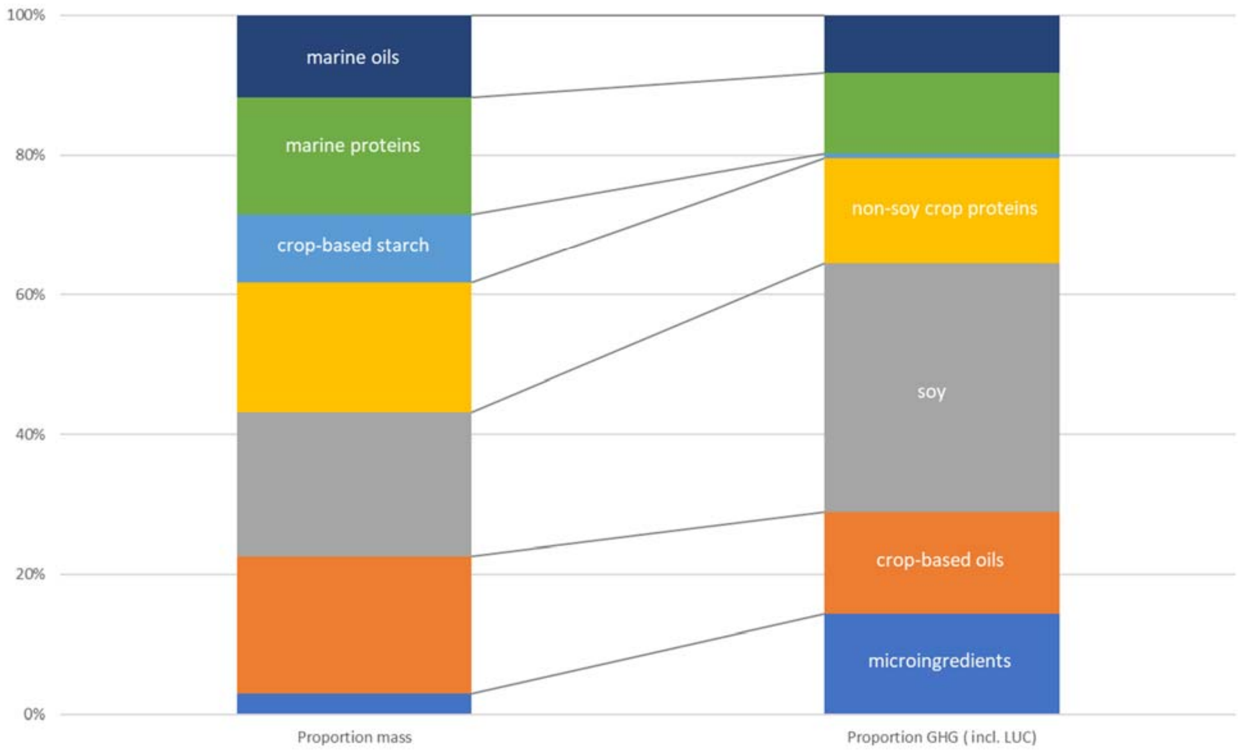


Figure 4-6 Relative contribution to mass and greenhouse gas emissions, respectively, of different components of salmon feed per kg of LW salmon.

4.3 Results for products from capture fisheries

The demersal species caught in fisheries, cod, haddock and saithe, cause lower greenhouse gas emissions than salmon, between 1.6-2.5 kg CO_2e/kg (Figure 4-7). Both cod and haddock have high stock biomasses leading to high catch per unit effort (or alternatively low effort needed to fish available quotas) and thereby a relatively low fuel use per ton of fish landed (0.19-0.24 L/kg). Low use of refrigerants with climate impact (HFC/HCFC) and high utilization of by-products in markets (50-100%) are other important factors. Demersal vessels often have quotas for all species and often target one species and the others are landed as by-catch. What is targeted depends on gear, location, season and available quotas among other things. The pelagic species, herring and mackerel, have an even lower fuel use (0.09 L/kg) and final product greenhouse gas emissions end at 1.1-1.4 CO_2e/kg (Figure 4-7). While they also have a low refrigerant use and an even lower fuel use in the fishery, the pelagic products are transported longer distances (Kiev and Tokyo) and have a slightly lower average by-product utilization rate (50-70%), which increases their footprint compared to demersals, still they are the most efficient type of seafood in production included, which confirms earlier findings.

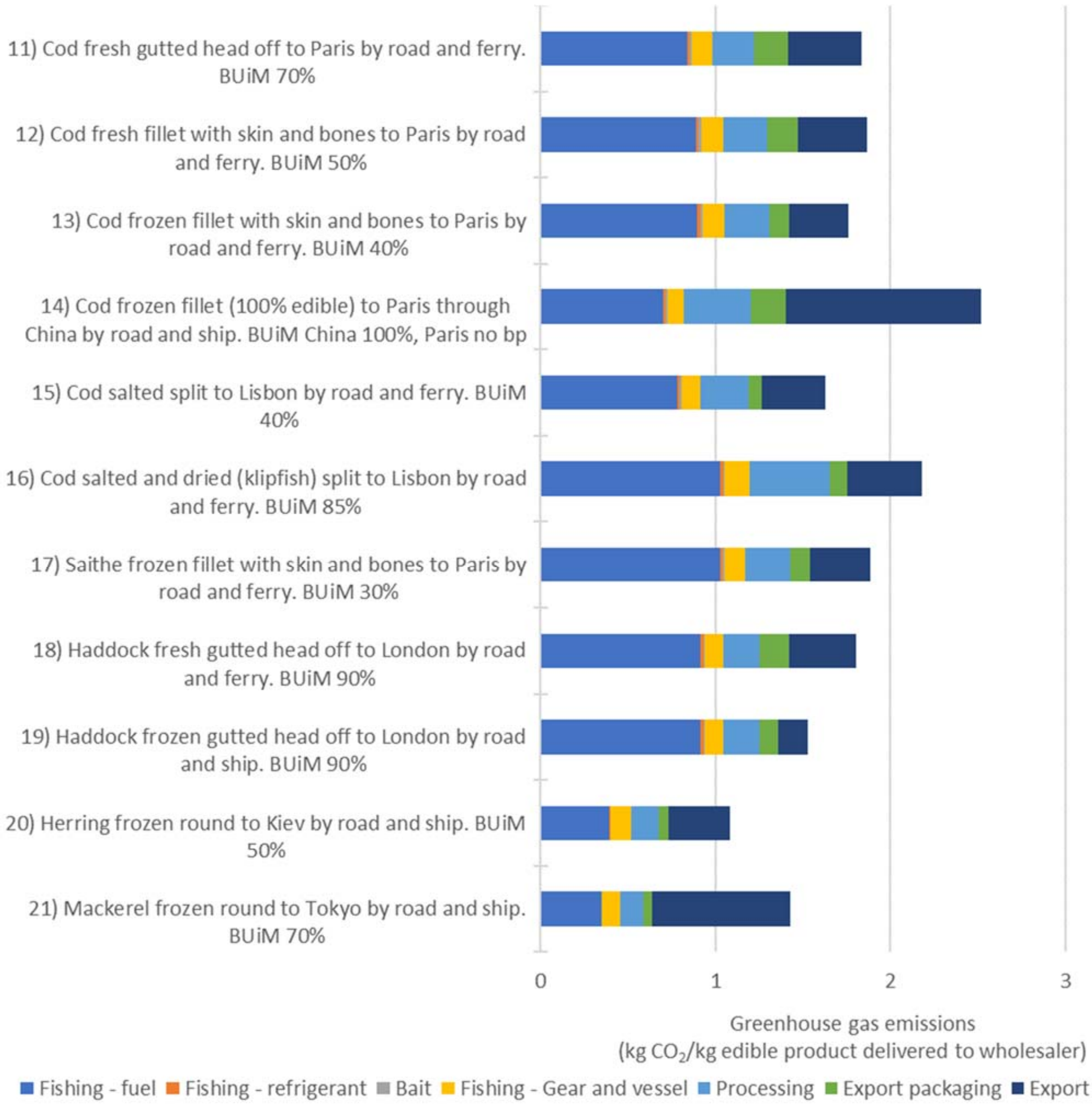


Figure 4-7 Greenhouse gas emissions of products from fisheries, except crustaceans. BUiM = By-product utilization in market.

The fuel efficiency of the fisheries for the crustacean species was less straightforward to model compared to the fish species. Fishing vessels targeting them also target other species in fisheries with a highly different fuel use intensity (and much larger landing volumes) and the annual data on fuel use from the profitability study, therefore, was challenging to use. In the case of king crab, it was abandoned entirely, and the data used came from four out of 30 king crab license holders that we were able to talk to.

In the case of shrimp, the data from the profitability survey was used, but the coastal shrimp trawl fleet segment was divided into those landing 25% shrimp or more (in landing volume) and less than 25% and only the ones landing 25% or more were used as data for coastal shrimp trawling. Shrimp is landed approximately half by the larger shrimp trawl fleet and half by the smaller trawlers. As larger shrimp trawlers since 2009 are merged with cod trawlers, their highly mixed fisheries targeting both fish and shrimp led to that the data could not be used to model shrimp trawling, it was too influenced by the fish catches dominating landings. This introduces some uncertainty, but it is important to remember that for each species, the species-specific fuel use was determined by calculating a weighted average between the medians of the fuel use of the segments landing them, meaning that a bias in a segment that lands very little of a species does not affect the weighted median very much. The smaller shrimp trawlers used on average 1.0 L/kg (still landing about 25% fish), but it was considered more representative to let the smaller trawlers represent the larger ones, than using the average value for large shrimp trawlers (who land 95% fish).

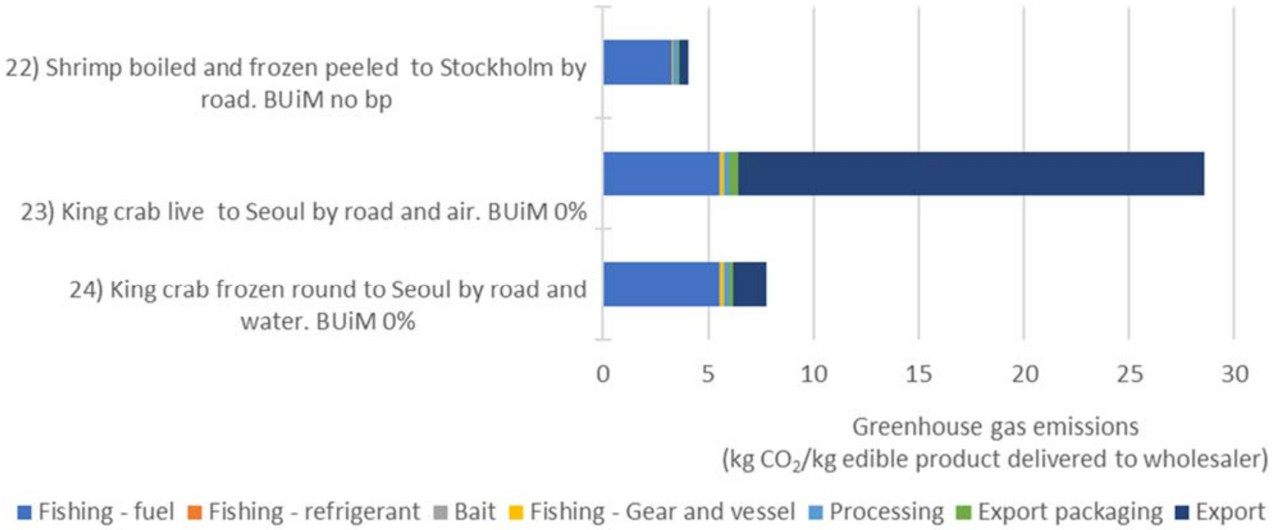


Figure 4-8 Carbon footprint of crustacean products delivered to the wholesaler. BUiM = By-product utilization in market.

The average fuel use from the four king crab fishers was 0.8 L/kg, which means that both crustaceans were more fuel intensive to fish resulting in higher greenhouse gas emissions at landing than the other species, which is in line with previous findings in energy analyses of fish and shrimp trawling [86]. The three post-harvest chains of the crustacean products are quite different with live king crab that is flown to Korea standing out, as already mentioned, at 29 kg CO_2e/kg edible meat as a result of airfreight and no by-product utilization in the market (Figure 4-8). Crustaceans exported in frozen form are considerably lower, shrimp at 4.0 and king crab at 7.8 kg CO_2e/kg edible in the market (Stockholm for shrimp, Korea for king crab). The edible yield of king crab was higher than that of shrimp (0.49 vs. 0.36 kg/kg LW), but 100% of shrimp by-products were used, whereas there was no such information for king crab, and this increases the relative result of king crab.

5 Sensitivity analysis including improvement options

Based on the results for 2017, a number of improvement and sensitivity analyses are performed to analyze the sensitivity of results and conclusions to single data points and changes due to the following measures:

5.1 Improvement options in salmon production

Each input and output forming the carbon footprint of a production system will show a considerable range within a sector using different technologies, strategies and operating under different environmental conditions. For salmon aquaculture especially important parameters for the carbon footprint, that also show a wide range, is the feed efficiency, the feed ingredients that are used and energy use.

Greenhouse gas emissions of salmon products can be reduced in many ways. Based on our assessment and understanding of the industry, the following aspects are identified as especially important:

- **Improving feed efficiency**: All measures that improve the resource efficiency of salmon farming will have considerable impact on the salmon CF, including everything that reduces mortality. Animal health and welfare is therefore an important climate aspect. Efficient feeding, to not releasing more feed than what is eaten is important, as well as investigating how feed nutrients not retained in the fish can be retrieved, e.g. through collection of sludge and/or multitrophic aquaculture. These resources could be used to produce new feed, i.e. the salmon industry needs to close important nutrients loops, like other food producers. Increased circularity done the right way to increase the overall resource efficiency of salmon farming can be an important way to reduce GHG emissions of the Norwegian salmon industry.

- **Changing feed composition:** The current salmon CF shows that it is critical to change what the salmon is fed. Simply shifting between existing feed inputs, like from marine to terrestrial inputs leads to tradeoffs between environmental impact categories. Changing the sourcing of major current feed type like soy can send important signals to producers, but the Norwegian salmon industry is a minor player in the global feed market and it can be questioned if a change in Norwegian salmon feed leads to changes in global agricultural systems. Major improvement could potentially come from exploring and developing feed ingredients that close the nutrient loop in the salmon industry (increase over all resource efficiency) and to develop ingredients from resources that are not utilized today.

- **Ensuring full by-product utilization along the entire seafood supply chain:** Further increasing salmon by-product utilization in seafood processing in Norway and elsewhere and continue developing high value products from them as well as improving the data available on by-product utilization.

- **Minimizing the need for transportation:** Historically, cod was mainly processed in Norway, either salted, dried or filleted. There has been a shift towards increased export of whole fish to other countries (e.g. China, Denmark and Poland) for processing before distribution to the final market, partly driven by EU customs duties (which are higher on processed than unprocessed fish). The proportion processed in Norway has declined to approximately 58% in recent years, with differences between species. Almost all mackerel is exported unprocessed- in 2018, only 5% of mackerel was processed in Norway[87]. The shift from processing in Norway to outsourcing it abroad increases the transportation need, both for main products and by-products, but sometimes the processing abroad gives higher yields which balances some of the transport emissions as it reduced the need of raw material.

- **Finding alternatives to airfreighting of salmon and generally shift to lower greenhouse gas transport modes and product forms:** This can involve changing the product form from fresh to processed forms allowing more efficient transportation, e.g. frozen or other products with a long shelf life. When that is not an option, producing the salmon closer to the market or developing/using technologies as super chilling can reduce the need for airfreighting. When airfreighting in unavoidable, measures can be taken that reduce emissions, like only flying the intercontinental part, but using other transport modes for the first and last part of the supply chain and avoiding flights with stopovers if direct flights are possible.

- **Increasing energy efficiency and changing to renewable energy carriers:** The Norwegian salmon industry has started to replace fossil fuel use (diesel generators) with electricity, which is an important step, but reducing energy use must remain top of the agenda. Through our interview with service and well boat companies it came to our attention that the fish farmers pay for the fuel use which gives low incentives to vessel operators to save fuel. It was also clear that fish farmers generally don't include the energy use of sub-contractors in their environmental/energy accounting, indicating that low hanging fruits that would reduce both emissions and costs are missed.

To illustrate the potential effect of a selection of these changes, a few cases of farmgate salmon and of a full salmon supply chain are presented below in which a number of these parameters are changed to maximize and minimize the GHGs of salmon farming and a full salmon supply chain. Table 5-1**.** shows the parameters that are changed, and the values used for each case. Note that the parameters are set within the range that is identified as actual real values.

Table 5-1 Parameters and values changed, the default being product 5 of which a low and high GHG version is presented.

Parameter	Low GHG	Default	High GHG
eFCR	0.86	1.32	1.57
Share of Brazilian soy – Impacts LUC climate impacts.	0%, all European soy	100%	100%
By-product utilization in market	100%	80%	0%
By-product utilization at processing plant	100%	91%	60%
Energy intensity service companies (L fuel/kg wfe produced)	0.01	0.015	0.02
Energy intensity well boats (L fuel/kg wfe produced)	0.03	0.08	0.10
Energy use fish farm	All electric, 0.026 kWh electricity/kg wfe	0.044 liter fuel/kg wfe	0.066 liter fuel/kg wfe
Load utilization returning trucks (after fish is delivered)	100%	65%	0%

Feed efficiency is the most important parameter in the CF of salmon at landing. Figure 5-1 shows the range of the eFCR within the Norwegian salmon and trout aquaculture industry. In 2017 the range in the eFCR was 0.86 to 1.57 (kg feed bought per kg salmon sold). Five companies report an eFCR <1 and 18 companies an eFCR >1.5. Chapter 3.2.5 presents more details on the eFCR data.

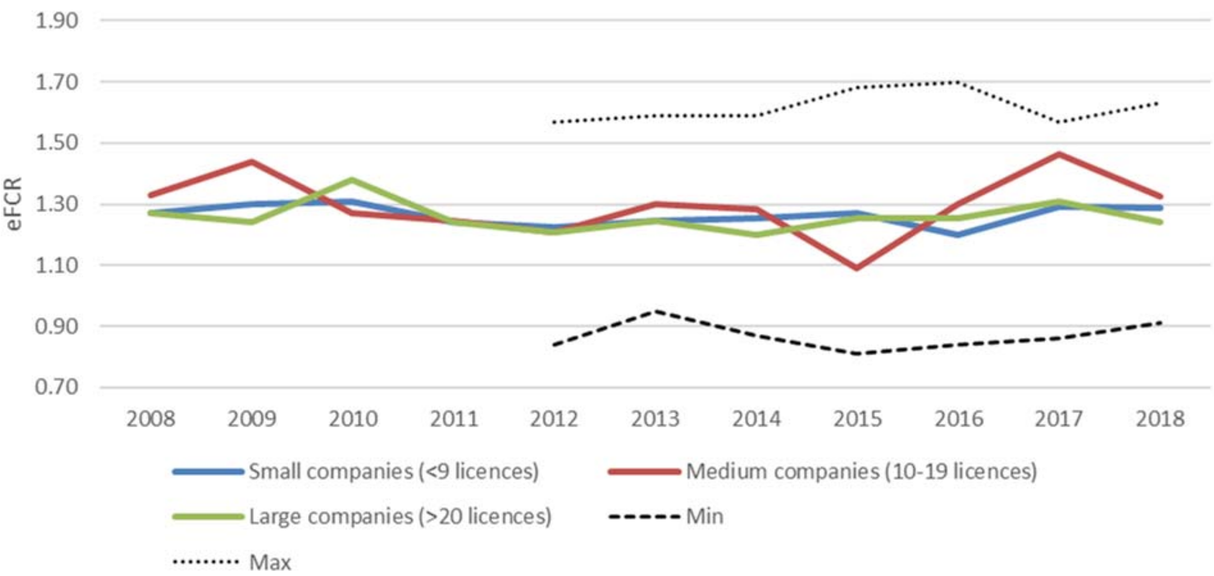


Figure 5-1 Variation in eFCR for the Norwegian salmon and trout industry. Black lines show the min/max eFCR each year. The colored lines show the variation for different company sizes, defined through how many production licenses they obtain. All data from Directorate of Fisheries [88]**.**

For the feed, a particularly important decision is where the soy is sourced from and if it is associated with land use change climate impacts. For the "Low GHG salmon" it is assumed that all soy is sourced from Italy instead of Brazil, The biggest soy producer in Europe is Ukraine, but Agri-footprint did not include data from Ukraine, and Italy, the second biggest soybean producer in Europe, was used [89] .

Energy use by well boats, service companies and the fish farm also shows considerable variation in how much energy is spent per unit produced, and what energy sources that are used. The range in energy use of these activities is presented in chapter 3.2.2.

The result of these two cases are compared with the base case in Figure 5-2: It shows that Norwegian salmon can be produced with a carbon footprint of 3.3 kg CO_2e/kg wfe salmon at slaughter gate. At the same time the producers that are the least feed efficient produce at a carbon footprint above 6.8 kg CO_2e/kg wfe salmon at slaughter gate.

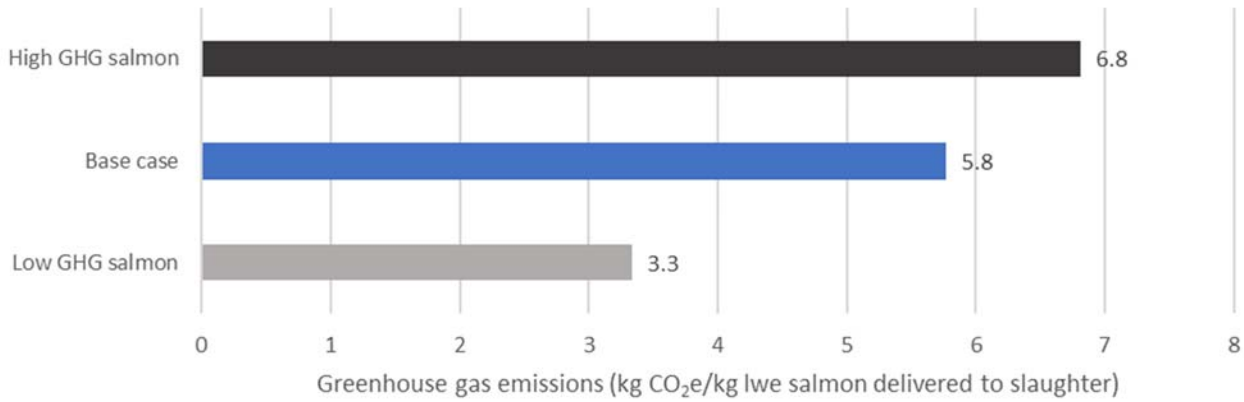


Figure 5-2 Variability in greenhouse gas emissions of Norwegian salmon at landing, based on changes in eFCR, sourcing of soy and energy intensity and sourcing.

In the same way, two cases of the product fresh salmon fillet to Paris by road is produced, one where selected parameters are set to minimize the GHGs and one where it is maximized. These cases illustrate the space in which salmon producers can operate regarding these aspects, using current technology. Table 5-1 presents the parameters changed for each case, with the default being product 5 as described in chapter 3. Figure 5-3 presents the resulting GHG of these cases. It shows that by optimizing feed; energy use by fish farm, service vessels and well boats; transport capacity utilization and by-products utilization GHGs can be reduced with more than 50% (from the default value). At the same time the poorest performers have GHGs three times higher than the best performers. Here we emphasize that the parameters are set to values that already achievable today. There are also several important climate aspects that are not changed, e.g. sourcing of micro ingredients and other feed ingredients and optimizing packaging, which would further influence the product GHGs.

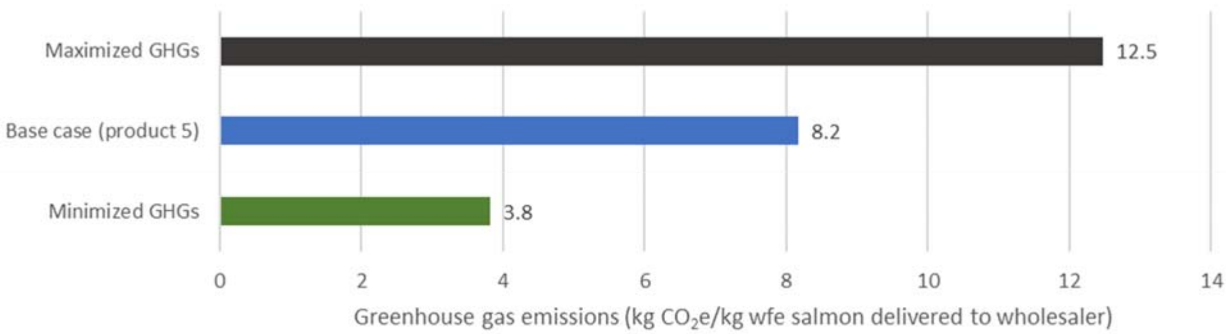


Figure 5-3 Change in greenhouse gas emissions of fresh salmon fillet to Paris when a number of parameters are varied, including the feed conversion ratio, the sourcing of soy, by-product utilization, energy intensity in various steps and the load on return trips.

5.2 Variability in greenhouse gas emission of products from fisheries at landing

Based on the results (Figure 4-7 and Figure 4-8), it is evident that the operation of fishing vessels represents the largest contribution to fuel consumption and GHG emissions in the value chain of seafood from capture fisheries, except when airborne transportation is involved. The contribution of fishing vessels' fuel use to CF of species (Figure 4-7 and Figure 4-8) is based on median fuel use intensity of these species (Table 3-4) and, correspondingly, median fuel use intensity of the fleet segments that land them (Table 3-3). In order to investigate the effect of changes in fuel use intensity of fleet segments on the CF of species, the following sensitivity analyses are performed for 2017:

1. Scenario I: Minimum fuel use intensity of various fleet segments are used instead of their median fuel use intensity in Equation 3-1 (Table 3-3 shows these values in 2017). Minimum fuel use intensity shows the lowest datum within 1.5 interquartile range (1.5*(Q3-Q1)) of Q1. Q1 and Q3 are lower and upper quartiles, respectively.

2. Scenario II: Maximum fuel use intensity of various fleet segments are used instead of their median fuel use intensity in Equation 3-1 (Table 3-3 shows these values in 2017). Maximum fuel use intensity shows the highest datum within 1.5 interquartile range of Q3.

Table 5-2 Fuel use intensity (L fuel/ kg liveweight catch) of landing species under two scenarios in 2017. Scenarios I and II consider minimum and maximum fuel use intensity of fleet segments that land the species, respectively. The base scenario using median fuel use intensity is also shown.

Scenario	Cod	Haddock	Saithe	Mackerel	Herring	Shrimp	King crab
Base	0.189	0.237	0.215	0.088	0.086	1.013	0.841
I	0.104	0.145	0.121	0.047	0.043	0.387	0.167
II	0.298	0.356	0.329	0.132	0.134	2.247	1.405

Regarding Table 5-2, in all scenarios, shrimp and king crab are the most fuel consuming species to land. However, their fuel use intensity spans over a wide range compared to other species: if the most efficient coastal shrimp trawlers land all shrimp, the fuel use intensity of shrimp would be reduced by approximately 62% compared to the base scenario (i.e. using the median fuel use intensity). On the other hand, if the least efficient coastal shrimp trawlers land all shrimp, the fuel use intensity of shrimp would increase by approximately 122% compared to the base scenario. As mentioned earlier, only data from four vessels are used for estimating the fuel use intensity of king crab (see section 3.1.1.2). Assuming that this data is representative of vessels that land king crab, the fuel use intensity of king crab can reduce by 80% and increase by 67% compared to the base scenario if the most and least efficient of the vessels land all king crab, respectively.

5.3 Improvement options for capture fisheries

Greenhouse gas emissions of products from fisheries can be reduced in many ways. Based on our assessment and understanding of the industry, the following aspects are identified as especially important:

- **Improving the fuel efficiency** (i.e. reducing fuel use intensity) of fishing vessels reduces their fuel consumption and indirectly reduces CF of species. In general, a higher fish stock biomass and quota improves fuel efficiency [41], by enabling vessels to spend less time at sea to catch their quota, resulting in higher fuel efficiency. In general, higher fuel price and emission taxes may act as incentives to change fishermen's behavior or invest in energy-efficient systems (e.g. fuel cells, diesel-electric power systems, etc.) in order to improve fuel efficiency. Operational profile of fishing vessels includes diverse operations with different power demands (e.g. steaming to fishing grounds and towing fishing gears). Considering the fluctuations in power demand of fishing vessels, hybrid and electric propulsion systems using batteries and fuel cells, among others, can improve fuel efficiency of vessels [90] .

- **Switching to alternative fuels**: Changing the vessel fuel from marine gas/diesel oil to hydrogen [90] but also to the fossil fuel liquefied natural gas (LNG) [91], can reduce air emissions significantly. However, a life cycle perspective should consider the environmental aspects of such fuels in their whole value chain (e.g. fuel production, fuel transportation etc.) [92]. Development is also ongoing with regard to electrification of the Norwegian fishing fleet.

- **Using low GHG refrigerants and improving fuel efficiency of onboard refrigeration**: In addition to the energy used for steaming and catching fish, electric energy is needed for refrigeration systems onboard vessels. There has been limited research on the latter in fisheries, and there is room for improving energy efficiency of refrigeration systems onboard vessels. Vessels use excess heat from propulsion for space and tap water heating. However, this may not be enough for other processes onboard. The surplus heat from refrigeration systems could also be utilized. The surplus heat is normally available at lower temperature levels and the installation of a heat pump to lift the temperature level is needed. Heat pump systems work well with the refrigerant CO_2. Such systems are used by most Norwegian supermarkets and some industrial processes and can be adapted to fishing vessels. The CoolFish project at SINTEF aims at developing such alternative cooling concepts for fishing vessels. If vessels use fuels that are stored at low temperature onboard, such as LNG and liquefied hydrogen, they can use the evaporation heat from the gasification of these fuels to cover a significant part of the cold needed to cool down and freeze the catch. The present assessment of Norwegian fisheries has shown the great potential of GHG mitigation by reducing the use of high-GHG refrigerants, as the contribution from these has reduced sharply. It is very important to incentivize shifting to natural refrigerants and avoid taking the step over HFCs, which have a high global warming potential and would increase GHGs of products form capture fisheries again.

- **Ensuring full by-product utilization:** Today, 100% of by-products from pelagic fisheries are used. However, there is room for improvements in utilization of by-products from whitefish and crustaceans. Further increase of by-product utilization in these fisheries and seafood processing in Norway and elsewhere, continuing the development of high value products from them and improving the data available on by-product utilization are needed.

- **Minimizing the need for transportation (e.g. avoid unnecessary transport for processing and transport of by-products):** Historically, cod was mainly processed in Norway, either salted, dried or filleted. There has been a shift towards increased export of whole fish to other countries (e.g. China, Denmark and Poland) for processing before distribution to the final market, partly driven by EU customs duties (which are higher on processed than unprocessed fish). The proportion processed in Norway has declined to approximately 58% in recent years, with differences between species. Almost all mackerel is exported unprocessed- in 2018, only 5% of mackerel was processed in Norway [87]. The shift from processing in Norway to outsourcing it abroad increases the transportation need, both for main products and by-products, but sometimes the processing abroad gives higher yields which balances some of the transport emissions as it reduces the need of raw material.

- **Shifting to lower GHG transport modes and product forms**: As shown in the results (Section 4.3), mode of transportation significantly affects the carbon footprint of fisheries. Most of the products from capture fisheries are exported via road and sea. However, some products, such as king crab are airfreighted, and, consequently, their carbon footprint is high. Shifting from air transport to sea transport (and by that the product form) would considerably reduce the carbon footprint also for products originating in capture fisheries. There are also more efficient systems for transportation of live crustaceans by sea [93] and when airfreight cannot be avoided altogether, it can be optimized by selecting direct cargo flights and only airfreighting the intercontinental legs of the chain, while using other transport modes for continental/domestic transports. To enable a shift to e.g. frozen products, high quality products that can handle longer travel time are needed as well as customers willing to pay sufficiently for such products.

To illustrate the potential effect of changed fuel use and by-product utilization, a cod product (product 12) for which fuel use is minimized and maximized is modelled (Figure 5-4), which demonstrates a large scope for improvement.

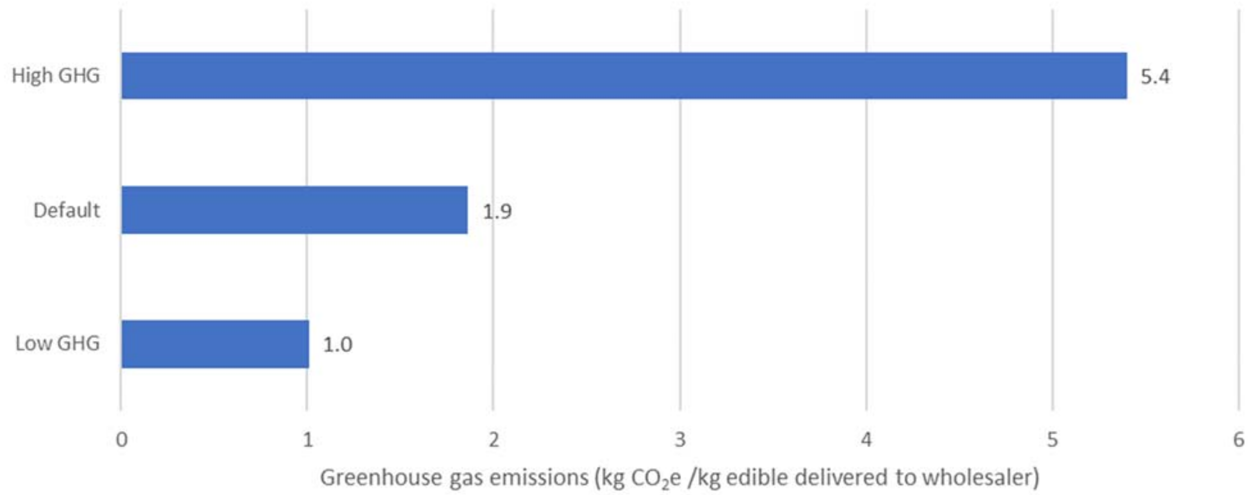


Figure 5-4 Greenhouse gas emissions of fresh cod (product 12) with fuel use in the fishery varied between best and poorest current performance. Note that only fuel intensity is varied maintaining the 2017 distribution between fleet segments.

In Figure 5-5, by-product utilization is varied up and down for fresh haddock, which shows that the difference between no by-products and all by-products utilized results in a factor 3 difference in product GHGs.

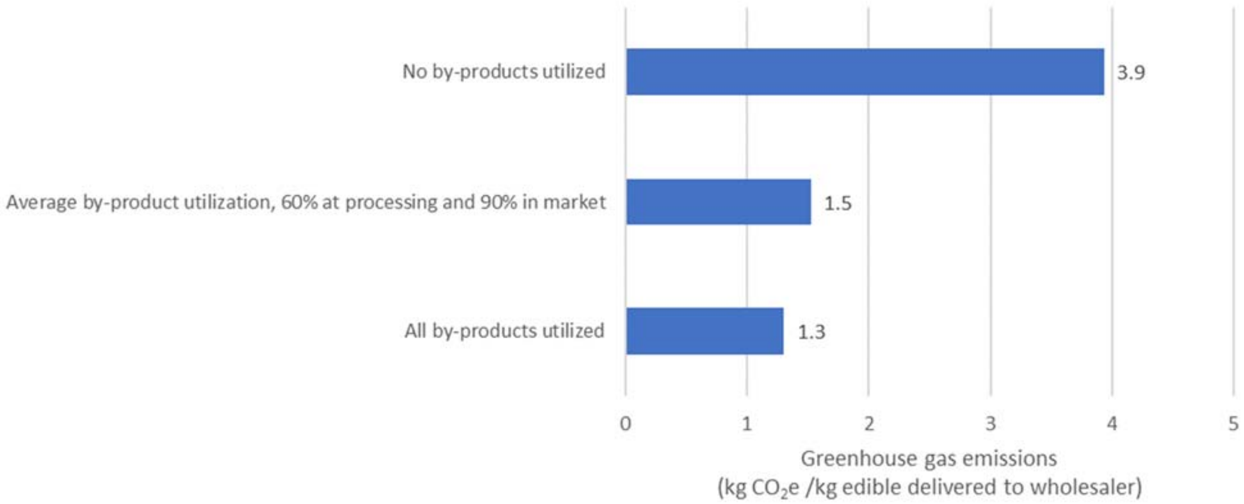


Figure 5-5 Greenhouse gas emissions of fresh haddock (product 18) with different by-product utilization rates.

Figure 5-6 presents comparable products, one fresh and one frozen, taken to the same market (London). The frozen product has an advantage from the slower and more efficient transport by sea, instead of road. These calculations show that there is considerable room for improvement from only optimizing production and post-harvest supply chains using currently available technology.

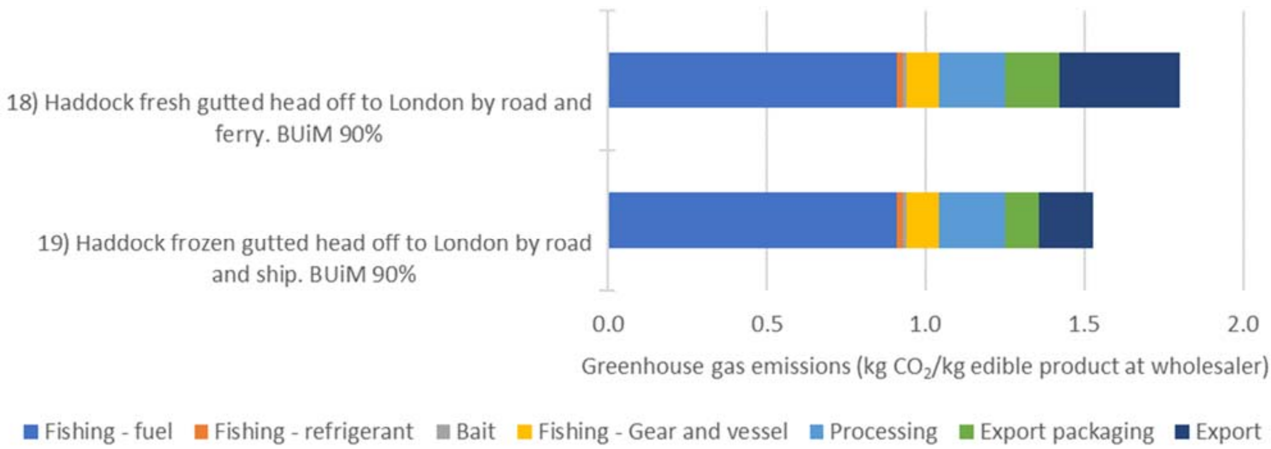


Figure 5-6 Greenhouse gas emissions of fresh and frozen haddock trucked and shipped to London, respectively.

5.4 Product loss

For this work, we did not have access to representative data on product losses, i.e. products that are damaged, or in other ways become unsuitable for human consumption and are turned into waste (not in any way utilized) during processing, transport and at wholesaler, and is therefore not taken into account. Product loss at any stage post-processing increases impacts proportionally as more of the product has to be produced up until that step without adding to the volume of product output. Note that this is loss of edible product and is not the same as the non-edible by-products and their utilization that has been discussed broadly in this work and was included in the modelling.

It is well known that food waste is considerable, not the least in the seafood sector, dealing with perishable products It is also well known that the environmental impacts of food waste are larger, the further down the supply chain (closer to the consumer) they take place. [94]. Knowing this, every action that helps to ensure that edible food is not wasted is very important. Losing one kg of seafood of any product at the wholesaler will have the climate impact that each product has (Figure 4-2). In other words, if one kilo is lost per 9 kg that reach the consumer (a 10% loss rate), GHGs per kg of product at the consumer will increase by 11%. A 20% loss rate increases emissions by 25% etc. As loss rates are different for different products and product forms and there are strong indications that losses of frozen and canned seafood are considerably lower that those of fresh, this is an aspect not accounted for in this study that would likely constitute another advantage of a longer shelf life (in addition to enabling slower transportation).

5.5 Land-based salmon production

Land-based farming of salmon in RAS (recirculating aquaculture systems) is often suggested as a more sustainable form of producing salmon since it is expected to reduce nutrient emissions to surrounding waters and reduces other risks, e.g. escapes of salmon. In addition to simply representing an alternative to conventional net-pen farming for the grow-out phase, there are two additional cases where recirculating systems can be used that affect supply chain GHGs:

Salmon smolt can be grown to a larger size before being transferred to grow-out in order to reduce the risk for disease/parasite infection and to better utilize farming permits in the sea. Both aspects can influence the FCR: If mortality and disease occurrence is reduced, the eFCR will be reduced. A higher production volume can also improve efficacies beyond just the eFCR, e.g. fuel intensive activities like well boats and service activities can probably handle more fish without an equal rise in fuel consumption. Also, the possibilities to recycle the sludge are better in land-based systems than currently in sea-based farming.

Producing the fish in RAS in the market to slaughter size can also be seen as a way to avoid airfreight of fresh fish to the same market.

The most important climate challenge from more land-based production is that ecosystem services, e.g. ocean currents, to maintain suitable conditions and water quality for the salmon need to be created using technology and energy (to pump, oxygenize, filter and clean the water).

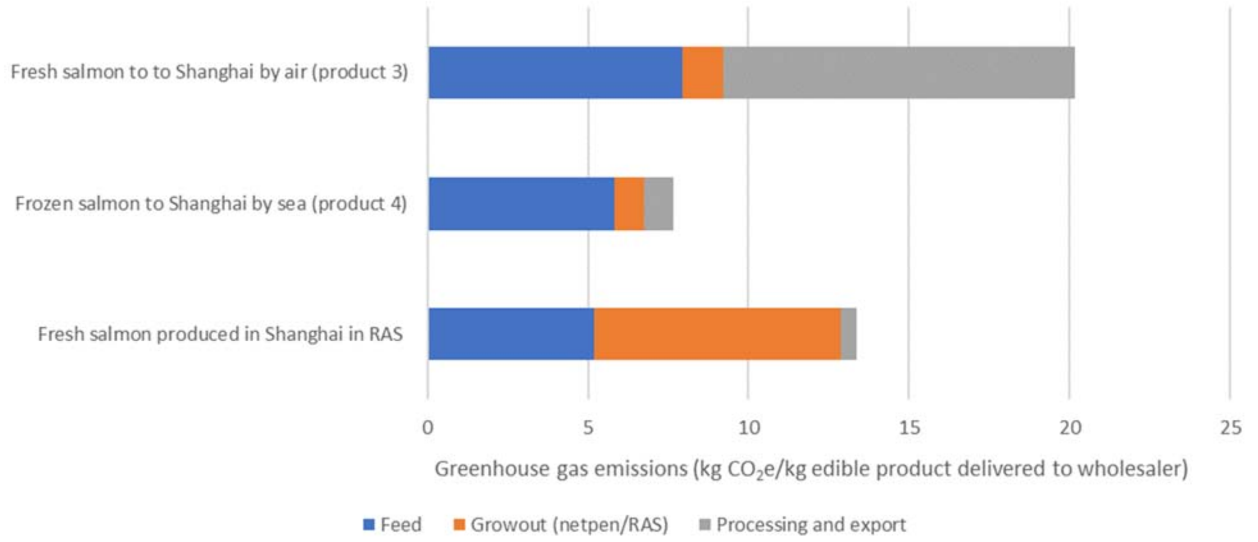


Figure 5-7 Comparison of fresh and frozen salmon products shipped and flown to China from Norway or produced in a recirculating aquaculture system in China.

In Figure 5-7, the carbon footprint between salmon products transported over long distances or produced and in the market in a recirculating aquaculture system (RAS) plant is shown. The RAS plant is modelled using the data for juvenile production (chapter 3.2.1), this includes the assumption that they achieve a eFCR of 1. Thus, this must be understood as a "best case" for the RAS product. Also, it is assumed that future production will be able to achieve an electricity input similar to the average European production of today (chapter 3.6). This is a critical point: If the electricity that is used is similar to the Chinese electricity production of today the RAS production would deliver fresh salmon with similar or even slightly higher CF than the air transported salmon. On the other side the electricity intensity used in the RAS case is 10 kWh/kg lwe produced, from dialogue with experienced people in the RAS industry they expect to achieve energy intensities as low as 5 kWh/kg lwe produced, that range was also confirmed by an expert group evaluating large scale effects of more land based salmon aquaculture [56]. So, for RAS production to be sustainable in a climate perspective it is critical to achieve a high feed efficiency, become more energy efficient and that they are partly self-served with renewable energy sources.

5.6 Electricity production

As presented in chapter 3.6, electricity input was represented by European electricity with a carbon footprint of 0.42 kg CO_2e/kWh. If this is replaced with electricity with a certificate of origin the carbon footprint of the electricity would be only 0.02 kg CO_2e/kWh [95]. This will mainly lower the contribution from processing, and even though electrification is high on the agenda, the use of fossil fuels was still the dominant energy source in 2017. Juvenile production in salmon farming also uses electricity but considering the small tonnage of juveniles produced compared to the tonnage produced/slaughtered in grow-out, this energy use is not an important climate aspect in the carbon footprint of the salmon.

To illustrate the effect of changing electricity input, Figure 5-8 and Figure 5-9 show how the CF at the processing gate changes, for a fresh salmon and a round frozen herring, when the electricity is modelled as Norwegian electricity with certificate of origin instead of average European electricity.

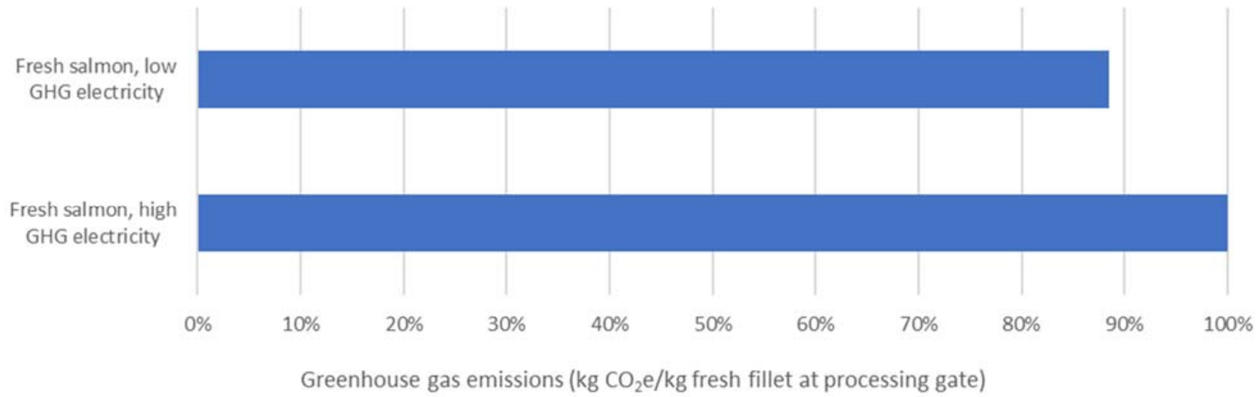


Figure 5-8 Change in CF of salmon at the processing gate, when electricity is changed from European to Norwegian electricity with certificate of origin.

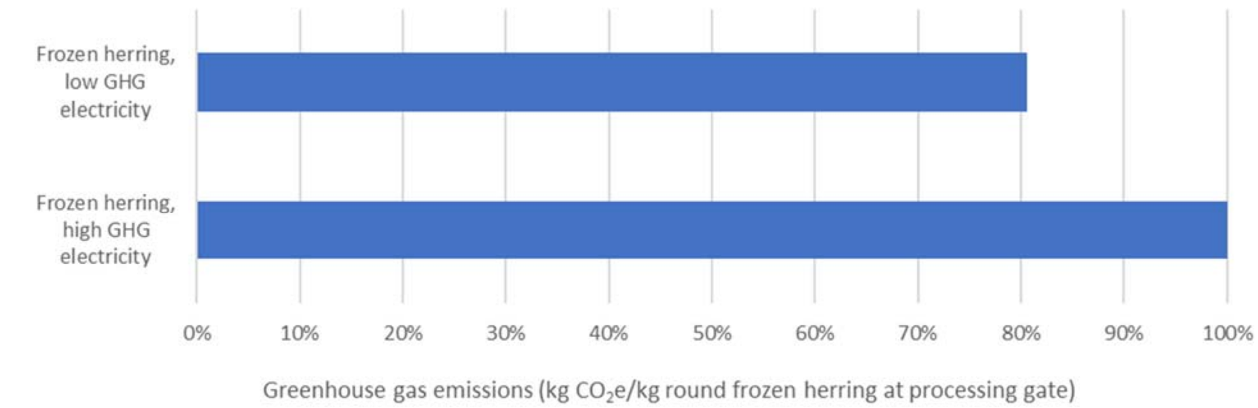


Figure 5-9 Change in CF of round frozen herring at the processing gate when electricity is modelled as Norwegian electricity with certificate of origin rather than average European electricity.

5.7 Airfreight scenarios

Two products include air transport, fresh salmon to Shanghai (product 3) and live king crab to Korea (product 23). These transports are modelled using data from the NTM database (chapter 3.5.3). Looking at the salmon case, we have used what we consider an efficient cargo transport: 1) The flight goes directly, avoiding several fuel intensive take-offs and landings and 2) we used a load utilization factor of 85%, which is the maximum possible for the distance. On very long-distance flights, the maximum load is reduced due to the large volume of fuel needed which occupies a part of the load capacity. The maximum load factor therefore depends on the distance. A cargo load factor of 85% must be considered high compared to the industry average, which was less than 50% for cargo and less than 55% for passengers in 2017 (figure 9 in IATA annual review [96]) .

Figure 5-10 presents the result for three different cases for intercontinental export of fresh salmon by air:

A. Fresh salmon 8,252 km (an intercontinental flight from Norway to China) by an efficient cargo flight. This case includes positioning of the aircraft from Europe to Oslo (1,200 km), i.e. flying in of an empty aircraft from Europe to pick up salmon (identical to product 3 as presented in the results chapter)

B. Same as case A, only positioning of aircraft from airport in Europe to airport in Norway is not included.
C. Fresh salmon 8,252 km (an intercontinental flight from Norway to China) by a cargo flight with a more average load utilization of 65%. Includes positioning of the aircraft from Europe to Oslo (1 200 km)
D. Fresh salmon with passenger flight with one stop, first flight 2,525 km and second 8 097 km. Average load utilization factor, 65% for both cargo and passenger flights. No positioning of the aircraft is included for this case.

The most important finding from all cases is that intercontinental export of fresh fish by air results in very high GHGs compared to alternatives, including export by sea and production in the market (see chapter 5.5). When air transport is unavoidable, the cases highlight the importance of achieving high load utilization, avoiding stops and that passenger flights are result in higher emissions than cargo flights (explained in section 3.5.3).

Case A compared to C show that when the load utilization is average instead of maximum the CF increase by over 10%.

Case A compared to B (and partly D) show the effect of stopovers and positioning of the airplane. Landing and take offs is particularly energy demanding, why a long-haul flight is more efficient per ton*km than a short-haul flight. An aircraft like Airbus A300 burns up to 1.7 ton of fuel during landing and take-off [97]. The positioning of the airplane from Europe to Oslo increases the CF of airfreighted salmon by 13%.

Case A and D demonstrates the effect of transporting on a passenger flight rather than cargo flight. Even though these two cases don't cover the exact same distance, they show that salmon transported on passenger flights can have a CF that is almost 90% higher than a comparable export with an efficient cargo flight, even when positioning of the cargo airplane is included. It is often argued that the goods are taken on flights that would leave anyway, however this argument does not hold since these goods contribute to the profitability of the flight.

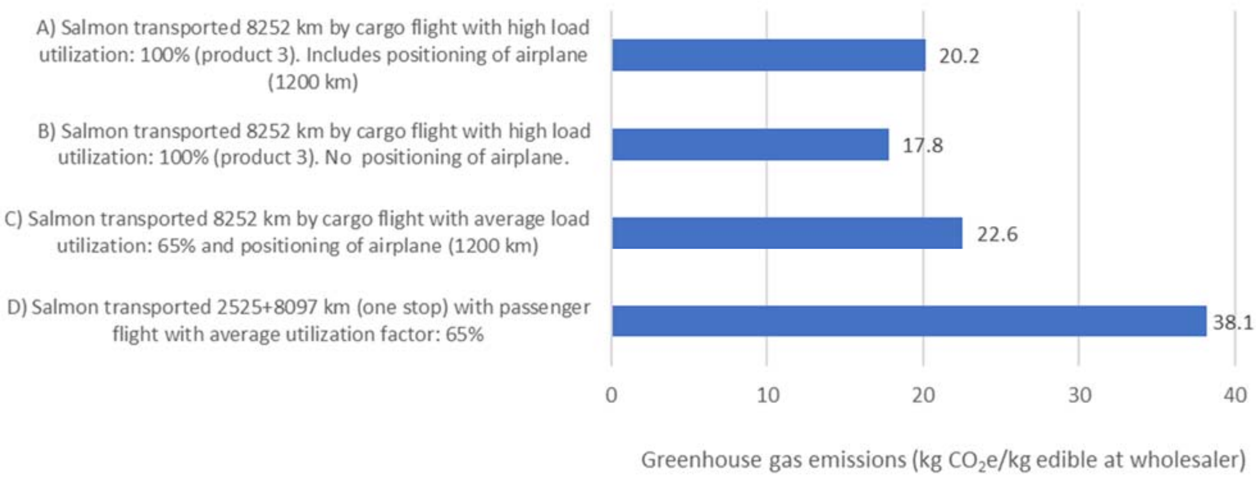


Figure 5-10 Greenhouse gas emission of alternative airfreight scenarios.

6 Development over time in climate impact of Norwegian seafood production

As stated earlier, the **GHG results in Winther et al. 2009** [1] **and Winther et al. 2020 (this report) cannot be compared straightaway due to methodological and data differences** (e.g. new version of IPCC indicators for GHGs, electricity mix used, land use change and micro ingredients included, method to account for fuel use in fishing, edible yield data, and method to account for refrigerant use). In order to evaluate temporal trends in GHG emissions in Norwegian fisheries and aquaculture, a new methodological approach was developed.

6.1 Development of greenhouse gas emissions of the Norwegian salmon industry from 2007 to 2018

This chapter presents a method to study how the climate impact of Norwegian salmon farming has developed over time. The method used for this purpose is also suggested as a method to monitor development over time in a simplified way. The method only covers the production up to farmgate, thus excludes processing and export of salmon. These are also important climate aspects, but not included here as historical data was not available within the scope of this work.

The greenhouse gas emissions at salmon slaughter are dominated by the following three parameters (ranked according to importance):

1) The economic feed factor (eFCR)
2) The composition of the feed in terms of major feed types
3) Service vessel and well boat activity

In 2017, these three parameters; the production of feed, and energy use of well boats, service vessels and on the fish farm covered almost 95% of the farmgate salmon GHGs. The feed alone represented 85%. So, in a simplified carbon footprint, only composed of these two components, the feed will contribute with 90% and well boats, service vessels and energy use at the fish farm 10%. Figure 6-1 presents the development of these key parameters and the (simplified) GHGs of salmon farming (at farmgate) has developed over the same period. The figure presents the following:

- The blue dotted line presents the development of the eFCR over the period. This is based on data from the Directorate of Fisheries [63]. The values are normalized against the highest value during the period. It shows that the eFCR first dropped (less feed per unit of salmon produced was used), but then started to increase again. Chapter 3.2.5 and 5.1 presented more details on the eFCR data and variability.

- The green dotted line indicates how the carbon footprint of the feed has developed. Here the carbon footprint is normalized against the highest value during the period. The development of the feed CF is estimated based on the feed composition in 2010, retrieved from a report by Ytrestøyl et al [20] and the feed composition in 2017 as defined in this work (chapter 3.2.4) [20] and the feed composition in 2017 as defined in this work (chapter 3.2.4). The feed CF of 2010 was calculated using the same data as that of 2017 only with the composition, e.g. how much of the feed that is fish oil, of 2010. This is a rough estimate, but it reflects the effect of increasing the share of crop-based ingredients, and in that replacing marine ingredients with a relatively low CF with crop-based ingredients with a relatively high CF. It is simply assumed that the change in feed composition from 2010 to 2017 has happened gradually over that period and that changes also happened at the same rate before 2010 and after 2017. Based on this simple analysis the carbon footprint of the feed increased by around 3% from 2010 to 2017.

- The red dotted line presents the development of "other costs" as it is defined in the annual profitability survey of the Norwegian salmon industry [63]). This is used as an indicator of the change in activity at sea: well boats, service vessels and the fish farm. These numbers are also normalized against the highest value during the period. This is transformed into a GHG contribution by the assumption that that "other costs" each year constitute 10% of the climate impact of the salmon at slaughter entry gate.

- The grey line shows how the carbon footprint of the salmon at slaughter gate will have developed assuming that 90% it is composed of the feed (the product of the feed footprint and the eFCR each year) and 10% is composed of "other costs". This estimate shows that the carbon footprint of the salmon has increased up until 2017, but now seems to go down, mainly because of an improvement in the eFCR.

    - The result for each year is calculated this way, each value is between is normalized against its highest value during the period:

        - $0.9 * eFCR\ (year\ x) * CF_{Feed}(year\ x) + 0.1 * Other_{cost}(year\ x)$

Equation 6-1

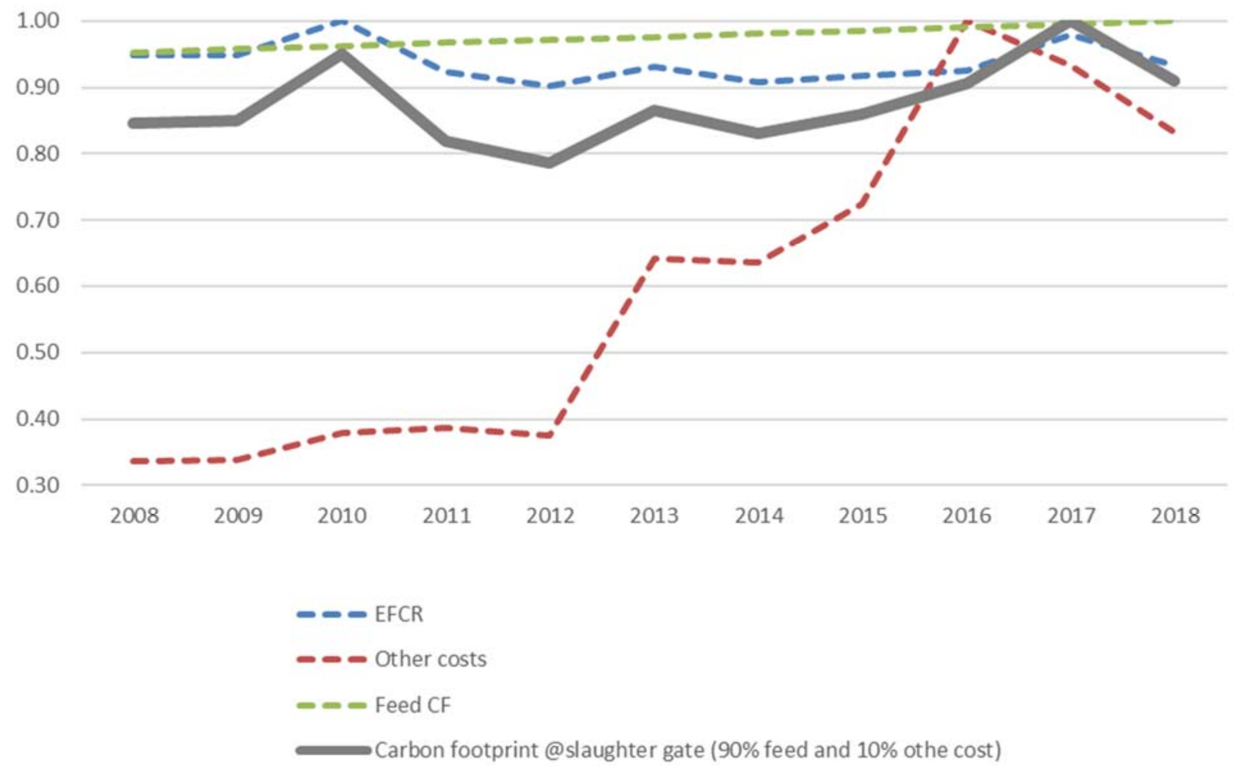


Figure 6-1 Development for key parameters and greenhouse gas emissions of salmon at slaughter 2010 – 2017. All values are normalized against the highest value during the period.

The method presented above allows studying the development of climate impact of the Norwegian salmon aquaculture industry based on data available as of today. The industry could in this way get a simplified but accurate picture of their climate performance each year:

1) Reporting the eFCR is already done in well-established industry wide statistics through the profitability survey of the Directorate of Fisheries

2) The feed CF can be calculated based on the Product Environmental Category Rules (PEFCR) feed developed by the global feed industry and adopted by the European Commission, which is a framework recognized by industry and government.

3) The fuel use of the fish farmers, service companies and well boats can simply be reported from each company. All companies know their fuel and energy use today.

There is a high probability that environmental reporting, including energy use and GHG emissions, will become mandatory, and will be required in important markets.

6.2 Development in climate impact of the Norwegian fisheries from 2007 to 2017 using the simplified method

Based on the results (Figure 4-7 and Figure 4-8), the fuel use of fishing vessels often represents the largest contribution to GHG emissions in the value chain of seafood from capture fisheries, except when airborne transportation is involved. Fuel use in fisheries represented 76%–97% of the total GHGs in fisheries (per kg LW) (Figure 6-2), meaning that production of gear and vessel, bait and production and emission of refrigerants are of minor importance. For the most fuel-efficient fisheries (herring and mackerel) and energy-intensive post-harvest chains (in particular the airfreighted king crab), post-harvest steps have the highest importance (up to 75% of total supply chain emissions). Still, fuel is often the single most important input and also reflects abundance and catchability, which are important factors for fuel efficiency. Therefore, changes in fuel use intensity of catching species can indicate changes in climate impact of the Norwegian fisheries over time, since there is a direct relationship between the volume of fuel burnt and fuel related GHGs.

Developing a simplified method to derive GHG trends for capture fisheries is complicated, even though we focus only on the fishing stage. This is because various species are landed by individual vessels that employ different gears and fishing methods. The available data resolution usually does not allow the allocation of fuel use to specific species and fishing gears (see chapter 3.1.1). Therefore, Equation 3-1 and, consequently, changes in fuel use intensity of fleet segments and catch composition based on the profitability surveys' population of fishing vessels can be used as a simplified method to derive GHG trends for different species. The simplified method, therefore, only builds on the fuel efficiency of fisheries for different species, which depends on the fuel efficiency of each fleet segment landing that species and its share in total landings of that species.

For king crab, only 2017 data is available (Figure 6-3), and no conclusions regarding the development of its emissions can be drawn. The fuel use intensity of mackerel and herring has reduced slightly (7%-8%) from 2007 to 2017 (Figure 6-3). Using the simplified method, the carbon footprint of mackerel and herring is reduced slightly from 2007 to 2017. Purse seiners and coastal seiners land most of mackerel and herring (see Figure 3-5 for 2007 and 2017). However, the fuel use intensity of purse seiners and coastal seiners has increased slightly from 2007 to 2017: approximately 2.5% and 0.1%, respectively (Figure 6-5; Figure 6-6 gives a better resolution for these fleet segments.). Therefore, the changes in catch composition of profitability survey's population in 2007 and 2017 can explain the slight reduction in the fuel use intensity of mackerel and herring: although in both years purse seiners landed more mackerel and herring than coastal seiners, the share of purse seiners has reduced from 2007 to 2017. In contrast, the share of costal seiners has increased. Coastal seiners have a lower fuel use intensity than purse seiners and this may explain the reduction in fuel use intensity of these species. Although the fuel use intensity of mackerel and herring in

2017 is less than 2007, the trend shows a slight increase in fuel use intensity of these species during 2007–2017 (Figure 6-3; Figure 6-4 gives a better resolution for mackerel and herring).

The fuel use intensity of cod, haddock and saithe has been reduced in 2007–2017 (Figure 6-3; Figure 6-4 gives a better resolution for these species), as have fisheries related GHGs during the years of interest. From 2007 to 2017, the fuel use intensity of cod, haddock and saithe decreased by 18%-23%. Cod trawlers and coastal and ocean-going conventional vessels mainly land these species (see Figure 3-5 for 2007 and 2017). Decreasing fuel use intensity of these fleet segments in 2007–2017 (i.e. a 14%, 31% and 27% decrease, respectively) is a reason for reduced carbon footprint of these species (Figure 6-5; Figure 6-6 gives a better resolution for coastal conventional vessels). It should be noted that the changes in catch composition of profitability survey's population in 2007–2017 also affects the trend.

In this study, it was assumed that coastal shrimp trawlers with 25% shrimp catch or more land all shrimp. Therefore, the increasing fuel use intensity of this fleet segment (Figure 6-5) is the only reason for increasing fuel use intensity and, consequently, increasing carbon footprint of shrimp in 2007–2017 (Figure 6-3). From 2007 to 2017, the fuel use intensity of coastal shrimp trawlers with 25% shrimp catch or more and, consequently, the fuel use intensity of shrimp increased by 46%.

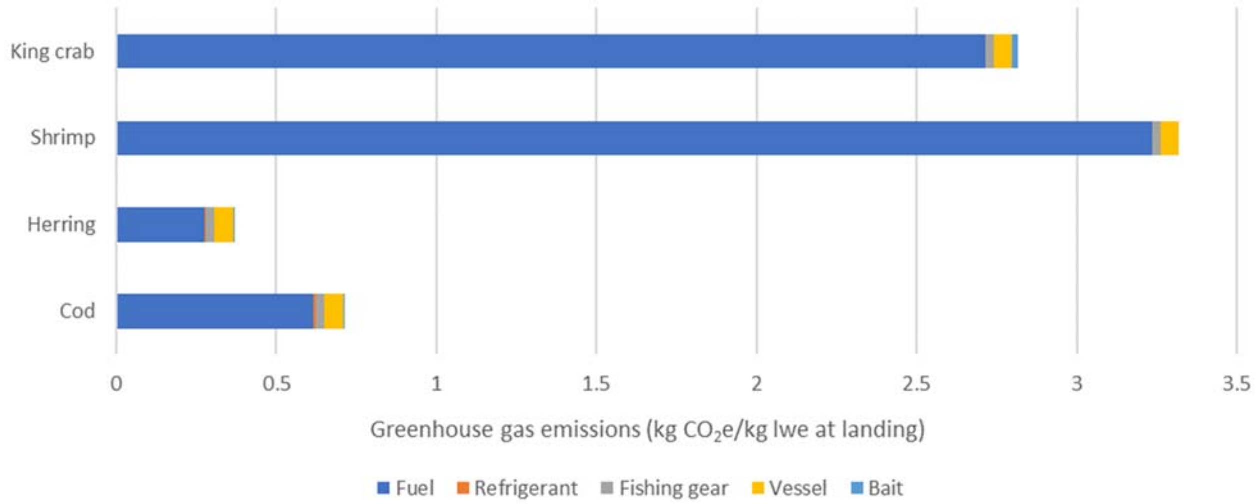


Figure 6-2 Greenhouse gas emissions of fisheries at landing per process.

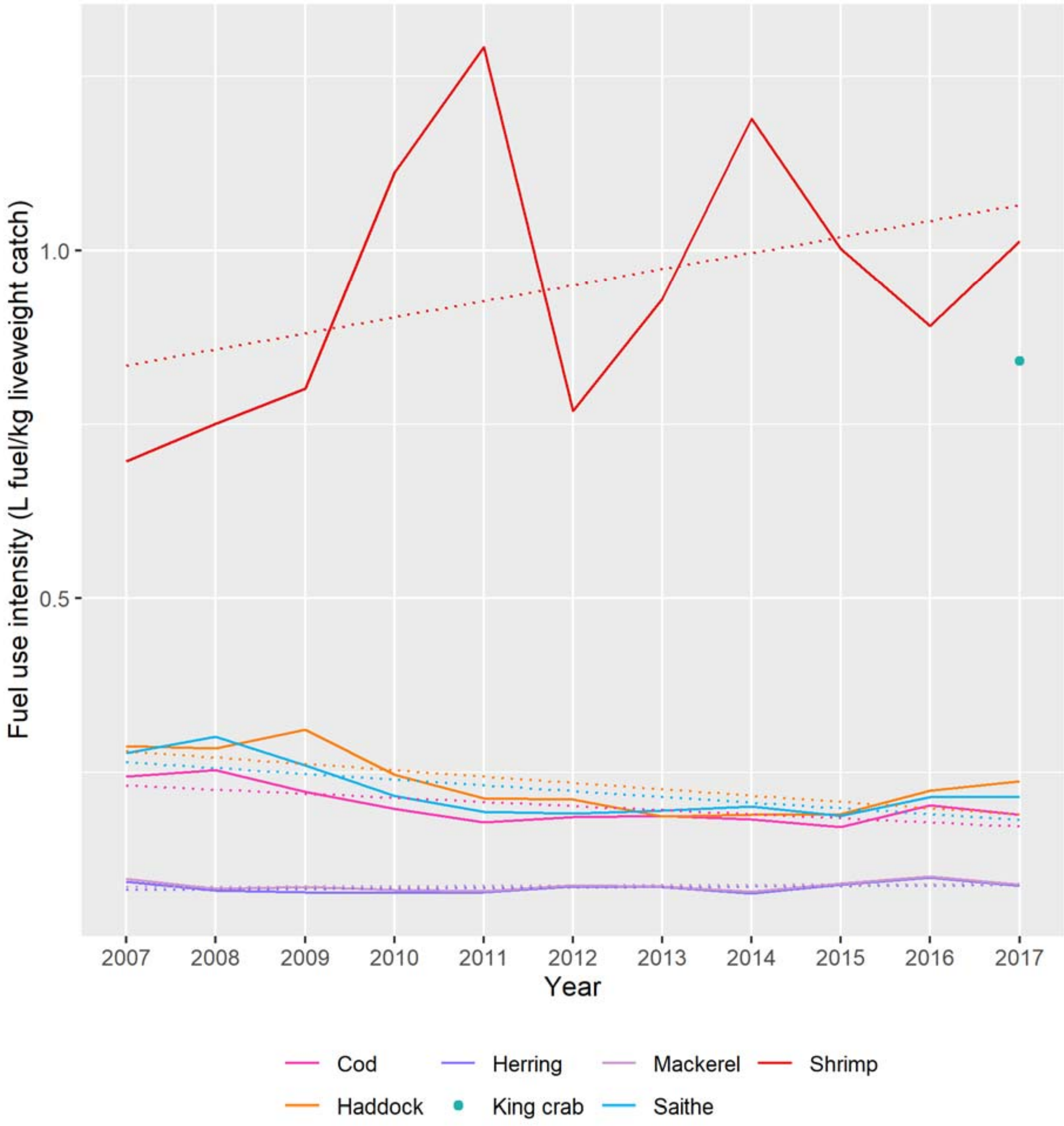


Figure 6-3 Fuel use intensity (L fuel/kg liveweight catch) of species in 2007–2017. For king crab, only data for 2017 is available. The values are based on the median fuel use intensity of fleet segments. Dotted lines represent trends.

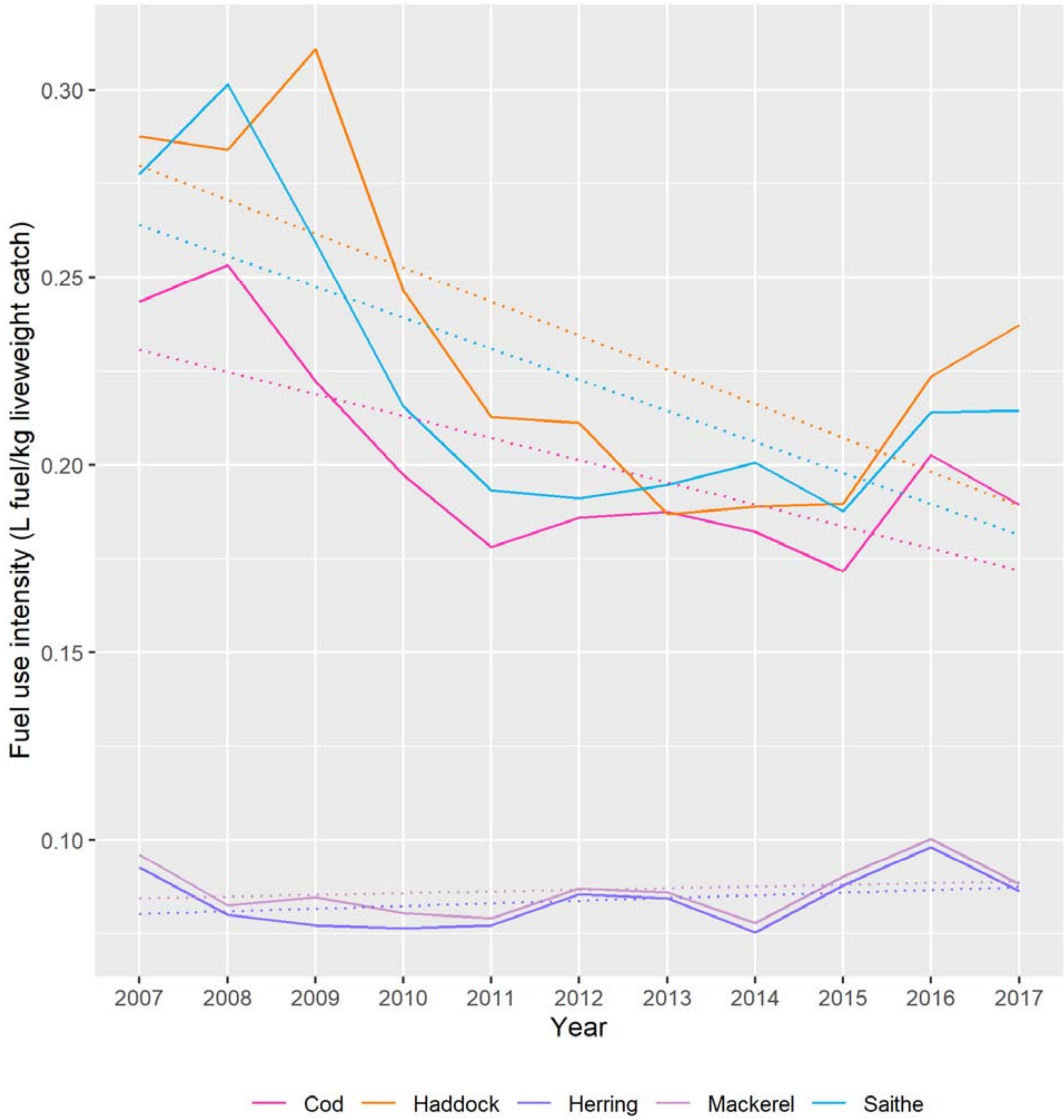


Figure 6-4 Fuel use intensity (L fuel/kg liveweight catch) of cod, haddock, herring, mackerel and saithe in 2007–2017. The values are based on the median fuel use intensity of fleet segments. Dotted lines represent trends.

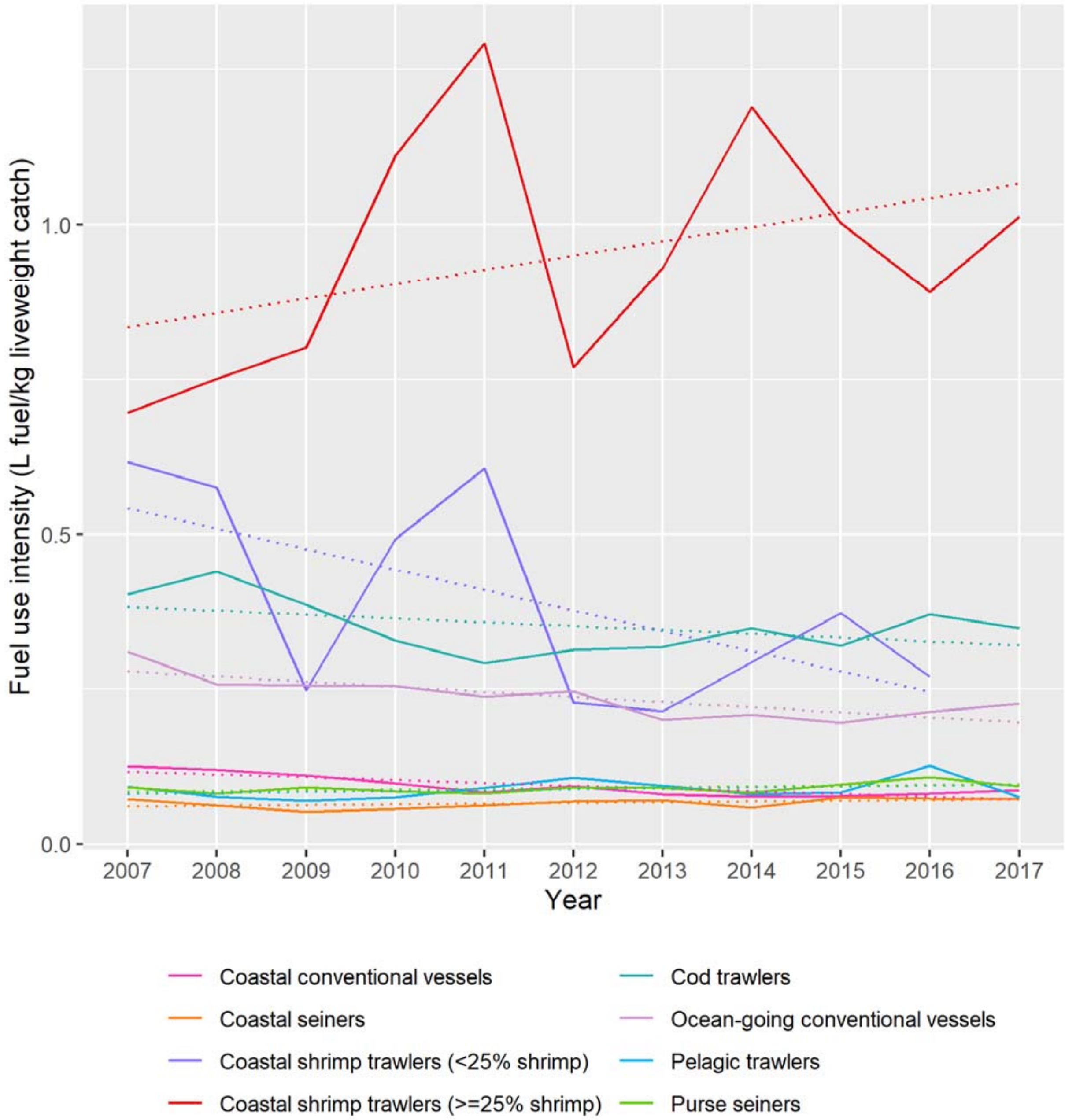


Figure 6-5 Median fuel use intensity (L fuel/kg liveweight catch) of fleet segments in 2007–2017. In the data used for 2017 [44] , no coastal shrimp trawlers with less than 25% shrimp catch exists. Dotted lines represent trends.

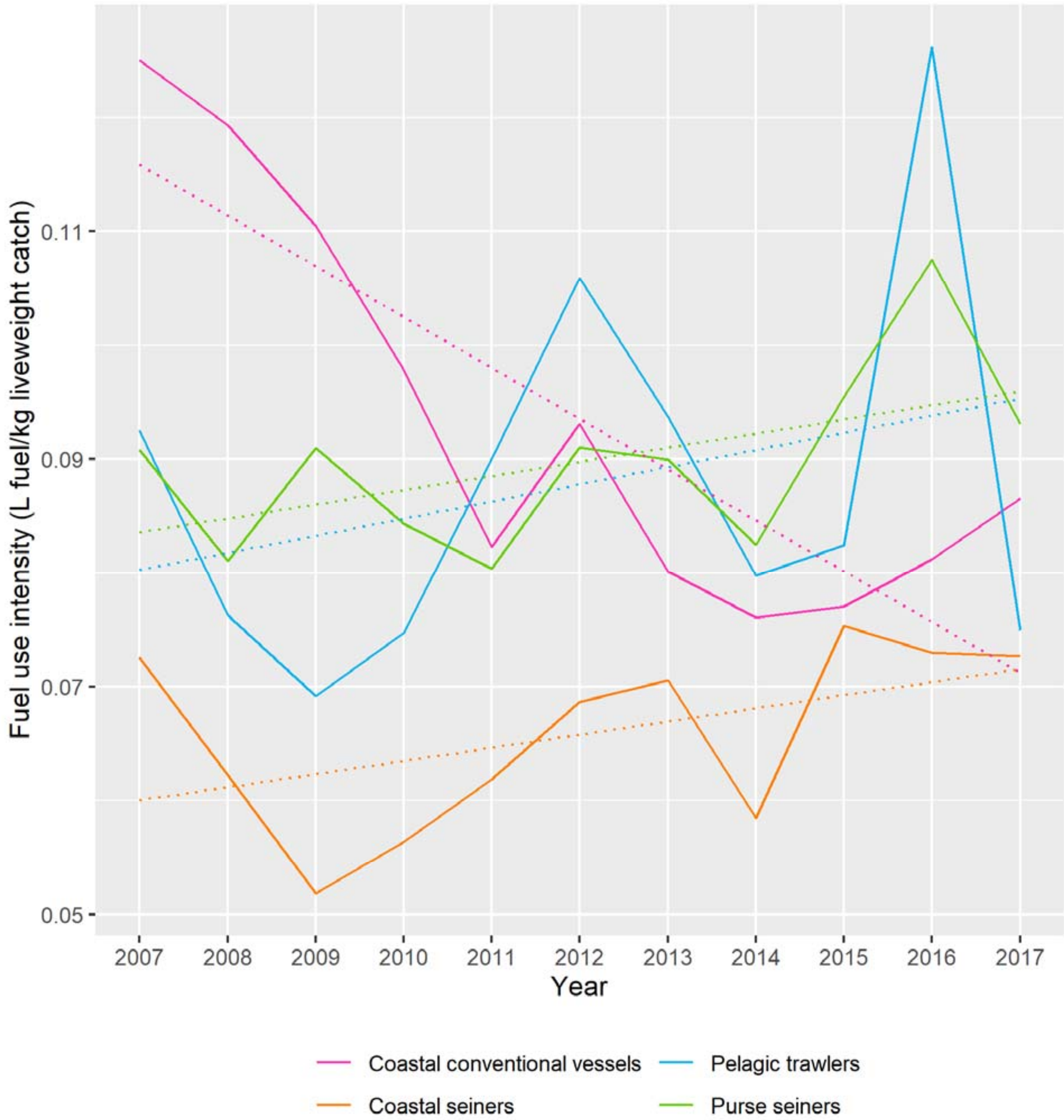


Figure 6-6 Median fuel use intensity (L fuel/kg liveweight catch) of coastal conventional vessels, coastal seiners, pelagic trawlers and purse seiners in 2007–2017. Dotted lines represent trends.

7 Comparison with terrestrial animal foods

7.1 Method

The GHGs of Norwegian seafood products were also compared with livestock products using literature data for European livestock products, which compete with seafood on European markets. For this, we used data from the most recent assessment of European livestock production available, a study by Leip and colleagues [98], adjusting results to broadly align with the methodology used for seafood, in terms of system boundaries and method for co-product allocation, to allow comparison of results per edible yield. Originally, we aimed to adjust the modelling of land use change of seafood and livestock using the same method, which would have required to process feed used by animal species in the Blonk tool. However this proved to be impossible as information about the detailed feed composition underlying each species [98] was not easily accessible to calculate their LUC using the same model that was used for salmon. Leip et al. reported the data including/excluding estimates of LUC emissions[24]. LUC emissions were calculated including CO_2, CH_4, and N_2O emissions from above- and below ground changes in organic matter, as well as from biomass burning. Allocating LUC emissions by country over those crops with increasing area in the period 1999-2008 (FAOSTAT) and making assumptions on the original land use [99]. Total emissions are allocated to crops with expanding area according to their share on total cropland expansion in the country or regional block.

An alternative approach would have been to instead apply the method/model used to account for LUC for terrestrial foods in the work by Leip and colleagues to salmon feed, but this was for several reasons not considered a feasible option, including different cropland expansion time series used. Therefore, the decision was taken to compare the various animal-source foods *without emissions from LUC.* Instead we discuss how the inclusion of feed raw materials with high land use change emissions impacts affects the footprint of different livestock products. Another modification was that micro ingredients in the salmon feed were not included, as these were not included in terrestrial animal production.

In the study by Leip and colleagues [98], emissions are allocated over animal products (meat, milk, eggs); emissions of meat are presented per carcass weight with all liveweight emissions allocated to the carcass weight. To convert from carcass weight to edible yield, we then applied factors for edible yield for each species to convert all results to be compared to the same functional unit (kg of edible meat) and, just as for seafood, allocated based on mass, assuming no use of by-products (i.e. allocating emissions entirely to the edible portion) for the comparison (Table 7-1).

Table 7-1 Data used from Leip et al. (2010) to compare Norwegian seafood with terrestrial animal products.

Animal product	GHGs per carcass weight excl. LUC ($kgCO_2e/kg$ CW)	Yield carcass weight from liveweight[1]	Yield bone free meat from carcass weight[2]	GHGs per edible weight ($kgCO_2e/kg$ edible)
Beef	27.3	0.54	0.70	39.0
Pork	7.19	0.78	0.59	12.2
Poultry	4.74	0.80	0.77	6.15

[1]Source: Leip et al. 2010 [2] Source: Clune et al. 2016 [100].

[24] Data are available at request at https://jrcbox.jrc.ec.europa.eu/index.php/apps/files/?dir=/afoludata/GGELS_2010&fileid=9337703

The latter also affects the result of salmon, as we in the base scenario had access to information on the use of seafood by-products for different products in different export markets and incorporated this knowledge into the calculations. Due to the method differences in the calculations of the GHGs for 2017 and for the purpose of this comparison (no LUC, no by-product use and no micro ingredients in the feed), it was decided to *present results of the comparison only in relative terms*, i.e. emissions of all animal-source foods are presented in relation to the poorest performing food, which is beef. This was done because here, the *focus is on the comparison* and not on absolute values and to avoid presenting several different results for the seafood products.

The data in the study by Leip et al. [98] spans the entire production of EU countries building on an agricultural economic model (Common Agricultural Policy Regional Impact- CAPRI), and all types of systems occurring in a country are integrated in the results (e.g. all forms of beef production within a country including milk-beef, pure beef, extensive-intensive are included).

The approach used in the comparison with terrestrial animal production has been chosen after consulting with three leading scientists in life cycle impacts of European livestock production systems: Christel Cederberg (Chalmers University of Technology, Sweden), Hannah van Zanten (Wageningen University, the Netherlands) and Adrian Leip (Joint Research Centre of the European Commission, Italy).

7.2 Results

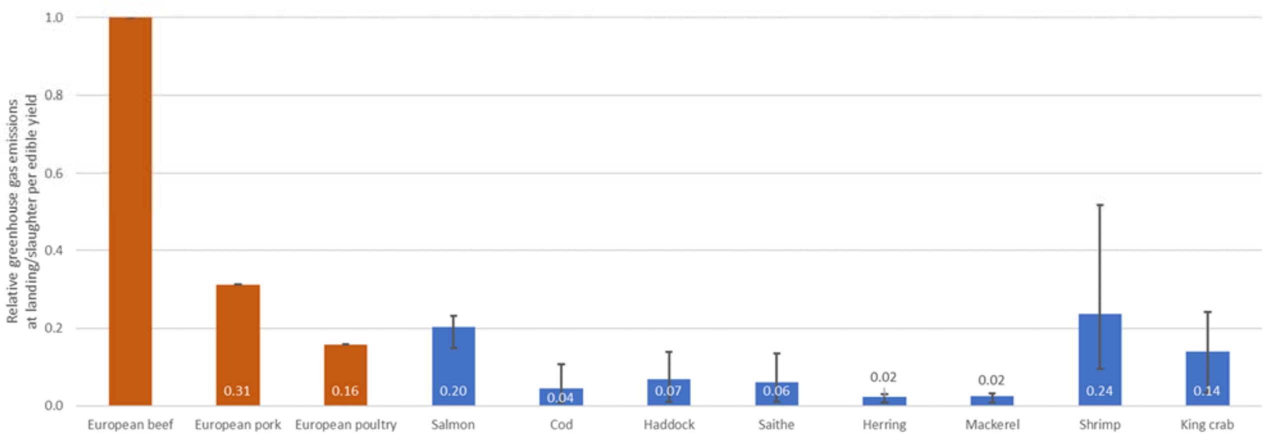
Relative results of the comparison of Norwegian seafood products with terrestrial animal-source foods are reported relative to the emissions of first beef and then pork (Figure 7-1). Results show that pork has around 31% of the emissions of beef and poultry about half of that (16% of beef). Shrimp is the seafood product with the highest GHGs at landing, 24% of that of beef. Farmed Norwegian salmon has an emission intensity that is 20% of that of beef and both shrimp and salmon fall in between poultry and pork. It is important to note that although direct Land Use Change was included in the assessment of farmed salmon, for the sake of the comparison with terrestrial animal products it was excluded, as it was not possible to harmonize the methods for its assessment between seafood and livestock.

Poultry is the species that consumes most soy (currently 20%-25% of the feed), whereas a typical inclusion of soy in pig feed is 5% and for beef it is even lower (Cederberg, pers.comm). As soy comprised 21% of the salmon feed modelled (Table 3-10), if land use change related emissions were consistently accounted for across all fed systems, the greatest increase in total GHG emissions would occur for poultry and salmon, then pig and finally beef and the differences would be reduced.

Therefore, the most important conclusion from this comparison is that pork and chicken cause greenhouse gas emissions on the same order of magnitude as salmon and shrimp and that each sector needs to identify and implement various improvements to decrease GHG emissions. Minimizing the inclusion of feed ingredients causing land use change is one option, not only in salmon, but there are many other ways to improve efficiency. It is not a safe long-term strategy for any sector to not attend the need to reduce emissions just because it currently compares favorably with another sector

It should also be kept in mind that the data used for terrestrial animal production was published in 2010 but represents agricultural production practices in 2004. It was not possible to find more recent data other than case studies representing single geographies or technologies and since the goal was to compare Norwegian seafood to other competing animal foods, it was important that the data used represents a broad European production mix. However, this means that we compare data for Norwegian farmed salmon using data for 2017 with European livestock products using data from 2004, and while technological or other development usually leads to improved efficiency over time (e.g. pig production has become more efficient over time through changed feed composition, increased fertility and piglet survival rates, Woodhouse, in prep.), this is not the case for Norwegian salmon farming during the past decade. Whether the European livestock products today are produced at lower (or higher) emissions than presented here, we simply cannot tell. A general conclusion from this effort to compare terrestrial and aquatic animal-sourced foods is that it is very difficult to do this in a meaningful way due to all the major and minor methodological differences, including everything from system boundaries, allocation principles, impact assessment indicators and differences in temporal coverage of the data. To be able to make a fully comparable carbon footprint for livestock and seafood products, these would ideally have to be studies in parallel, using the same methods.

a)



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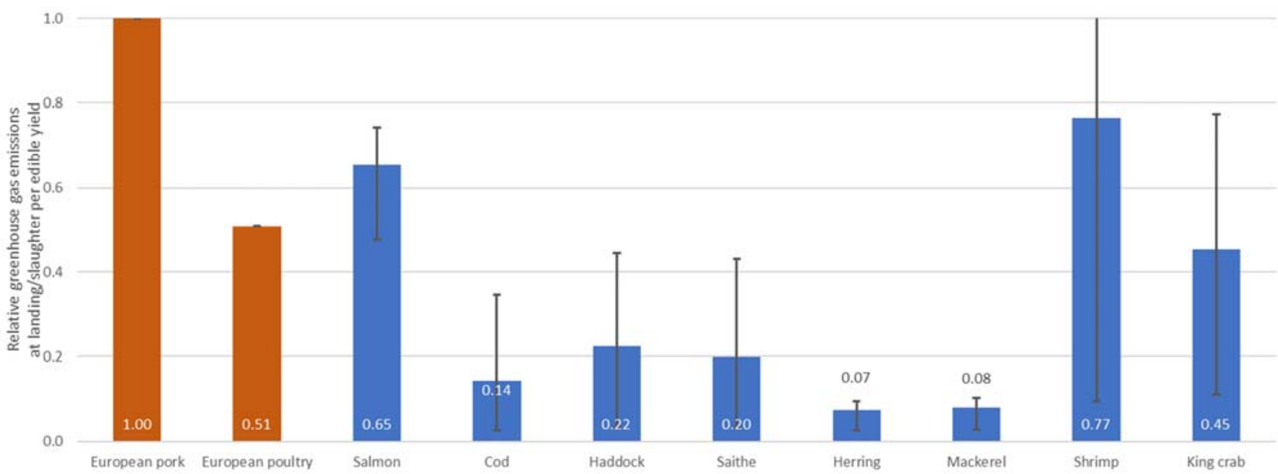

Figure 7-1 Relative greenhouse gas emissions of seafood (blue bars) at landing/slaughter vs. terrestrial animal-source foods (brown bars), with average values in relation to a) beef and b) pork presented. Error bars correspond to min and max values based on current best and poorest practice. Emissions due to Land Use Change are excluded, by-product use set to zero for all products and micro ingredients in salmon feed were excluded for comparability.

8 Discussion

Carbon footprint 2017

This work has shown that the Norwegian seafood products studied result in greenhouse gas emissions between 1.1 and 29 $kgCO_2e/kg$ edible product delivered to wholesaler, depending on many factors including species, production technology, product form, transport mode and distance to market, the edible yield and utilization of by-products. Pelagic species and products are once again shown to be the most efficient ones among the products analyzed, even without taking into account their high nutritional value in the functional unit [101] . The demersal fish species cod, saithe and haddock were also found to result in relatively low emissions, while crustaceans and salmon had the highest emissions among the seafood products. Crustaceans are known to be at the high end of capture fisheries in terms of fuel use intensity [86], mainly because of a low catch per unit of effort. By-product utilization was high for shrimp (100%), if this had not been the case, emissions would have been higher. The seafood product with the highest emissions of all at landing/harvest, with or without accounting for LUC, was farmed salmon, mainly due to the feed (representing 85% of farmgate emissions including LUC). While the importance of feed confirms all previous findings of LCAs of salmon farming, results for salmon at farmgate were considerably higher than the average found for net-pen farming in Norway and elsewhere [102]. The large variability in GHG performance within each seafood species shows that there is considerable scope for improvement.

Comparison over time

In chapter 6, temporal trend using the simplified methodology for greenhouse gas emission accounting for seafood showed clear trends of decreasing emissions for products from capture fisheries and increasing emissions for salmon products, which corresponds well with the interpretation of the main results for 2017.

The increased emissions associated with farmed salmon compared with ten years ago are due to several aspects included here that were not included in Winther et al. (2009) [1], which, therefore, partly underestimated the footprint of salmon. Land use change of crop-based feed ingredients was not included due to major methodological uncertainties at the time, while it is included here. The impact of land use change is very dependent on the scale of data used, but there is today a more coherent view on 1) that land use change needs to be included and 2) methods for doing so, several standards even mandate inclusion. The other major exclusion (in that case due to lack of data) was micro ingredients, which in the Winther et al. (2009) [1] report simply were treated as an average of the main feed. However, using some preliminary data for the various micro ingredients used showed that these contribute with a disproportionate share to the total feed (and salmon) footprint due to high energy use in their production. Potential positive effects of micro ingredients that could outbalance impacts caused in their production, i.e. reducing feed use and increasing fish health and growth cannot be evaluated with the data and approach used here.

Another important explanation for the increase is reduced production efficiency over the last decade, stemming from increased problems with disease and salmon lice, which besides animal welfare issues result in reduced growth and in some cases higher mortality. Both reduced growth and increased mortalities lead to a higher economic feed conversion ratio, which is the single most important input parameter to a salmon LCA as it directly relates the amount of feed needed to produce a certain volume of fish. If salmon die or grow more slowly due to disease, the feed is still used, but with less output. The eFCR had increased from 1.2 to 1.32, i.e. 10% between 2007 and 2017, but is also subject to annual variation.

In addition to higher FCR compared to ten years ago, the use of service vessels has also increased over the same period. This can partly be attributed to the increased need to manage disease/parasite problems (surveillance and treatment). This means that disease and parasites cause much larger impacts than indicated by the contribution of production of medical and biological treatment (e.g. H_2O_2 and farming of cleaner fish), as it also increases the eFCR and need for wellboat activity.

In 2009, farmed salmon and wild-caught cod had similar total emissions, based on data from 2007, with totally different processed contributing to the total [1]. For products originating in capture fisheries, as mentioned, the opposite development has occurred since 2007, with reduced emissions, in particular for demersal species and these products now have a lower carbon footprint than salmon, despite the fact that gear and vessel construction were included (which they were not in 2009). This reduction results mainly from reduced fuel combustion and refrigerant leakage and a high by-product utilization rate. The improvement over time is due to two separate developments. First, the stocks of cod and haddock are significantly higher in 2017 than they were in 2007, resulting in larger quotas which can be utilized more efficiently (larger landings per unit of effort measured in trawl hours or fishing days). Another change that appears to have happened since 2007, although there is some uncertainty around this, is the almost complete phasing out of HCFCs (R22) as a coolant on fishing vessels. These appear to have been replaced primarily by so called natural refrigerants (e.g. NH_3 and CO_2) with a low global warming potential. Replacing them by HFCs, often with an even higher global warming potential than HCFCs (HFCs were introduced because of their low ozone depletion potential), would instead have led to increased GHGs with the same leakage rates.

In the 2009 report (based on 2007 data), it was assumed that by-products were not used in cases where no data on utilization was available, which in practice was the case for all processing abroad, except for whitefish filleting in China. In this report, by-product utilization data were available for almost all products from seafood market analysts (Kontali Analyse AS), except for king crab. For this product, a zero by-product utilization rate was therefore used in the calculations, which increases the emissions. When a by-product utilization rate was known, it led to a reduction of emissions for the main (studied) edible seafood product forms compared to no utilization of by-products. It is difficult to estimate the uncertainty of these numbers and since they do affect results, it would be optimal if official data were presented on by-product utilization in different sectors. In order to favor more circular systems, collecting this type of data is important. A related important data gap that we were not able to include other than through estimations in the sensitivity analysis was supply chain product losses. Even when production of many seafood products is low in greenhouse gas emissions, small losses along the post-harvest supply chain could easily erase this advantage, and this could also represent important differences between different product types, e.g. fresh and frozen products. To be able to properly account for this essential part of a carbon footprint and suggest improvements, representative data on post-harvest losses is needed for different products, product forms, transport modes etc.

Results presented here are as far as possible built on data from 2017, meaning that results are a snapshot of the production and distribution in that specific year, which does not necessarily have to be a typical year. In fact, 2017 could be an outlier due to extreme events in some parts of the seafood sector. For example, the eFCR in farmed salmon production in 2017 was higher than the one both in the year before and after. More useful than doing this exercise in a detailed way every ten years, would be to implement strategies in the sector to collect the most central data in a standardized way that does not require exhaustive data collection efforts via surveys, e-mails or through skype meetings. From the collective experience gathered, these critical data were defined and shown to provide a useful rough picture of the climate impact of each system, particularly useful for monitoring of performance from year to year. As a follow up to this project, a strategy to monitor these data in a more automated way will be discussed in a series of workshops with the Norwegian seafood sector next year.

Seafood-livestock comparison

In terms of the comparison with land-based animal-source foods, seafood in general still has lower impacts than livestock products, although there is variability within each of these groups and overlap between them (Figure 7-1). The data used shows that pig and poultry are on the same order of magnitude as salmon and shrimp and that the absolute GHG value for European poultry production was slightly lower than that of farmed salmon, contrary to what was found in 2009 when the data used to characterize livestock emissions was drawn exclusively from Swedish production data. It is important to recognize though that the comparison was made without emissions from LUC due to methodological inconsistencies and that these would likely affect the relative position of poultry and salmon most as these two species have the highest inclusion of soy in the feed. The large variability in GHGs within species between best and poorest performers demonstrate a scope for improvement and the outcome of this comparison as a result may change.

Soy
As mentioned earlier, 21% of the salmon feed formulated in Norway in 2017 is soy meal (or soy protein concentrate Table 3-10). Soybeans are farmed in many places in the world both for food and as a protein-rich feed used as a major component of feed for many different animals, including salmon. As demand for soy is growing, based on a growing demand for animal feed in general and the replacement of marine ingredients in aquafeeds in particular, the agricultural land used to farm soybeans has expanded over the last couple of decades. Though the expansion has occurred in many countries, it is most pronounced in Brazil, one of the world's leading producers of soybeans. In Brazil, the expansion of soy cultivation has resulted largely from the expansion of land in agriculture not through the displacement of other crops on existing farmland. This means that land previously not used in agriculture (different types of land occurring in Brazil, including rainforest) is being actively converted to agricultural land and such conversion of land results in greenhouse gas emission, by releasing the carbon bound in the former vegetation and soil, termed direct land use change (dLUC) emissions. In addition, when increased demand for one crop, possibly produced under certain production criteria to reduce its land use change impacts, leads to that the production of other crops, not under such criteria, are displaced to the new land, leading to indirect land use change emissions of the first crop (iLUC). Such indirect emissions are very hard to quantify due to the links between productions systems that still need to be defined. It is also important to note that in this report, only direct emissions were accounted for, using the dLUC tool of Blonk Consultants (https://tools.blonkconsultants.nl/tool/3/). This tool assesses land use change during a 20 year period, which is compliant with the product environmental footprint (PEF) rules for feed currently developed by the European Union, which also requires the assessment of dLUC emissions, either on a general level, or if specific information is available on the origin of the crop (e.g. in terms of former land use and time since land use was changed), then this information can be used [12].

The main part of the soy in Norwegian salmon feeds originates in Brazil and is certified by ProTerra and/or the Roundtable for responsible soy (RTRS). These organizations have a number of criteria that aim to minimize the environmental and social impacts of soy production, which when met can result in the certification of soy. These include that soy farmed on land that was deforested up to 8 years ago cannot be certified. However, this means soy farmed on land 9 or more years ago can be certified. Demand for soy from Brazil, even if certified and produced in areas that have not been deforested during the most recent 8 years, risks displacing production of other crops or grazing animals to newer agricultural areas. For these two reasons (the shorter timespan for which there was no deforestation and the unaccounted indirect effects of displaced land use due to increased demand also for certified soy), all use of soy has been modelled as average soy from Brazil, i.e. no difference in emission modelling has been made on the basis of whether soy was certified or not.

That said, it is important to state that certification can be an important driver for change, also of the conventional farming and in the long-term could change production practices, although it is not currently possible to quantify the differences in a reliable way. It is also important to recognize that soybeans can be and are farmed in many other areas in the world, without land use change, e.g. in the US and in Europe. Based on discussions with experts on land use change and soybean production, if soy is used in a feed the following priorities for its sourcing are recommended:

1. European soy (it would be advantageous if more protein feed was farmed in Europe)
2. Soy from other countries where agricultural land use does not expand
3. Certified soy
4. Non-certified soy (last option)

The models estimating dLUC are still subject of discussion and variability, leading to highly different values for GHGs for soy circulating, which is confusing not only for non-experts. However, the fact that soy does cause land use change is not subject of discussion and it is merely how to account for it that is being debated and still under development. As mentioned, inclusion is mandated by standards today and for the modelling of Norwegian salmon feed in 2017, the approach described was chosen based on the line of reasoning presented above. Consequently, feed and salmon producers that stops using soy from countries with land use change will be able to document a major improvement and feed producers having access to detailed information about the soy they source stating the land has been used for farming for at least 20 years can also get a credit for that. So to reduce land use change emissions from soy, feed producers either need to increase the traceability of the soy they are sourcing, or stop sourcing from countries where these crops and agricultural land use is expanding. It is interesting to note that Salmon Group, a network for smaller Norwegian salmon farmers, replaced Brazilian soy with European soy in 2019 [103].

Micro ingredients

The major importance of micro ingredients is a finding that to our knowledge has previously only been shown by Hognes (2014) [7]. Here, major efforts were made to connect with feed producers and micro ingredient producers to obtain representative data, efforts that were mostly unsuccessful. The data that has been used must be considered crude and uncertain, but again large efforts were made to verify the order of magnitude of GHGs per kilo for the various ingredients that were found. This was done with the same feed producers and producers of micro ingredients and two of them gave similar ranges and said they had seen similar numbers as those presented here. It is clear though, that much more knowledge is needed and that the large ranges indicate that how these micro ingredients are sourced will make a big difference, e.g. their method for production, the energy sources used etc. As mentioned earlier, some micro ingredients, e.g. vitamins and amino acids are added to improve fish health and may in this way reduce the eFCR which could be more important than the emissions from their production. More knowledge about the role of micro ingredients and data for their production is highly needed.

Salmon feed composition

It is clear that the composition of the feed is important, and that micro ingredients and soy come out as hotspots. A trend in Norwegian salmon feed is that marine inputs (meals and oils from whole fish from dedicated reduction fisheries as well as processing by-products of pelagic and demersal fish) are being reduced and crop-based inputs are instead increased. In the 2009 report, the crop/marine ratio in 2007 was 60/40, in 2017 it was 70/30. This trend is driven by a need of the industry to become independent from a limited resource in order to be able to continue growing, and from an environmental debate about the sustainability of fish meals and oils and the use of fish to produce feeds rather than as food directly. The increasing use of processing by-products (35% of fish meals are today produced from processing by-products, and here 9 % of the salmon feed was composed by oils and meals from fish processing by-products)

From this work, it is clear that there are tradeoffs involved when replacing marine inputs with crop-based ones, in particular if using Brazilian soy. Previous studies have drawn the opposite conclusions with regard to animal vs crop-based inputs, but then it also involved poultry products as animal inputs in salmon feeds in certain countries and for the crop-based ones, land use change was not included and this has changed the picture. However, it is clear that there are large differences within each feed input group (marine oils and meals, crop-based proteins, meals and starch and micro ingredients) which means that climate-conscious sourcing of feed inputs in each of these groups fulfilling certain nutrient requirements represents an important improvement option. In addition, the composition in terms of the groups can also to some extent be changed, but obviously starch cannot replace more protein-rich ingredients, despite it being low-GHG.

Airfreight

Another "hot topic" is airfreighting of live or fresh seafood to distant markets and results confirmed previous findings that airfreighting is indeed an emission hotspot. The method choices made to model airfreighting (load factors for passengers and cargo) were made in favor of airfright, while in reality conditions are likely less optimal and emissions even higher, which was shown in the sensitivity analysis. It is often argued that seafood only utilizes empty capacity on passenger flights when belly freighters are used, but this argument does not hold as the activity will give an income and makes flights more profitable than they would be without the seafood cargo. Using the method defined by the International Air Transport Association (IATA) to distribute emissions between cargo and passengers for belly freighters (based on the relative mass of passengers vs cargo) gives that cargo flown on belly freighters causes higher emissions than when flown as pure cargo, as a result of the much lower cargo capacity of belly freighters and more stopovers of passenger than cargo flights. Due to the higher fuel use during takeoff and landing, the number of flight legs is more important than the total distance flown. Recently avoiding airfreighting of seafood was suggested as an important improvement option of the seafood sector to contribute to climate emission reduction goals [4] and while that is a valid recommendation, there are chains where shifting transport mode entirely will be difficult. Tweaking all of the parameters mentioned and reducing airfreight only on the intercontinental distances, while doing the intracontinental transportation before and after airfreight by other transport modes, can reduce transport emissions considerably [93].

Klimakur 2030

In January 2020 the Norwegian Environment Agency launched the report "Klimakur 2030" providing recommendations for reducing Norwegian GHG emissions by 50% until 2030. This report will be an important background material for a White paper on how to achieve the cuts Norway has committed to in the Paris agreement.

Klimakur 2030 points at a reduction potential of around 2 million ton CO2e in the Norwegian aquaculture industry and around 0.2 million ton CO_2e for the fishing fleet within 2030. Most or all of this reduction potential results from replacing fossil fuels with alternative energy carriers such as biofuels, ammonia, LPG and electricity. Since the Norwegian Environment Agency only consider direct emissions, important climate aspects such as the carbon footprint of the production of the energy used is not included. The major part of the climate impact from aquaculture products, which is feed production, is also not included. It is our recommendation that the Norwegian fishery and aquaculture industry should assess their full greenhouse gas emissions, i.e. both direct and indirect upstream emissions as part of their climate environmental management strategies, since only focusing on direct emissions will limit the measures and improvement potentials.

Limitations

In terms of data availability, little has changed since the data collection undertaken for the Winther et al. report 2009 [1], despite that that work gave clear indications on what type of data is central to collect in order to undertake a robust, data-driven analysis of the carbon footprint of seafood products in Norway. It would simplify the process considerably both for the LCA practitioner and the industry if the most critical data were collected in a standardized way so that they at least are available upon request, or ideally are made publicly available.

It is important to keep in mind that greenhouse gas emissions are only one dimension of sustainability, and while often in line with other types of environmental impact, in particular in fisheries, in some cases there may exist trade-offs between greenhouse gas emissions and other environmental impact categories. An example is when fishing with selective gear, designed to be less efficient in order to save certain components of the catch, but this can reduce the fuel intensity of the fishery and thereby increase its greenhouse gas emissions.

For the modelling of fuel use in fishing, the fleet segment was used as the basis for weighting of species-specific values (rather than the fishing gear as was done in 2007), this was due to the resolution of the data, which is annual, and the fact that fleet segment and gear is linked, i.e. certain gear types are linked to certain fleet segments. Still, in every fleet segment, there is a mix of different fisheries in terms of fishing gear and target species. This can create problems when highly different fisheries are mixed in one segment, e.g. demersal trawling for fish and shrimp or demersal and pelagic trawling. Some adjustments were made to minimize the influence of "other" fisheries on the fisheries modelled, but it cannot be excluded that there is some influence of these other fisheries (e.g. shrimp trawling and pelagic trawling on the trawling of whitefish). For example, the fuel use of shrimp fisheries might be underestimated due to mixing with fish in the catches of the coastal shrimp trawlers used to represent shrimp (although the mixing was less than in larger shrimp trawlers, whose data could therefore not be used). The fuel use for whitefish could be underestimated due to the removal of vessels catching shrimp in their assessment, but when this was checked, it appeared that the shrimp trawlers, although having a high proportion of fish in their landings, landed a very small proportion of all Norwegian cod, saithe and haddock. The underlying data for estimation of fuel efficiency is the annual Norwegian fisheries profitability study and important changes were introduced in 2009 in how vessels were selected to participate in this survey (fewer and more profitable vessels were included in each fleet segment) that also potentially could influence the results. It was surprisingly hard to understand how representative the number of vessels in the profitability study were for the whole Norwegian fleet as number of vessels belonging to each segment do not seem to be available. Collecting fuel data at a higher resolution and designed for the purpose of estimating fisheries greenhouse gas emissions would considerably improve the precision in these estimates. Likewise, data on the use of refrigerants in fisheries is much needed in order to be able to monitor these over time.

By-product utilization as well as product losses were shown to be very important in the assessment of greenhouse gas emissions of seafood supply chains and low utilization and high losses can compromise good performance of a product supply chain. Data on these important aspects are scarce and uncertain and results presented here are highly dependent on the accuracy of these data. Systematic collection and reporting of this type of data from the Norwegian seafood sector would be very beneficial and is highly recommended.

In this report, the aim was to present results for average Norwegian seafood products in each category. For products produced using various technologies, this means the average is a weighted average between these technologies. For all products, it means that results are an aggregate of good and poor performers and the results represent no one producer. Consequently, no producer should therefore use the results presented in this report as their current or 2017 carbon footprint. These should instead be used as benchmarks to rank Norwegian producers against, which is shown by the various improvement options demonstrated.

Recommendations

- Identify means to shift away from soy originating in countries with expanding agriculture and soy farming, instead favouring soybeans farmed in countries where it does not cause land use change - or shift to alternative feed ingredients.

- Carefully evaluate the full supply chain effects of replacing feed ingredients. Shifting to lower input ingredients may not lower the carbon footprint of the product if e.g. the feed conversion ratio increases, or fish growth is reduced.

- Better understanding on the role of micro ingredients for the GHG of salmon and other animal production systems is urgently needed.
- Identify means to improve the fuel efficiency of fisheries through technology or policy. Better understand the reasons for vessels being best performers and learning from their behaviour.
- Monitor the use of HFC refrigerants in Norwegian fisheries and identify means for further reduction.
- Per sector identify the most central data that need to be monitored and stored in a standardised way in order to be able to monitor performance from year to year in a simplified way.
- Partially or fully shift supply chains away from airfreight.
- Improve data collection on by-product utilization and supply chain product losses.
- Stimulate processing close to production and product forms with a long shelf-life.

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A Product table and transport distances

Table A-9-1 Product description and transport distances

Product full name	Road (km)	Sea (km)	Rail (km)	Air (km)
Product 1: Salmon, fresh, gutted head on, in EPS box with ice, to Paris by road and ferry. Byproduct utilization in market: 80%.	2,642	95		
Product 2: Salmon, fresh, gutted head on, in EPS box with ice, to Oslo by road and ferry. Byproduct utilization in market: 75%.	942			
Product 3: Salmon, fresh, gutted head on, in EPS box with ice, to Shanghai by road and air. Byproduct utilization in market: 20%.	992			1,200 + 8,252
Product 4: Salmon, frozen, gutted head on, in cardboard box, to Shanghai by road and ship. Byproduct utilization in market: 70%.	50	21,030	200	
Product 5: Salmon, fresh, fillet B-trim, in EPS box with ice, to Paris by road and ferry. Byproduct utilization in market: 30%.	2,642	95		
Product 6: Salmon, frozen, fillet B-trim, in cardboard box, to Paris by road and ferry. Byproduct utilization in market: 0%.	2,642	95		
Product 7: Salmon, fresh, fillet B-trim, in EPS box with ice, to Paris through Poland by road and ferry. Byproduct utilization in market: Poland 100%, Paris 30%.	3,217	315		
Product 11: Cod, fresh, gutted head off, in EPS box with ice, to Paris by road and ferry. Byproduct utilization in market: 70%.	3,150	95		
Product 12: Cod, fresh, fillet with skin and bones, in EPS box with ice, to Paris by road and ferry. Byproduct utilization in market: 50%.	3,150	95		
Product 13: Cod, frozen, fillet with skin and bones, in cardboard box, to Paris by road and ferry. Byproduct utilization in market: 40%.	3,150	95		
Product 14: Cod, frozen, fillet (100% edible), in cardboard box, to Paris through China by road and ship. Byproduct utilizationt: China 100%, Paris no byproducts.	404	41,890		
Product 15: Cod, salted, split, in cardboard box, to Lisbon by road and ferry. Byproduct utilization in market: 85%.	4,880	95		
Product 16: Cod, salted and dried (klipfish), split, in cardboard box, to Lisbon by road and ferry. Byproduct utilization in market: 40%.	4,880	95		
Product 17: Saithe, frozen, fillet with skin and bones, in cardboard box, to Paris by road and ferry. Byproduct utilization in market: 30%.	3,150	95		
Product 18: Haddock, fresh, gutted head off, in EPS box with ice, to London by road and ferry. Byproduct utilization in market: 90%.	3,180	95		
Product 19: Haddock, frozen, gutted head off, in cardboard box, to London by road and ship. Byproduct utilization in market: 90%.	300	2,121		
Product 20: Herring, frozen, round, in cardboard box, to Kiev by road and ship. Byproduct utilization in market: 50%.	500	8,900		
Product 21: Mackerel, frozen, round, in cardboard box, to Tokyo by road and ship. Byproduct utilization in market: 70%.	50	26,230		
Product 22: Shrimp, boiled and frozen, peeled, in cardboard box, to Stockholm by road. Byproduct utilization in market: No byproducts.	2,340			
Product 23: King crab, live, in cardboard box, to Seoul by road and air. Byproduct utilization in market: 0%.	2,050			
Product 24: King crab, frozen, round, in cardboard box, to Seoul by road and ship. Byproduct utilization in market: 0%.	213			2,525 + 8,097

B External review

KINGFISHER ENVIRONMENTAL ANALYTICS
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January 25, 2020

Dr. Ana Karina Carvajal
Research Manager
SINTEF Ocean AS
7465 Trondheim, Norway

Dear Dr. Ana Karina Carvajal:

It is my pleasure to provide this final report of my review of a research project report titled: "Greenhouse gas emissions of Norwegian seafood products in 2017" authored by a team of Norwegian and Swedish researchers led by Dr. Ulf Winther. I was contracted by SINTEF in April, 2019 to undertake this external review in accordance with ISO standards for life cycle assessment (LCA) research. In addition to attending to issues specifically related to LCA practice (e.g. issues of scope, conformity with secondary LCA guidance documents, choice of methodological practice, etc.), in my review I chose to also provide the research team with input on issues related to foreground data sourcing and analyses, reporting clarity and transparency, and at times editorial suggestions. I recognize that these forms of review and input were beyond the scope of my formal mandate but I hope that the additional input has been of value.

My formal input on the research conducted included:

- Substantive input along with minor editorial suggestions on a document describing the methods to be used to undertake this research in feedback provided to the team in June of 2019, and
- Detailed substantive input along with substantial editorial suggestions on a near complete draft of the final report in early January of this year.

In both instances, my feedback was provided using the Track Changes function within Word versions of the documents as this was the most efficient way of providing the detailed input I wished to provide.

What follows is my high level assessment of the work undertaken based on the detailed reviews provided along with a read of the penultimate version of the final report that was provided to me on January 24th.

The scope, complexity, and detail of the research undertaken is remarkable and should not be discounted. It is easy to say that work will be conducted to characterize the life cycle greenhouse gas (GHG) emissions resulting from 24 consumer-facing seafood products, derived from eight primary seafood products sourced from fishery or aquaculture production systems, and delivered to various international markets, but it is a genuinely formidable task to complete such work. To have done so with the level of detailed foreground data compiled from public and private sources, use of thoughtful and creative analyses of available data to better reflect the systems to be characterized (e.g. fuel use intensity of trawl caught shrimp), and making potentially important contributions to how this sort of research should be conducted in the future is noteworthy. In particular, but non-exhaustively, I was impressed with the team's efforts to:

- Include within the scope of emissions characterized, those from (in no specific order):
  - salmon smolt production,
  - infrastructure used in many foreground systems including materials to build vessels and fishing gear,
  - service vessel support used in salmon farming
  - land use change associated with crop-sourced inputs to farmed salmon diets
  - micro-ingredient inputs to farmed salmon diets, and
  - loss of refrigerants used aboard fishing vessels.
- Incorporate detailed data on what are often easily overlooked and frequently simplified factors such as:
  - mode- and destination-specific transport load utilization rates,
  - species- and activity-specific yield rates,
  - by-product generation rates and fates in various settings where processing occurs, and
  - the extent to which Norwegian-sourced hydroelectricity can be used to characterize emissions from land-based activities when low GHG emission credits of the same electricity have been sold to other users.

As a consequence of the efforts that the team has made, some results may appear surprising to readers familiar with previously quantified emissions from the same or similar seafood systems. Importantly though, this appears to largely result from the inclusion in the current work of sources of emissions (e.g. emissions from land use change and micro-ingredients) that have not typically been included in similar prior analyses. As such, the reviewed report represents an important effort to undertake more detailed and accurate analyses of life cycle GHG emissions that arise from these important seafood systems and in doing so sets the bar higher for future work while at the same time pointing to important new ‘hotspot’ sources of emissions to be characterized in greater detail, managed or potentially avoided.

From my review of the penultimate version of the final report recently provided to me, I am very satisfied that the team has addressed the great majority of my suggested improvements and when they have not, it has been supported. As a result, the report is much more transparent, clear, and inclusive of details underpinning the research that was undertaken.

In conclusion, it has been a pleasure to serve as a reviewer of this very substantial and in many ways, methodologically ground-breaking effort to characterize life cycle GHG emissions from a wide range of contemporary Norwegian sourced seafood products.

Sincerely,

Peter Tyedmers, Ph.D.
Professor, School for Resource and Environmental Studies, Dalhousie University, and Director, Kingfisher Environmental Analytics

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