2022:01198 - Open

Greenhouse gas emissions of Norwegian salmon products

Author(s)

Ulf Johansen, Andrea Arntzen Nistad, Friederike Ziegler, Shraddha Mehta, Markus Langeland, Yannic Wocken and Erik Skontorp Hognes

2022-12-06

SINTEF

Address:

NO-
NORWAY

Enterprise /VAT No:

Report

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REPORT NO.	**PROJECT NO.**	**VERSION**	**DATE**
2022:01198	302006529	1	2022-11-15

KEYWORDS:
Norwegian salmon
Aquaculture
Greenhouse gas emissions
LCA

AUTHOR(S)
Ulf Johansen (SINTEF Ocean)
Andrea Arntzen Nistad (Asplan Viak), Friederike Ziegler (RISE), Shraddha Mehta (SINTEF Ocean), Markus Langeland (RISE), Yannic Wocken (RISE), Erik Skontorp Hognes

CLIENT(S)
Norwegian Seafood Research Fund (FHF)

CLIENT'S REF.	**NUMBER OF PAGES/APPENDICES:**
Norwegian Seafood Research Fund (FHF)	92 + Appendices

CLASSIFICATION	**CLASSIFICATION THIS PAGE**	**ISBN**
Open	Open	978-82-14-07907-4

ABSTRACT

Greenhouse gas emissions have been quantified for 11 Norwegian salmon supply chains. This is the third comprehensive assessment carried out for the Norwegian farmed salmon supply chains with some differences in the data used and the method chosen. Hence results presented in this report must be compared keeping in mind the differences and changes in the GHG emissions cannot be interpreted as a direct result of aquaculture industry's reduction measures. Greenhouse gas emission reduction potential of 19 improvement measures including changes in feed composition, distribution to the market, reduced losses and electrification of grow-out farms among others was quantified. The effects of the measures vary from 19% lower emission to 29% higher emissions than the base case farmgate salmon at 3.8 kg CO2e/kg liveweight. The analysis is mainly based on the LCA method while Environmentally Extended Input-Output method is used as a supplementing method. The present study is carried out in a collaboration between SINTEF Ocean AS, Asplan Viak AS and RISE Research Institutes of Sweden.

PREPARED BY	**CHECKED BY**	**APPROVED BY**
Ulf Johansen	Eric Young	Mimmi Throne-Holst
Ulf Johansen Ulf Johansen (Dec 8, 2022 22:03 GMT+1)	Eric Young Eric Young (Dec 8, 2022 22:14 GMT+1)	Mimmi Throne-Holst Mimmi Throne-Holst (Dec 9, 2022 05:33 GMT+1)

Document History

VERSION	DATE	VERSION DESCRIPTION
1	2022-12-06	First version submitted to FHF

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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	Carbon dioxide equivalents
dLUC	Direct Land Use Change
eFCR	Economic Feed Conversion Ratio
EPS	Expandable Polystyrene
FAO	Food and Agriculture Organisation of the United Nations
FCR	Feed Conversion Ratio
FPC	Fish Protein Concentrate
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 tonne, 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
Tonne	Metric tonne, 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
MRIO	Multi-regional input-output
EEIO	Environmentally extended input-output

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Summary

Greenhouse gas emissions were quantified for eleven of the most important Norwegian salmon supply chains in terms of volume and value. Life Cycle Assessment methodology was used, complemented by Environmentally Extended Input-Output analysis for completeness. Products included were fresh and frozen whole salmon and salmon fillets shipped to markets in Europe, the US and Asia by truck, sea and air. Results show emissions between 4.8 and 28 kg CO2e per kg edible salmon in the market, a range that is reduced to 4.8-5.7 kg CO2e/kg edible salmon when airfreighted products are excluded. Results confirm previous findings in terms of important emission drivers. When airfreight is involved, it dominates emissions, irrespective of market, distance, product form and type of airfreight. After airfreight feed production is the main impact driver and up to the farmgate representing 75% of total farmgate emissions. Slaughtering and processing contribute to less than 2% of the total carbon footprint for all products, while packaging accounts for 1-5% of the carbon footprint. The sensitivity analysis showed that implementing the current "best practice" in terms of eFCR, energy source of feed barge, energy efficiency in juvenile production and by-product utilization reduced emissions at farmgate by 24%.

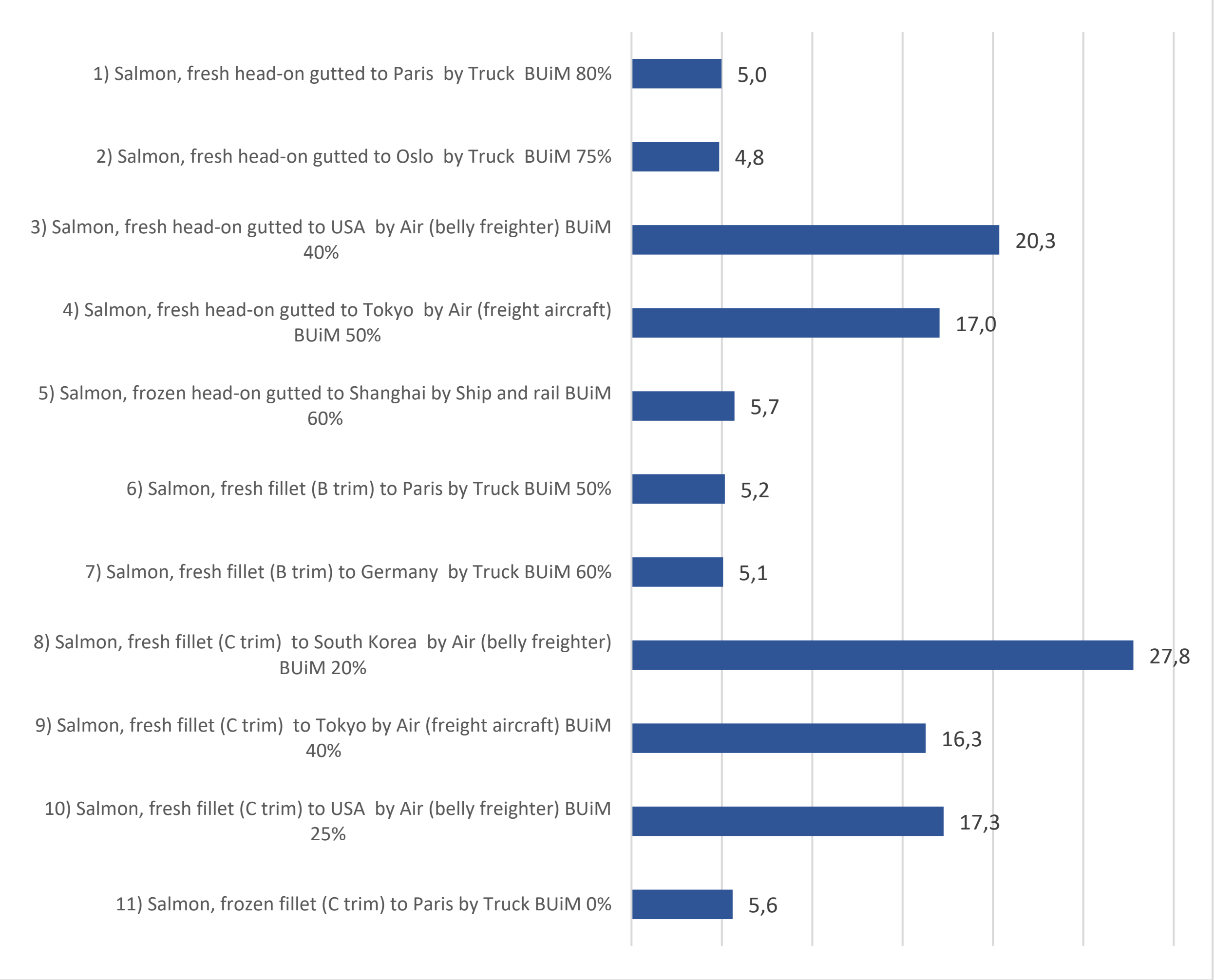


Figure S1: Total greenhouse gas emissions of all salmon products (kg CO_2e/kg edible product delivered to wholesaler) BUiM = By-product use in market.

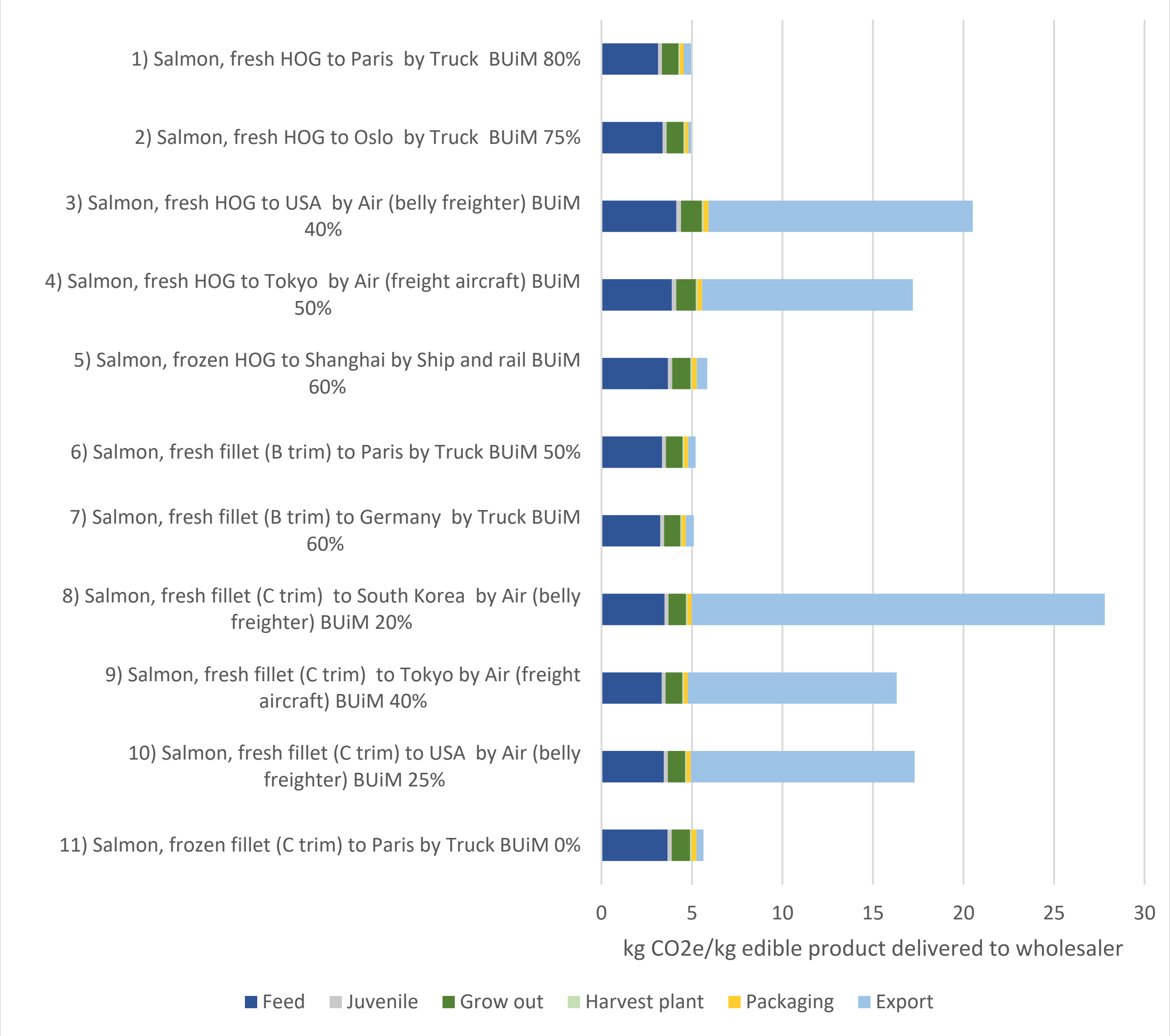


Figure S2: Greenhouse gas emissions per life cycle phase of all salmon products (kg CO_2e/kg edible product at wholesaler) BUiM = By-product use in market.

The emission reduction potential of five overall improvement areas (feed, loss, production system, distribution and energy source) with 19 specified measures across the different parts of the value chain have also been evaluated for emissions and more qualitatively for costs to identify the most cost-effective improvement measures. These are increased by-product utilization, better feed efficiency, on board processing and distribution by ship, farming in closed net pens and new energy carriers for vessels The emission reduction potential varied from 19% lower emission to 29% higher emissions than the base case farmgate salmon at 3.8 kg CO2e/kg liveweight.

Some of the high-cost measures that also result in increased emissions are larger smolt produced on land and exposed farming. The crude estimates used in the analysis highlight that this is mainly due to the increased energy demand on land for production of larger smolt and the high infrastructure requirement for exposed cages. Further investigation is suggested in order to be able to conclude whether these measures result in increased emissions compared to the base case.

The implementation of the reduction measures depend on many practical factors like technology readiness for onboard processing, availability and pricing of marine by-products and European soy, reconstruction of vessels to new energy carriers and consumer demand. It should be noted that the carbon footprint – and cost-assessment of the improvement measures is simplified and based on crude estimates for production parameters. Other environmental performance indicators than the greenhouse gas emissions need to be considered in future to compare the overall effects of the improvement measures.

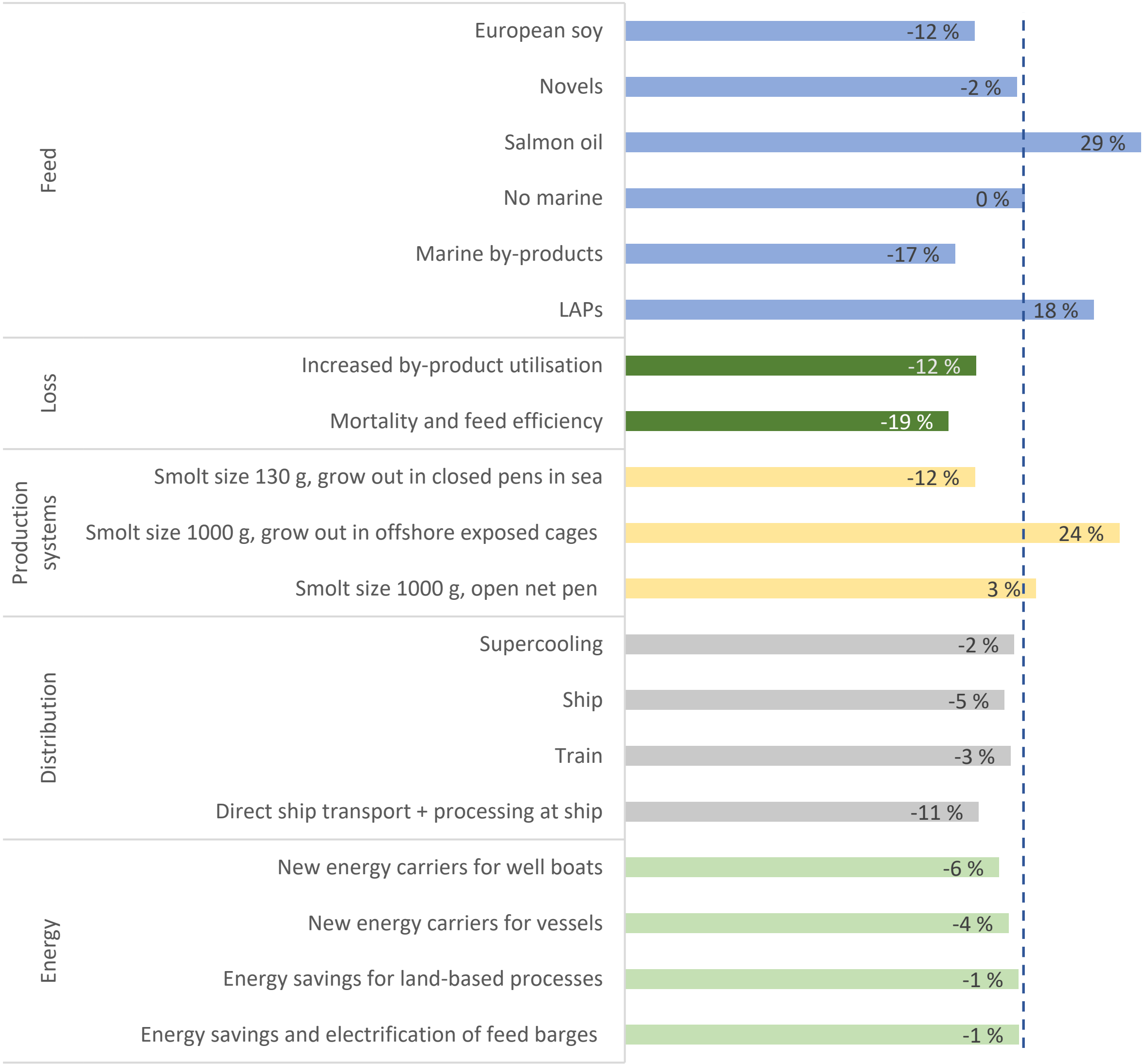


Figure S3: shows the measures evaluated and their effect on the carbon footprint per 1 kg edible fresh HOG in Paris.

Results from the EEIO shows that the 437 mill. NOK expenditures of services generated a total emission on 4.000 tonne CO_2e based on the accounting data from two large aquaculture producers in Norway. These two aquaculture producers used about 437 mill NOK on services whereas their total expenditures were about 6.5 billion. Then ~7 % of the average expenditures from aquaculture producers are related to service purchases. Emissions from services represents 0.03 tonne CO_2e for each tonne processed and represent less that ~1 % of the total carbon footprint of salmon at farmgate. This finding gives a good insight into the significance of services purchased by the aquaculture industry and its contribution to the total emissions. These numbers indicate that this effect is very limited.

The study covers the life cycle of the fish from growing and harvesting of feed ingredients to the point where the fish is delivered to a wholesaler in the market with a functional unit of one kg of edible seafood delivered to a wholesaler. The system boundaries are also extended to include investments and different services. Data has been collected from a variety of sources mainly from official Norwegian statistics and data from companies involved in the supply chains and ranges between 2018 to 2021, with a focus on data from 2021. This report is primarily targeted to increase knowledge in the seafood sector regarding the environmental performance of aquaculture products and to inspire improvement efforts. The goal of the study is to quantify the impacts of the average Norwegian farmed salmon supply chains based on the most representative data and does not represent one specific supply chain from one producer. Results are therefore more to be seen as a benchmark against which to evaluate own performance.

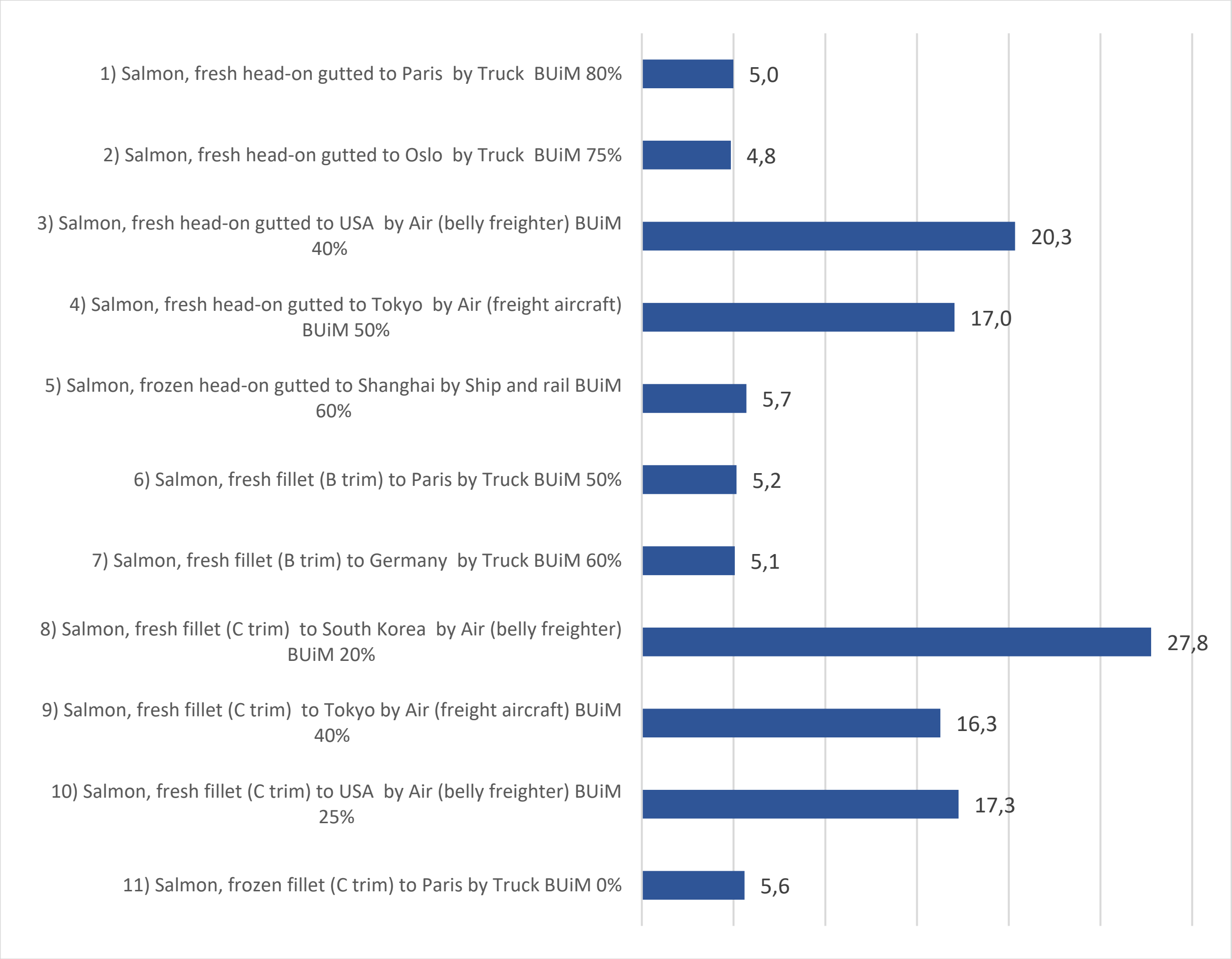
Differences in data and methods used leave results incomparable with those from previous assessments. To monitor performance over time, a comparison was done within this report using consistent methods which shows an emission reduction of around 10% since 2017, which is partly due to reduced inclusion of soy protein from countries with expanding land use. And inclusion of other crop-based protein with lower climate intensities.

All in all, it is shown that there are plenty of improvement opportunities in salmon supply chains that could reduce greenhouse gas emissions as well as production costs further.

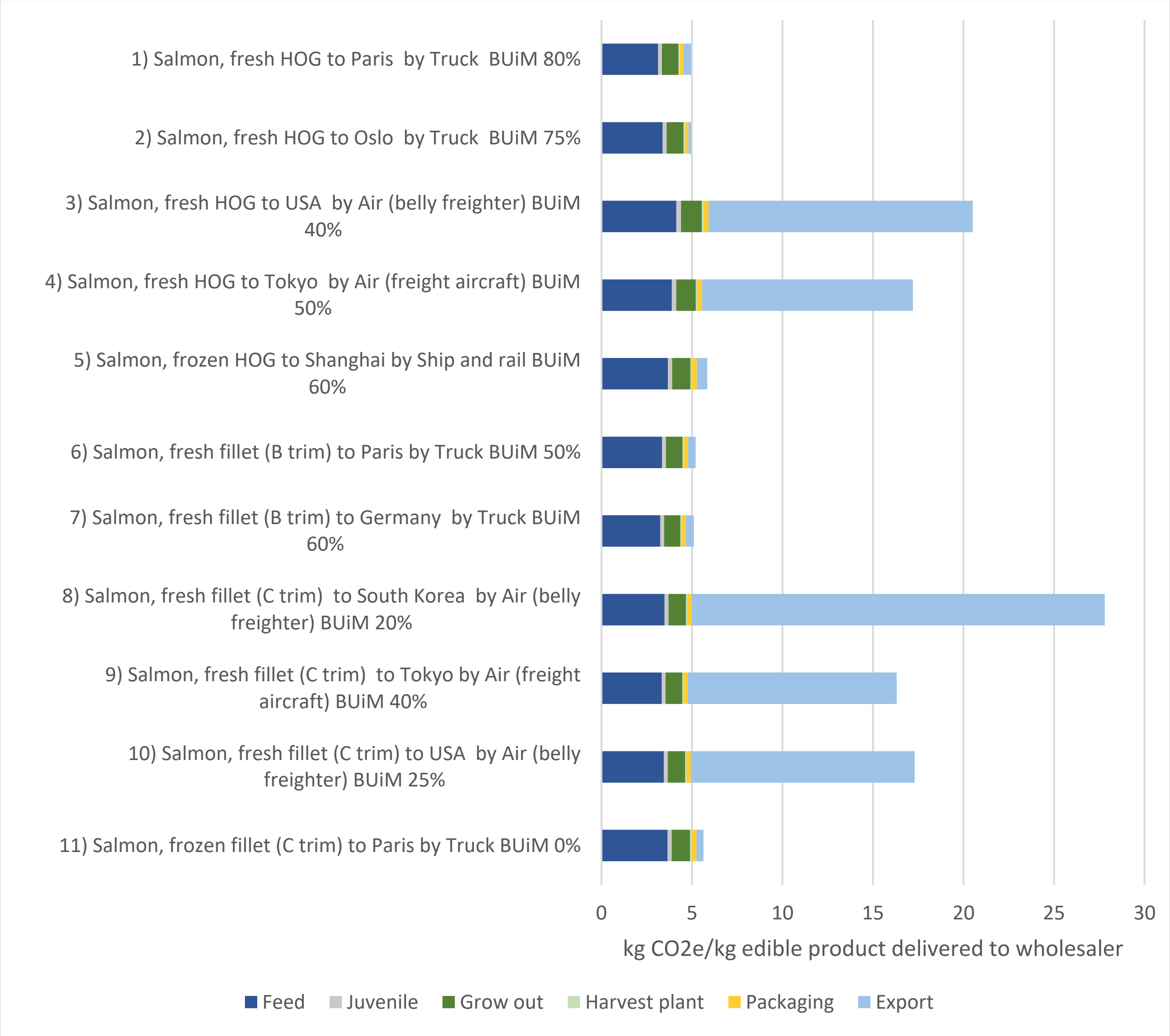
The work has been carried out by SINTEF Ocean AS, Asplan Viak AS and RISE Research Institutes of Sweden - during the period December 2021 to December 2022 and was funded by the Norwegian Seafood Research Fund (FHF). Representatives from Bellona, Cermaq, Grieg Seafood, Nova Sea, Sinkaberg-Hansen, Skretting and the Norwegian Seafood Council have served as the project reference group and contributed with data, industry and market insight as well as guidance in filling data gaps.

Sammendrag (norsk)

Klimagassutslipp ble kvantifisert for elleve av de viktigste norske lakseleverandørkjedene målt i volum og verdi. Livssyklusanalyse (LCA) og miljøutvidet kryssløpsmodellering (EE-MRIO) ble brukt som analysemetodene i studien. Produkter inkludert var fersk og frossen hel laks og laksefileter fraktet til markeder i Europa, USA og Asia med lastebil, sjø og fly. Resultatene viser et klimafotavtrykk mellom 4,8 og 28 kg av CO_2e/kg spisbart produkt hos forhandler. Produktene som ikke fraktes med fly hadde et klimafotavtrykk mellom 4.8-5.7 kg CO_2e/kg spisbart produkt. Resultatene presentert for norsk lakseoppdrett i 2021 bekrefter tidligere funn når det gjelder viktige bidragsytere. Der flyfrakt er involvert, dominerer det utslippene, uavhengig av marked, avstand, produktform og type flyfrakt (buk eller dedikert frakt). Etter flyfrakt er fôrproduksjon den viktigste bidragsyteren og ca. 75% av totale utslippet fram til slakting skyldes fôrproduksjon. Slakting og foredling bidrar til mindre enn 2 % av det totale klimafotavtrykket for alle produkter, mens emballasje står for 1-5 % av klimafotavtrykket. Sensivitetsanalysen viser at ved å iverksette tiltak som dagens "beste praksis" som for eks. eFCR, energikilde for fôrflåte, energieffektivitet i settefiskproduksjon og biproduktutnyttelse, er det et potensial på 24 % reduksjon av utslipp ved farmgate.



Figur S1: Total klimafotavtrykk fra alle lakseprodukter (kg CO_2e/kg spisbart produkt hos forhandler) BUiM = Biprodukt utnyttelse i markedet.

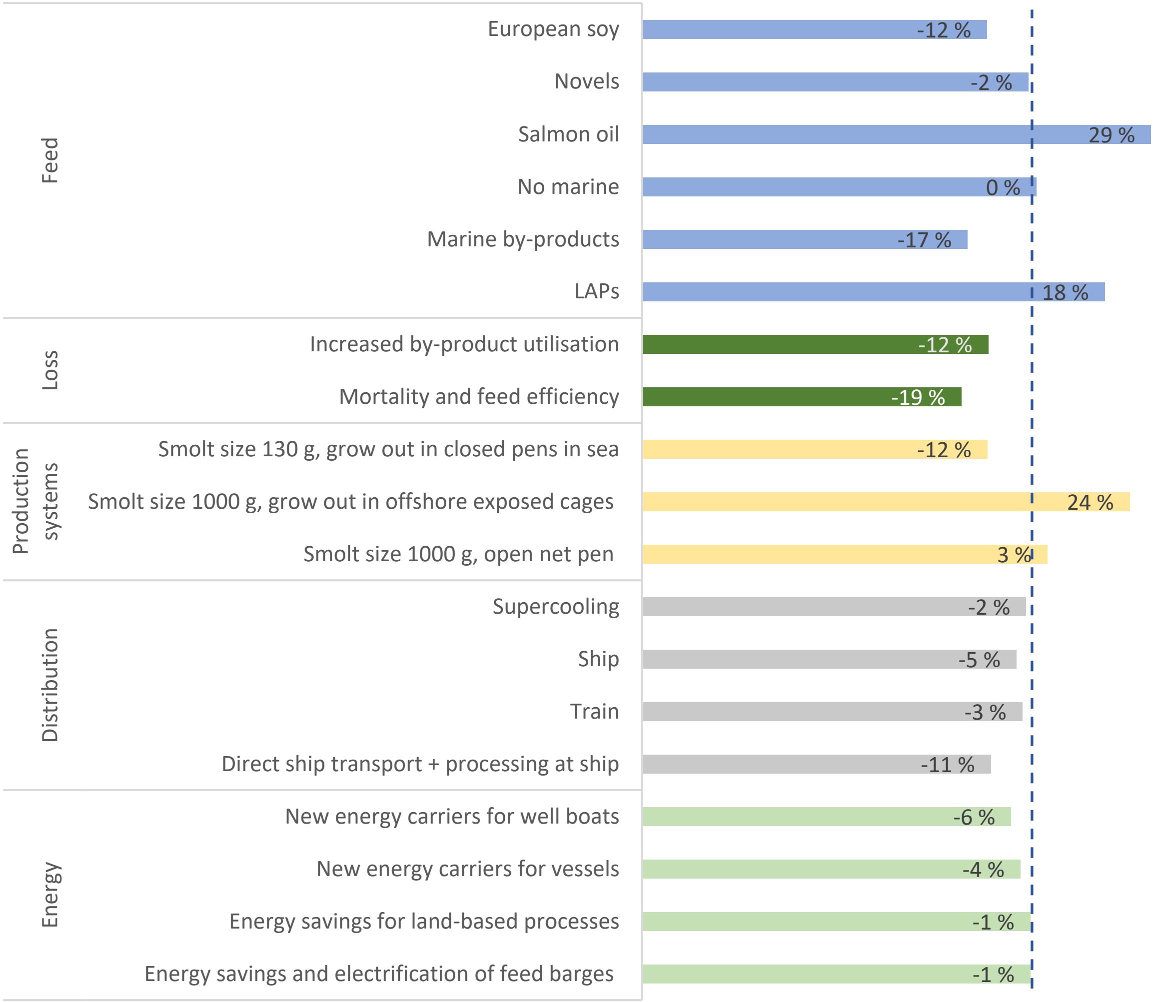


Figur S2: Klimafotavtrykk per livssyklusfase for alle lakseprodukter (kg CO_2e/kg spisbart produkt til forhandler) BUiM = Biprodukt utnyttelse i markedet.

I denne studien er utslippsreduserende tiltak grupper på 5 hovedtiltak (fôr, tap, produksjonssystemer, distribusjon og energi) med 19 del-tiltak på tvers av de ulike delene av verdikjeden evaluert for å identifisere de mest effektive når det gjelder klimagassutslipp og kostnader. Disse er endringer i om bord prosessering og transport til markedet med skip, oppdrett i lukkede merd samt nye energibærere på båt. Potensialet for utslippsreduksjon varierte fra 19 % mindre utslipp til 29 % høyere utslipp enn standard laks ved 3,8 kg CO2e/kg levende vekt.
Noen av høykostnadstiltakene som ga økte utslipp er storsmolt produsert på land og eksponert anlegg. Grove estimater viser at dette er i hovedsak på grunn av økte energibehovet på land for produksjon av større smolt og det høye infrastrukturbehovet for eksponert anlegg. Det er behov for bedre datagrunnlaget for kunne konkludere om disse tiltakene har faktisk høyere utslipp enn base caset.

I praksis vil implementeringen av de reduksjonstiltakene være avhengige av mange faktorer som teknologiberedskap for ombord prosessering, tilgjengelighet av marine biprodukter og europeisk soya, omlegging av fartøyer til nye energibærere og forbrukernes etterspørsel. Det skal bemerkes at karbonavtrykket – og kostnadsvurderingen av utslippsreduserende tiltak er forenklet og basert på grove

estimater for produksjonsparametere. Andre måleindikatorer enn klimagassutslippet må vurderes i fremtiden for å sammenligne de samlede effektene av forbedringstiltakene.
Det kan konkluderes at det en rekke mulige tiltak som kan både redusere klimagassutslippene samt produksjonskostnadene.



Figur S3: viser effekten av de tiltakene på klimafotavtrykket per spiselig andelen av 1 kg fersk HOG i Paris.

Resultater fra kryssløpsmodellering viser at utgifter på 437 mill. NOK til innkjøp av tjenester ga et samlet utslipp på 4.000 tonn CO_2e. Disse er basert på regnskapstall fra to store oppdrettsselskap i Norge hvor deres totale innkjøp av varer og tjenester var på 6.5 milliard NOK. Utslipp fra tjenesteleveranser representerer 0.03 tonn CO_2e for hvert tonn produsert laks. Resultatene viser at selv om tjenester utgjør om lag 7 % av alle kjøp av oppdrettsselskaper, representerer de mindre enn ~1 % av det totale karbonfotavtrykket til laks ved farmgate. Dette funnet gir et godt innblikk i betydningen av tjenester kjøpt av havbruksnæringen og deres bidrag til de totale utslippene. Resultatene viser at de betyr lite for det totale klimafotavtrykket til laksen.

Denne analysen dekker livssyklusen til fisken fra dyrking og høsting av fôringredienser til det punktet hvor fisken leveres til en grossist i markedet med en funksjonell enhet på ett kg spisbar sjømat levert til en forhandler. Systemgrensene utvides også til å omfatte investeringer og ulike tjenester for EE-MRIO. Data er samlet inn fra en rekke kilder, hovedsakelig fra offisiell norsk statistikk og data fra selskaper i havbruksnæringen, og strekker seg mellom 2018 og 2021. Særlig er data fra 2021 er fokusert på.
I tillegg sammenlignes også klimagassutslippene fra norsk lakseoppdrett over tid.

Denne rapporten er hovedsakelig rettet mot å øke kunnskapen i havbruksnæringen om miljøprestasjonene til lakseproduktene og gi et grunnlag for å prioritere utslippsreduserende tiltak. Målet med studien er å kvantifisere klimapåvirkningene av verdikjeden til norsk oppdrettslaks basert på de mest representative data. Analysen representerer ikke en spesifikk verdikjede til én produsent og viser fram klimapåvirkningene til den gjennomsnittlig laks produsert i Norge. Det innebærer at resultatene kan brukes som en målestokk for å evaluere egen ytelse og verdiene kan ikke brukes som et klimafotavtrykk til et spesifikt kommersielt produkt.

Forskjeller i data og metoder som brukes gjør resultatene usammenlignbare med tidligere vurderinger. For å overvåke ytelsen over tid, ble det gjort en sammenligning i denne rapporten med konsistente metoder som viser en utslippsreduksjon på rundt 10 % siden 2017, noe som delvis skyldes redusert inkludering av soyaprotein fra land med økende arealbruk og inkludering av andre plantebaserte proteinkilder med lavere klimaintensitet.

Arbeidet er utført av SINTEF Ocean AS, Asplan Viak AS og RISE: Forskningsinstituttet i Sverige i perioden desember 2021 til desember 2022 og er finansiert av Fiskeri- og havbruksnæringens forskningsfinansiering (FHF). Representanter fra Bellona, Cermaq, Grieg Seafood, Nova Sea, Sinkaberg-Hansen, Skretting og Norges sjømatråd har deltatt i prosjektets referansegruppe og bidratt med data, industri- og markedsinnsikt samt diskusjon rundt forutsetningene som ligger bak analysen.

1 Introduction

1.1 Background

Every day the scientific evidence grows about the urgency in mitigating climate change. Food production system plays an important role in the decarbonization of our society. More than 30 % of the global carbon emissions are caused by the food production system (Crippa et al., 2021). Environmental assessment of food production system systems and related products is getting increased attention, this is also the case for seafood products. The number of aquaculture life cycle assessment (LCA) case studies performed increases rapidly (Bohnes et al., 2019). The focus of studies varies from identifying hotspots and improvement options, monitoring performance over time (Ziegler et al., 2021a), or using existing LCA studies to benchmark across different foods (Hilborn et al., 2018), or evaluate the sustainability of different diets (Tilman & Clark, 2014).

Previous studies indicate that most seafood products have comparatively low carbon intensities to other land-based animal-sourced food production. This was recently documented for Norwegian seafood products in work that the Norwegian Seafood Research Fund (FHF) has previously funded. Efforts to quantify greenhouse gas emissions of Norwegian seafood supply chains, which were undertaken by the same team and reported in Winther et al., (2020), Hognes et al., (2011), Winther et al., (2009), Ziegler et al., (2013) and Ziegler et al., (2021). In 2021, FHF initiated a new project to focus on farmed salmonids, to make sure that updated results are available for salmon, as changes take place fast in the sector.

Customers in the global markets for the aquaculture industry are increasingly demanding documentation of the environmental performance of their products. Also, companies themselves are setting emission reduction targets that need to be achieved through various reduction measures. Several companies have set concrete carbon emission goals for 2030 and 2050. Thus, to see the development in carbon emissions for the industry, this analysis is a sought-after reference point for them.

LCA addresses carbon emissions that occur in the whole value-chain. This method can highlight where in the value chain the largest emissions occur and identify measures to significantly reduce emissions. With emerging technologies and production systems in the aquaculture industry, it is important to evaluate both their environmental and economic performance to avoid burden shifting within the supply chain or suggesting solutions that are not viable. For example, newer technologies or equipment that require increased material and energy inputs need to be evaluated to determine their contribution to the total footprint of the product.

1.2 Scope and organization of the project

The present analysis was initiated and funded FHF and 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 2021 to December 2022. Representatives from Bellona, Cermaq, Grieg Seafood, Nova Sea, Sinkaberg-Hansen, Skretting and Norwegian Seafood Council have served as the project reference group. Many of the reference group participants contributed to the project with primary data from their companies. FHF has participated in the meetings with the reference group. Dr. Frans Silvenius, LUKE, Finland, has served as the external reviewer of the project.

1.3 Contributions from project partners

SINTEF Ocean was the administrative leader of the project and mainly responsible for collecting primary data from the industry, the I-O modelling and collecting information of the costs of measures and communication and dissemination of the project results. Asplan Viak was responsible for the LCA modelling, including the reduction measures and analysis over time, as well as leading workshop 1. RISE was responsible for the collection and synthesis of data for feed composition and, has had the role of internal quality assurance of method choices, LCA models built, result presentation and report. All partners contributed to writing the report.

2 Overview of methods

In this study, greenhouse gas emissions (GHGs) are estimated using Life Cycle Assessment (LCA) methodology as defined by the ISO 14 000 family of standards for environmental management. A top-down approach building on the use of statistics is combined with a bottom-up approach collecting data from individual companies involved in the salmon chain to obtain a footprint as complete as possible.

In addition, to explore the system boundaries of the LCA an environmental extended multi-regional input-output model (EE-MRIO) (Martinez et al., 2018; Peters et al., 2011; Wiedmann & Lenzen, 2018) is used. Data used in the EE-MRIO model is mainly extracted from the inter-country Input-Output (ICIO) data from the OECD (OECD, 2021). Two separate methods are available for assessing climate footprints of products, companies, or industries – the LCA method which is the main method used in this analysis and environmentally extended Input-Output (EEIO) method. With their strength and weaknesses these methods could either operate side-by-side or they could be integrated in a hybrid modelling approach. Previous climate footprint studies on Norwegian fish products have only used the LCA method for calculating the carbon footprint. In this analysis we explore how the EEIO method could complement results from LCA in a hybrid approach.

It is important to recognize 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 where they are explained (in the present report). This study is done with the goal of quantifying impacts of normal/common? Norwegian farmed salmon supply chains for the purpose of comparison which is different from modelling a specific supply chain from one producer. *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.* Hence, this study does not fulfil the requirements of ISO 14044 to make comparative assertions towards the consumer for specific products.

The quality od data used in the analysis is assessed based on the scoring from the PEF method, which include *excellent, very good, good, fair* and *poor* and is described in detail in section 6.6.

As the most recent methods were used, e.g. with regard to the IPCC impact indicators for greenhouse gases, results of previous reports (Winther et al. 2009, 2020), in which e.g. older versions cannot be directly compared with the ones presented here, and comparison over time can only be done within the report.

2.1 Goal and scope

The main goal of this work is to provide a robust estimate of GHG emissions of the most important Norwegian seafood export products from salmonid aquaculture, delivered to their typical markets (Table 2-1). Additional goals are to:

1) Identify the largest reduction opportunities and quantify these both in terms of emissions and economic implications
2) Compare GHG emissions of Norwegian salmon aquaculture over time

In Table 2-1 we show the Norwegian seafood products studied defined by: species, product form, transport mode and market. These are all central aspects in the assessment of greenhouse gas emissions of farmed seafood. Trout products (in italics) were first included but could not be separated from salmon and were hence excluded).

Table 2-1 Products studied in the report. Products 12-15 were later excluded due to lack of data

No.	Product	Market/Destination	Main mode of transport
1	Salmon, fresh head-on gutted	Paris	Truck
2	Salmon, fresh head-on gutted	Oslo	Truck
3	Salmon, fresh head-on gutted	New York	Air
4	Salmon, fresh head-on gutted	Tokyo	Air
5	Salmon, frozen head-on gutted	Shanghai	Rail/Ship
6	Salmon, fresh fillet (B trim)	Paris	Truck
7	Salmon, fresh fillet (B trim)	Germany	Truck
8	Salmon, fresh fillet (C trim)	South Korea	Air
9	Salmon, fresh fillet (C trim)	Tokyo	Air
10	Salmon, fresh fillet (C trim)	New York	Air
11	Salmon, frozen fillet (C trim)	Paris	Truck
12	*Trout, fresh head-on gutted*	*USA*	*Air*
13	*Trout, fresh head-on gutted*	*Thailand*	*Air*
14	*Trout, frozen fillet*	*USA*	*Ship*
15	*Trout, frozen fillet*	*Oceania*	*Ship*

The primary target group of this report is the seafood sector, where the increased knowledge is intended to inspire improvement efforts, which is the primary use of this work.

The 11 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.

2.2 Functional unit

The functional unit is *one kg of edible seafood delivered to a wholesaler*. Results are also presented per unit of live weight fish at farmgate. 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 parts that are not consumed (skin, bones etc). Results are consistently presented per kg edible product, using conversion factors for edible yield for each product.

The functional unit does not include a quality parameter, thus comparison must be done with an understanding of this and that different products can have different quality (e.g. shown in remaining shelf-life or differential supply chain product loss).

2.3 System boundaries

The assessment covers the life cycle of the fish from growing and harvesting of feed ingredients to the point where the fish is delivered to a wholesaler in the market. Figure 2-1 presents an illustration of this system and the most important stages and material and energy flows included in each stage.

System boundaries are also extended to achieve an assessment as complete as possible by combining LCA with results from an environmentally extended input-output model. This model will particularly be used to evaluate the contribution of new types of investments and different services, e.g financial services.

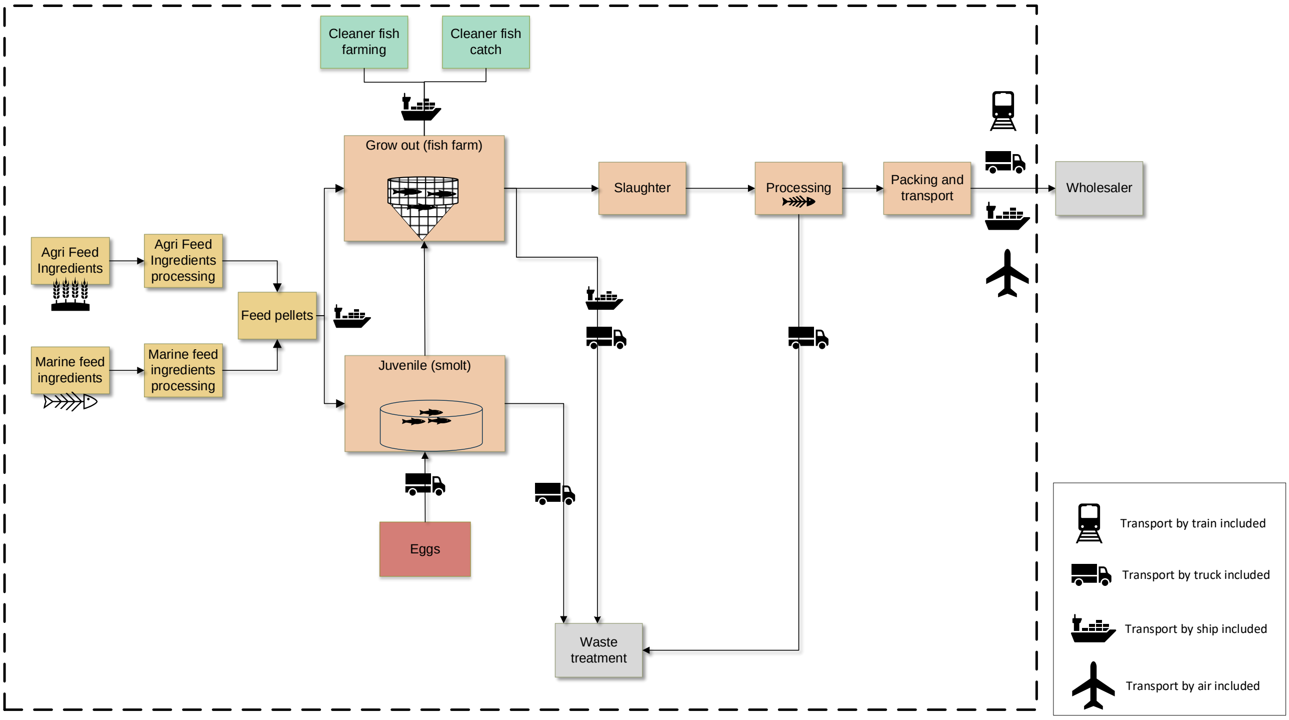


Figure 2-1 Illustration of the LCA system and the most important stages

2.4 Allocation

Allocation is a necessary methodological step in processes with multiple outputs where the process cannot be divided into sub-units and allocation avoided, which is the first option in the ISO hierarchy of allocation approaches. In this analysis allocation is especially important in the following stages:

- In the production of the feed raw materials where multiple products are produced from one crop or one fish (e.g. meal and oil).
- In the production of eggs, juveniles and grow out.
- In the processing of the fish where several co-products, e.g. guts, heads and fillets are produced.

Mass allocation is selected as the main approach, but results are also calculated using economic allocation in the sensitivity analysis. For the results presented with mass allocation the co-products (products that have an economic value for the producer and are further utilized in another supply chain) share the same footprint per unit of product. When economic allocation is used, the allocation takes into account that the economic value differs between the co-products. The data used for allocation is presented in section 4.2. When a co-product does not have an economic value, but is further utilized for example for energy recovery, the impacts from handling of the material and transportation up to the final treatment are included according to the ISO standard 22948:2020. Carbon footprint for seafood — Product category rules (CFP–PCR) for finfish since this is not specified in ISO 2006a,b). (ISO, 2022b, 2022a)

The rationale for choosing mass over economic value as the basis for allocation is that, despite lower economic value per tonne of biomass associated with some by-products, profit margins can be higher for the supply chain utilizing the by-products than of the main product, which makes it difficult to say which product is actually driving the production, a common motivation of economic 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 volatile economic values. Also, ISO recommend biophysical methods over economic allocation, which is according to them is the last option, while other standards recommend it (e.g. PEFCR and PAS 2050).

2.5 Data collection

Data has been collected from a variety of sources mainly from official Norwegian statistics and data from companies involved in the supply chains, including feed producers, farming companies, service providers and manufacturers of farming equipment. These data were complemented with data from LCA databases and in a few cases with literature data to build a model of current Norwegian salmon farming. In general, most of the data ranges between 2018 to 2021 but data from the production year 2021 was selected for the modelling whenever data was available for this year. In some cases, an average of the last few years or an average of data from different sources was used depending on the data availability and reliability. The data collected for each part of the supply chain is described in detail in section 3.

2.6 Impact assessment, modelling and background data

For impact assessment of GHG emissions, the 2021 version of the IPCC impact indicators was used. The model was built in the LCA software SimaPro Developer MultiUser version 9.3.0.3 using background data drawn from Agri-footprint v.6.0 (Blonk Sustainability, 2022) (mass and economic allocation) for feed input production and ecoinvent v 3.8 (Ecoinvent, 2021) (cut off by classification) for transports, energy production, fuels, materials, chemicals and infrastructure and from the database Network for Transport Measures (NTM) (NTM, 2022) for airfreight and ship 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 licensed to Asplan Viak AS. Land use change (LUC) is modelled as in Agri-footprint v 6.0.

2.7 Greenhouse gas emissions from Land Use Change

Several LCA and GHG standards, e.g. the EU's Product Environmental Footprint (PEF) method require the accounting of direct 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), that most of the big Norwegian seafood companies report to, also require that land use climate impact is included in scope 3 reporting.

In this work, dLUC is included for the cultivation of feed ingredients (for salmonid feeds) as calculated in the Direct Land Use Change Assessment Tool of Blonk Consultants. 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 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. 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" 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". The methods used by the Agri-footprint database seem to be fully in accordance with the rules of the Product Environmental Category Rules (PEFCR) for feed for food producing animals as this also requires the inclusion of carbon uptakes and emissions originating from carbon stock changes caused by land use change.

To illustrate the importance of assumptions around and modelling of land use change emissions, a linear reduction from assuming that all soy is from Brazil and modelled as in AgriFootprint to assuming all soy is sourced in Europe and connected to much lower land use change emissions was made in the sensitivity analysis.

2.8 Sensitivity analysis

As already mentioned, a sensitivity analysis was performed for a number of central data, assumptions and method choices. The selected aspects were:

- Variability in main parameters in production: eFCR, energy use at grow-out and juvenile production, by-product utilisation
- Allocation approach (using economic allocation instead of mass-based)
- Accounting method for Land Use Change emissions

2.9 Improvement measures

We have estimated the GHG reduction potential of 19 different measures (see Table 5-1) in different parts of the value-chain and, with help from the reference group, estimated costs and feasibility of each measure. The measures were selected by the project group together with the reference group. The purpose of the analysis of improvement measures is to provide identify the largest reduction opportunities and quantify these both in terms of emissions and economic implications. The GHG effects are calculated using the developed model for calculating the carbon footprint of today's industry, with extension to evaluate different production technologies and new feed ingredients. For evaluation of costs, we follow the framework suggested by Miljødirektoratet in their "Metodikk for tiltaksanalyser" from 2019 (Borge Håmsø et al., 2019). Three different cost parameters are considered:

1. *Investment and acquisition costs*
2. *Operating costs*
3. *Disadvantage costs*

Investment and acquisition costs – are costs for physical input factors that are necessary to initiate and implement a measure. One example could be investments in charging infrastructure for boats along the coastline, or cleaning technology for industrial companies. Often these costs occur only once in the initial phase of the measure.

Operating costs – are variable costs for operation and maintenance lasting throughout the lifetime of the measure. This could be costs related to energy use that is higher compared to a baseline, or higher costs for delivery/transport, more repairs than in a baseline and maintenance of equipment. Operating cost arising from more manual labour work is included here.

Disadvantage costs – can arise if a consumer is "forced" to buy or use a so-called imperfect substitute product. If the product does not have the same qualities for the consumer as the original product had, consumers will express that the shift has an inconvenience cost. As these costs are hard to measure quantitatively, valuation studies are the best method of collecting insight about these costs. One example in the salmon market could be that super chilled products differs from the quality of existing products.

It is beyond the scope on this analysis to give quantitative estimates of these three costs components for each measure. Instead, we indicate – a qualitative cost measure between -10 - + 10. The qualitative levels of costs are set by the project group together with the reference group.

2.10 Approach for analysis over time

In addition to providing an assessment as complete as possible of the greenhouse gas emissions of current Norwegian salmonid farming, one of the goals of this work was to analyze whether performance has improved over time. Methodological differences and data collection leaves the present results not directly comparable to previous efforts, as mentioned initially. To overcome this and to be able to compare between the assessment years and also monitor performance over time more generally, the simplified method for GHG assessment for seafood products (see Winther et al. 2020 and Ziegler et al., 2021) was refined, based on the complete results. The method is a 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 harvest. Feed composition and eFCR is used to estimate the temporal trend and the upscaling factor to translate feed use to farmgate GHGs. 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 aquaculture sector, which is the intention and can be followed up in coming years.

3 Data inventory and modelling methodology

3.1 Juvenile production

Production of juveniles includes eggs, feed, electricity and fuel, oxygen, chemicals, facility construction, waste and sludge handling. The production is assumed to take place in a recirculating aquaculture facility. The electricity consumption is on average 8.5 kWh/kg and fuel use (for back-up electricity supply) is 0.01 kg/gross production based on data collected from industry and Nistad et al.(2021) Based on industry information, oxygen consumption in a RAS facility is typically 0.5-1 kg per kg salmon produced, and 1 kg oxygen per kg production is assumed as a conservative estimate.

The use of acids and sodium hydroxide is 1.4 g and 0.2 kg per kg gross production respectively.

The eFCR for juvenile production is not included in statistics from Fiskeridirektoratet. Data from Brown et al. (2022) indicates that eFCR is in the same range as the eFCR in the grow-out phase, 1.3. Based on industry information, the eFCR in juvenile production is on average 1. Mortality is calculated based on the number of reported dead smolt and average weight in (Gåsnes et al., 2021). Based on the number of smolt sold to grow-out, the lost biomass from juvenile production represents approximately 3% of gross production (smolt sold and biomass waste from juvenile production). It is decided that the juvenile eFCR is set to 1, as the mortality is substantially lower than in the grow-out phase.

The average weight of smolt released to sea in 2019 was 130 gram (Iversen & Hermansen, 2019) The table below shows the number of smolt sold and salmon production in 2018-2020. Based on this, the input of smolt is 34g/kg salmon produced.

Table 3-1 Production of smolt and salmon in Norway 2018-2020. Data from the Norwegian directorate of fisheries.

	2018	2019	2020	Total
Smolt (1000 p)	341 524	351 720	365 950	1 059 194
Production salmon (tonne)	1 282 003	1 364 042	1 388 434	4 034 479

Materials for fish tanks, water treatment systems, piping and buildings on-land, as well as the associated production capacity, are based on industry data from established RAS facilities. It is assumed that the facilities have a lifetime of 20 years and operate at “full” production capacity during these years.

Data on production of salmon eggs is based on an LCA carried out on behalf of AquaGen AS, a major producer of salmon eggs in Norway.

Biomass waste from juvenile production is assumed to have no commercial value for the smolt producer. Hence, it is treated as a waste stream and is assumed incinerated or as a substrate for biogas production. 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 30 weight % is achieved. It is then assumed that sludge is treated at a biogas facility, located 500 km away.

3.2 Fish farm, service companies and well boats

On-farm energy use, i.e. energy use used to supply electricity for feeding, light and other activities at the feed barge was modeled based on industry data collected in the project mapping energy use in the aquaculture industry for Enova (Nistad et al., 2021). In the recent years a large share of the localities have connected to shore power. Based on data from 2019, 55% have shore power, 6% hybrid solutions with batteries and diesel generators (diesel use can be reduced by ca. 50%) and 39% diesel generators. Electricity demand was 0.09 kWh/kg lw produced. Converting this to diesel fuel required to operate diesel generators, this results in a fuel use of 0.3 kWh/kg lw produced or 0.03 litre fuel/kg lw produced. Using the distribution of farms with shore power, hybrid solutions and diesel generators this results in an average electricity use of 0.05 kWh/kg lw produced and 0.01 litre fuel/kg lw produced. Note that this is a weighted average of a farm supplied by shore power, hybrid solutions and diesel generators.

The industry uses several different vessels to transport fish and undertake maintenance and service operations. In the same study for Enova (Nistad et al., 2021) fuel use by different vessels used in the industry were mapped (Nistad et al., 2021). The number of data points for well boats were in that study limited, and fuel use data were regarded as uncertain. In this work, data from additional well boat companies were collected. We have collected fuel use from two of the largest well boat suppliers in Norway. Based on their fuel use in 2020 and their estimated market share, the numbers were scaled to estimate the total fuel use for well boats in Norway. Total fuel use for these two actors was 53 million litres. The market share for these companies was collected from a market analysis (Analyseselskapet Manolin, 2021). The fuel use of all well boats were estimated to 130 million liter of fuel in 2020.

Based on the production volume displayed in Table 3-1, this yields a fuel use for well boats of 0.09 L/kg lw production.

Table 3-2 Fuel use per production by vessel type. All data from Arntzen Nistad et al., (2021), except for data on well boats which was collected in this study.

Vessel type	Fuel use per gross production (L/kg lw production)
Well boats	0.09
Service vessels < 15m	0.02
Working vessels at fish farm	0.15
Service vessels > 15m	0.007
Smaller working vessels	0.14

3.3 Fish farm equipment

Equipment for fish farms was included using the same data as in Winther et al. (2020), as this still is found to be the most reliable, representative data available.

The values are based on data from a report that investigated waste handling of plastics and metals in the Norwegian salmon aquaculture industry (Hognes & Skaar, 2017). That report included an 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 3-3 Data for material use for fish farm equipment per unit production. Data from (Hognes & Skaar, 2017).

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

3.4 Salmon feed composition

3.4.1 Data collection

Feed composition and feed input source data was requested from the five largest feed companies in Norway, covering >99 % of the Norwegian market for salmon feed in 2021 based on volume. Data for all feed produced for Atlantic salmon and rainbow trout, during the years 2019-2021 was asked for. A data inventory form was circulated for this purpose, asking for data on species, volume and country of origin, or in the case of additives that did not originate in fisheries or agriculture, a specification of the product and producer, if possible. The form was followed up by individual meetings with each company for clarification of the data inventory (e.g. resolution of the data, production (fisheries or agriculture), species, country and region of origin, certification etc.). Feed ingredients were grouped into their main nutrient composition (i.e. crop based proteins, plant oils, marine protein sources, marine oils, carbohydrate sources and micro ingredients). The feed producers provided data at different resolution, in particular for some types of ingredients. For producers providing too crude data, data from the other feed companies was used to achieve the desired data resolution. The temporal coverage of data differed, and it was decided to use data only for 2021 as data was available for all producers for this year.

3.4.2 Data treatment

The feed composition data from the five companies was merged to represent ingredient sources in the average Norwegian salmon feed in the three years by modelling average mixes of the six feed input groups mentioned above. This was done by categorizing each feed input into one of the six groups and then simply creating a long spreadsheet of the volumes reported by each company, each year. Components grouped as micro ingredients (such as vitamins, minerals, amino acids, astaxanthin, and other feed additives) were classified and grouped according to product name and thereafter its function in the feed, and consequently matched with background data indicated in table 3-4. In Winther et al. (2020) a lower granularity on the data of the micro ingredient composition in general, and pigments in particular, where collected. Consequently, the inclusion of natural astaxanthin in Norwegian salmon feed in 2017 was overestimated, which has been corrected for in the present report. A small proportion of feed is reused, this amount was excluded as the inputs were already covered.

3.4.3 Feed composition

Overall, the average Norwegian salmon feed in 2021 was composed of 71% crop-based feed inputs (crop based proteins and oils, and carbohydrates/starch), 25% marine inputs, 3.6% microingredients and 0.5% ungrouped feed inputs which includes algae oil and insects (Table 3-4). Of the marine oils used, nearly 30% were produced from trimmings and 70% from targeted reduction fisheries around the globe (Table 3-5). In the data, marine oils are predominantly sourced from the Northeast Atlantic (38%), but also from the US (27%), and South American (13%) and African (0.7%) countries. The most important species used for oil are US Gulf menhaden and Atlantic herring and the most important species used as proteins are Atlantic herring, blue whiting and sandeel. A mix of whitefish trimmings has also become an important source of protein. Large posts appear as “unknown” due to one of the producers not disclosing information on species and origin of their salmon feed (pointing to the sustainability report which only presented species composition for all feed production, which includes feeds for many other species), which as mentioned led to the modelling of these inputs using data from other producers.

One third of fish meals in 2021 was produced from trimmings, two thirds from whole fish (Table 3-5). Fish meals were sourced in the Northeast Atlantic (48%) and in South American (3%) and African (0.6%) countries, again with a large balance being of unknown origin due to lack of data resolution from one producer.

Crop-based proteins are dominated by soy protein concentrate which is both of South American (81%), and European (19%, including Russia) origin. The second most important crop protein is wheat gluten. Less than 3% of crop-based protein originated in Russia (“less than” because some companies reported origin from Russia together with Croatia, Romania, Moldova and Serbia and these volumes were included). Crop-based oils are heavily dominated by rapeseed oil which is sourced in European countries (59%) or Russia/Belarus (25%) and the remaining 17% are of unknown origin (from the producer not disclosing origin). Microingredients are mainly composed by minerals and amino acids, but also vitamins and pigments.

Tabell 3-1 Composition of salmon feed per ingredient with source of LCA data used indicated (AFP= AgriFootprint v6. AB=Agribalyse v3. WFD= World Food Database. EI = Ecoinvent v.3.8) Country-specific versions of the processes were used (e.g. for sunflower protein) to represent flows when the country of origin was known and the more general process (market mix) stated below when the specific origin was not known.

Ingredient group	Ingredient	Volume (ton)	Proportion of feed (%)	Process and/or source for LCA data used (LCA database)
Crop based protein 36.9%	Corn gluten protein	3944	0.2%	Corn gluten meal (gluten 60). national average. animal feed. at plant/FR U (AB)
	Guar protein	120345	5.8%	Guar gum splits. at plant (WFLDB)/IN U (WFD)
	Pea protein concentrate	33304	1.6%	Pea protein-concentrate. at processing/DE (AFP)
	Soy protein poncentrate (SPC)	345814	16.7%	Soybean protein-concentrate. at processing/BR (Brazil. AFP) Modified dataset for Soybean protein-concentrate. at processing/[1]FR (AFP) is used to model soybean protein-concentrate production from soybean cultivation in Europe.
	Sunflower Protein	54440	2.6%	Sunflower seed meal (solvent). market mix. at regional storage/RER (AFP)
	Wheat Gluten	196902	9.5%	Wheat gluten meal. at processing/DE (AFP)
Microingredients 3.6%	Amino Acids	25797	1.2%	MetAMINO®. 99% DL-Methionine. at Evonik plant {BE} (AFP). ThreAMINO®. 98.5% L-Threonine. at Evonik plant {HU} (AFP). 50-50 split.
	Flavour	148	0.0%	Not included
	Guar gum	14	0.0%	Not included
	Inositol	2693	0.1%	Not included
	Microingredients. other	2857	0.1%	Not included
	Minerals	27941	1.4%	Total minerals. additives. vitamins. at plant {RER} (AFP)
	Pigment Astaxanthin	1062	0.1%	Winther et al. (2020)
	Vitamins	11996	0.6%	Total minerals. additives. vitamins. at plant {RER} (AFP)
	Yeast	1790	0.1%	Protein feed. 100% crude {GLO}| fodder yeast to generic market for protein feed (EI)
Crop based oil	Camelina Oil	4522	0.2 %	Included as linseed oil as proxy

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[1] Soybeans, dried, market mix, at regional storage {RER} is modified to only represent a mix of soybeans produced in the EU region by setting non-EU shares to 0. The rest of the value chain from soybean cultivation, soybean meal (solvent) to soybean protein concentrate is modelled as for Soybean protein-concentrate, at processing/NL.

20.9%	Lecithin	6062	0.3 %	Soybean lecithin (solvent). at processing {BR} (AFP)
	Linseed Oil	12622	0.6 %	Crude linseed oil (solvent). market mix. at regional storage/RER (AFP)
	Rapeseed Oil	398071	19.5 %	Crude rapeseed oil (solvent). market mix. at regional storage/RER (AFP)
	Soy Oil	5713	0.3 %	Crude soybean oil (solvent). market mix. at regional storage/RER (AFP)
Carbohydrates 12.8%	Peas	53074	2.6%	Pea starch-concentrate. at processing/NL (AFP)
	Tapioca	11	0.0%	Tapioca starch (with use of co-products). at processing/TH (AFP)
	Wheat	107707	5.7%	Wheat starch. at processing/DE (AFP)
	Fava beans	101415	5.0%	Broad bean meal. at processing/NL (AFP)
Other/ungrouped 0.5%	Algae oil	11082	0.6%	Industry data (confidential)
	Insect	122	0.01%	Average based on LCA-studies (Joensuu & Silvenius. 2017; Oonincx & de Boer. 2012; Smetana et al.. 2016. 2019; Thévenot et al.. 2018)
Marine oil - trimmings 2.3%	Blue Whiting	12	0.00 %	As in Winther et al. (2020). See Table 0-1 in Appendix for fuel use and yield data.
	Capelin	336	0.02 %	
	Cod	435	0.02 %	
	Herring	26275	1.28 %	
	Mackerel	6061	0.30 %	
	Menhaden (Atlantic)	769	0.04 %	
	Plaice	308	0.02 %	
	Saithe	261	0.01 %	
	Sprat	190	0.01 %	
	Unknown	8291	0.41 %	Modelled as the composition of known ingredients
	Whitefish mix	4747	0.23 %	As in Winther et al. (2020). See Table 0-1 in Appendix for fuel use and yield data.
Marine oil - Reduction fishery 8.1%	Anchoveta - Pasific	2021	0.10 %	
	Anchoveta - Peruvian	15968	0.78 %	
	Anchovy	11172	0.55 %	
	Blue Whiting	1528	0.07 %	
	Chilean jack mackerel	205	0.01 %	
	Herring	8408	0.41 %	
	Horse mackerel	180	0.01 %	
	Mackerel	258	0.01 %	
	Menhaden (Gulf menhaden)	47631	2.33 %	
	Mote	57	0.00 %	
	Norway pout	5239	0.26 %	
	Plaice	120	0.01 %	
	Sandeel	8271	0.40 %	
	Sardine (chile)	4386	0.21 %	
	Sardine (European pilchard)	2657	0.13 %	
	Silver smelt	54	0.00 %	
	Sprat	12869	0.63 %	
	Unknown	44542	2.18 %	Modelled as the composition of known ingredients
	Capelin	1019	0.05 %	

Marine protein - Trimmings 5.0%	Cod	1982	0.10 %	As in Winther et al. (2020). See Table 0-1 in Appendix for fuel use and yield data.
	Herring	34651	1.69 %	
	Mackerel	7911	0.39 %	
	Plaice	1109	0.05 %	
	Saithe	311	0.02 %	
	Sprat	147	0.01 %	
	Unknown	23947	1.17 %	Modelled as the composition of known ingredients
	Whitefish mix	30928	1.51 %	As in Winther et al. (2020). See Table 0-1 in Appendix for fuel use and yield data.
Marine protein - Reduction fishery 9.8%	Anchoveta - Peruvian	13870	0.68 %	
	Anchovy	4673	0.23 %	
	Blue Whiting	38559	1.88 %	
	Boarfish	17	0.00 %	
	Capelin	1245	0.06 %	
	Haddock	27	0.00 %	
	Herring	7949	0.39 %	
	Horse mackerel	255	0.01 %	
	Krill/Calanus protein	9456	0.46 %	
	Mackerel	849	0.04 %	
	Menhaden (Gulf menhaden)	6660	0.33 %	
	Norway pout	11197	0.55 %	
	Saithe	20	0.00 %	
	Sandeel	33052	1.62 %	
	Sardine (chile)	185	0.01 %	
	Sardine (European pilchard)	34	0.00 %	
	Shrimp protein	9	0.00 %	
	Silver smalt	32	0.00 %	
	Sprat	18740	0.92 %	
	Stripped weakfish	191	0.01 %	
	Unknown	54188	2.65 %	Modelled as the composition of known ingredients
	Whiting	41	0.00 %	As in Winther et al. (2020). See Table 0-1 in Appendix for fuel use and yield data.

3.4.4 Fisheries and Fish reduction data

The landings from fisheries that is used in the salmon feed was modelled only in terms of fuel use. The fuel use per fish species and the meal and oil yields are shown in Table 9.1 The reduction process of fish silage to fish meal and oil require the following inputs per kg of fish meal or oil as listed in Table 3-4. In addition to the inputs, the fish meal plant infrastructure is also included.

Table 3-4 Resource use for fish oil and meal production from reduction fisheries per tonne of fish meal or oil

Input/activity	Data
Electricity	25 kWh
Light fuel oil	0.01 lit
Fresh water	0.3 m3
Nitric acid	1.5 kg
Sodium hydroxide	0.2 kg
Waste handling (organic waste)	5 kg

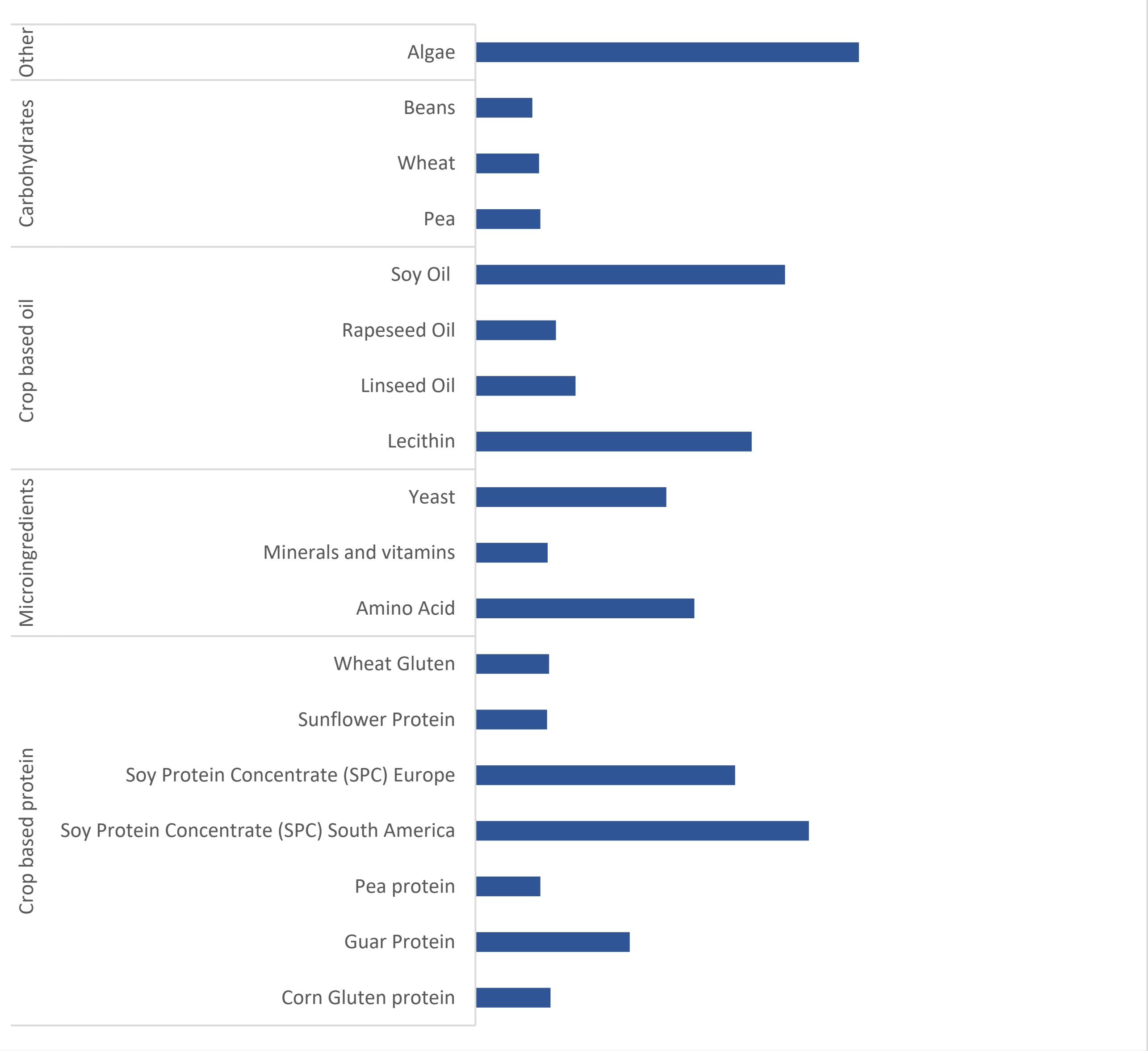

Figure 3-1 Relative greenhouse gas emissions per tonne non-marine feed ingredient (tonnes CO_2e/tonne feed ingredient at feed mill entry) presented relative to each other. Astaxanthin is not shown in the graph but is modelled with a carbon footprint 15 times higher than SPC and algae oil.

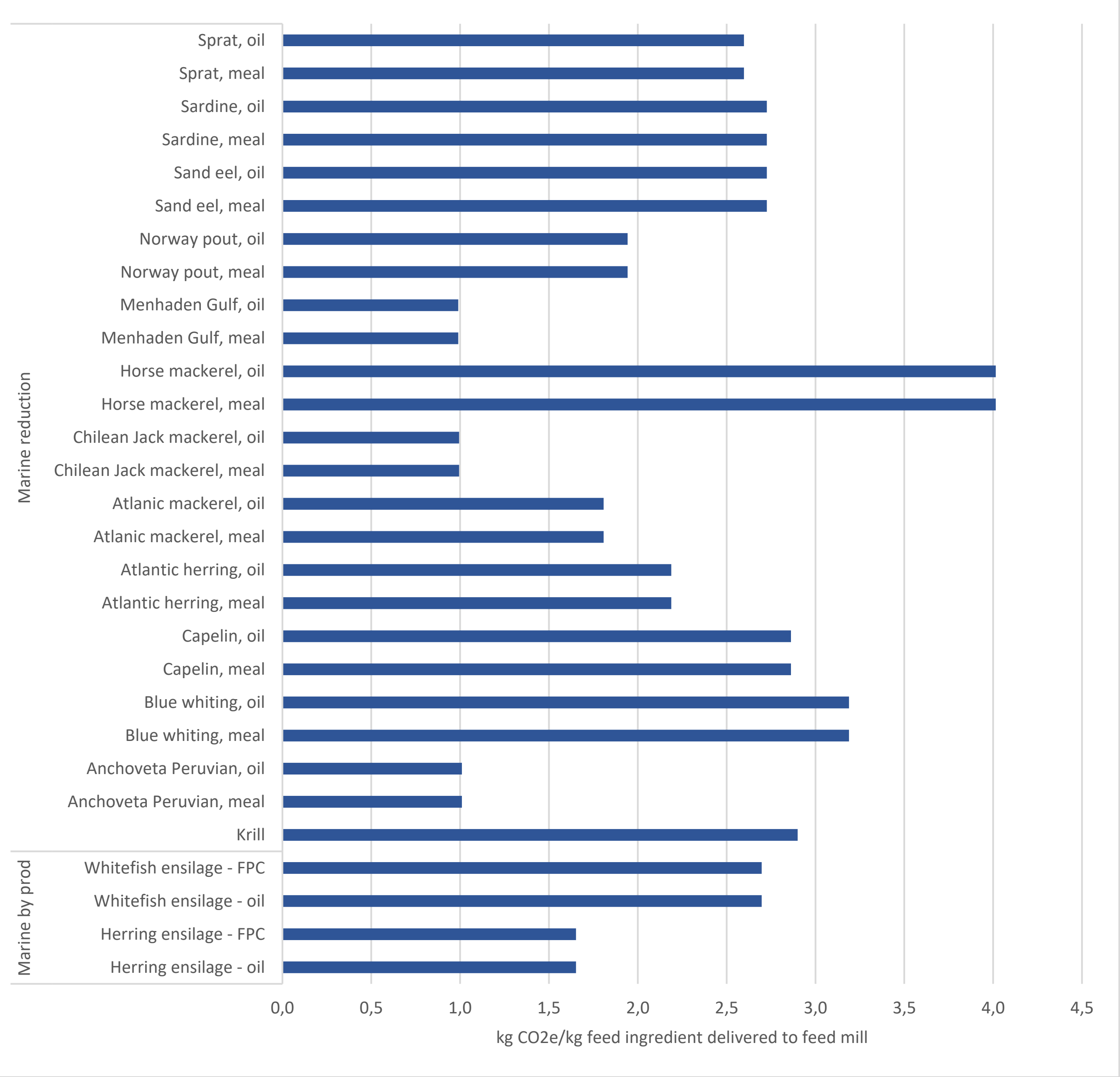

Figure 3-2 Greenhouse gas emissions per tonne marine feed ingredient (kg CO_2e/kg feed ingredient at feed mill entry).

3.4.5 Transportation of feed ingredients, feed milling and transportation of feed to fish farmer

Transport of feed ingredients from production to Norway is included for all ingredients. The transport from production location to the market is included in the Agrifootprint datasets. The transport distance is based on crude assumptions as in (Winther et al., 2020).

Table 3-5 Transport of feed ingredients, mode, distance and GHG emissions of transport per tonne ingredient.

Transport	Distances	GHGs (kg CO_2/tonne ingredient at feed mill entry)
Crop/Plant ingredients from Europe	1440 km road and 135 km sea (ferry)	252
Marine ingredients from Europe	500 km road and 1 617 km by sea	93
Crop/Plant/Marine ingredients from South America	500 km by road and 13 425 km by sea	170
Marine ingredients from North America	500 km road and 8 906 km sea	140
Marine ingredients within Norway	500 km road	82

Data used for feed milling is based on data from five plants reported to the Norwegian Environmental Agency (Miljødirektoratet, 2022). Table 3-6 presents the energy use of the feed mills. Construction of the plant or the equipment is not included. It is assumed that no loss of feed resources occurs at the feed mill.

Table 3-6 Energy use and waste at feed mill.

Input/activity	Unit	Value
Electricity	kWh/tonne	117
LNG	kg/tonne	6.33
LPG	kg/ tonne	4.36
Light fuel oil	kg/ tonne	0.045
Diesel	kg/ tonne	0.032
Mixed waste (plastic, cardboard, metals etc.)	kg/ tonne output	8

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

3.4.6 Feed efficiency

The feed efficiency was modelled using data from the Norwegian Directorate of Fisheries and their annual survey on the profitability of the Norwegian salmon and rainbow trout aquaculture industry. Figure 3-3 presents the eFCR for the Norwegian aquaculture industry for the period 2008-2020. The green dotted line presents a linear regression over that period, indicating that the eFCR has increased and varies slightly between years. The profitability survey for 2021 was not released at the time this analysis was carried out, and eFCR for 2021 was thereby not available.

The survey from which these data originate, covers all companies with a license to produce salmon or rainbow trout. For companies that also engage in other activities, their data is included if other activities represent less than 10% of the income. In 2020, the survey covered 1051 out of a total of 1159 operating licenses, around 90%.

There is a considerable variation in the eFCR. Figure 3-3 presents the eFCR for different company sizes, measured as number of operating licenses. The minimum and maximum eFCR observed are also indicated[2]. Knowing that eFCR is a key factor for the footprint of the salmon products, it is important to underline that the results presented are an average of an industry represented by large variation, which appears to be larger within each company size segment than across.

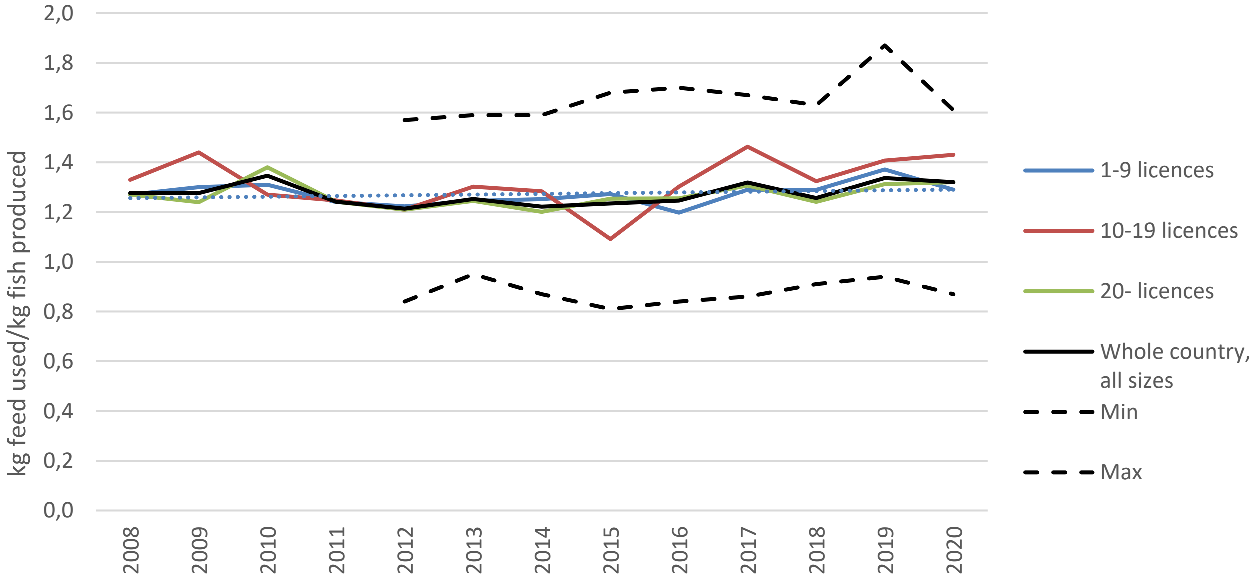

Figure 3-3 eFCR for different sizes (number of licences) for the period 2008-2020. Data from the annual survey on the profitability of the Norwegian salmon and rainbow trout aquaculture industry (Table C.5.2)

The following formula presents how the Norwegian Directorate of Fisheries define the eFCR. Note how standing/live biomass is translated into round fish equivalents (or roundweight), i.e. the weight after starving and bleeding, which is 6.7% lower than liveweight.

$$eFCR = \frac{feed\ in\ storage\ Jan\ 1 + feed\ bought - feed\ storage\ Dec\ 31}{Sold + stored\ (frozen)\ Dec\ 31 + \frac{live\ fish\ Dec\ 31 - input\ juveniles - live\ fish\ Jan\ 1}{1{,}067}}$$

In the LCA model, feed intensity is represented as feed per gross production in live-weight. Gross production includes output of fish sold and fish not sold. The conversion from eFCR to feed use per gross production is calculated as:

$$feed\ intensity\ \left(\frac{kg\ feed}{kg\ gross\ production}\right) = \frac{eFCR}{1{,}067} * (1 - mortality)$$

eFCR is divided by 1,067 to arrive at eFCR per kg output in live-weight instead of kg output in round-weight which is used by Fiskeridirektoratet. The factor (1-mortality) indicates live-weight biomass output per gross production.

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[2] .

3.5 Loss in grow-out

The assessment separates between fish sent to harvest plant and fish lost. Lost is defined as the share of the gross biomass production that does not enter the harvest plant. This ratio is set based on data on losses in the Norwegian salmon and trout industry. The main source for these numbers is data collected by Norwegian Directorate of Fisheries and the Norwegian Food Safety Authority according to the §44 of the Norwegian Aquaculture Operations Regulation. These data are mainly focused on the numbers of fish lost, thus assumptions are used to estimate how much of the gross biomass production that is lost.

Barentswatch (2021) presents sustainability data from the Norwegian salmon aquaculture industry. They write “In recent years, 15-20 % of the number of salmon and trout in sea farming have been lost. In terms of weight, this corresponds to 6-9%”. Based on these numbers, a 9% loss of gross biomass production is included.

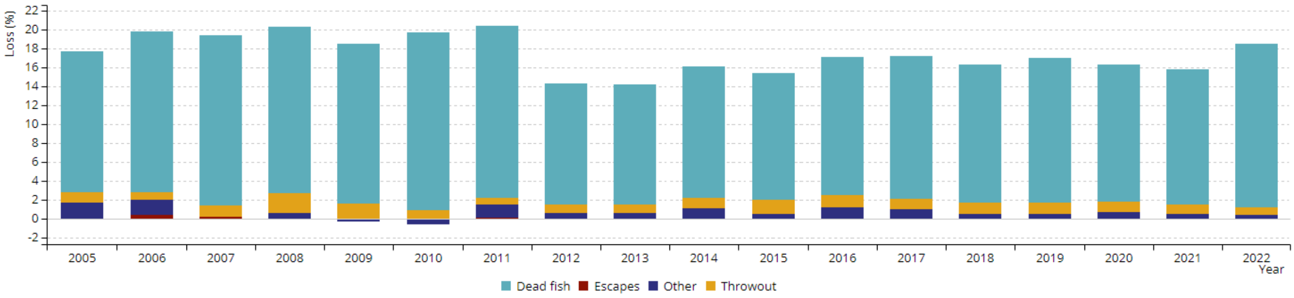

Figure 3-4 Mortality in production by cause. Data from Barentswatch (2021)

3.6 Treatment of sea lice

The energy that is used for lice treatment is already included in the total energy use of the fish farm service vessels and well boats (chapter 3.2). The fuel use for lice treatment could not be separated from fuel use for transport of smolt and harvest-sized salmon for the industry as an average. 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.

The average input of H_20_2 in 2019-2021 was 4556 tonnes. Divided by the production volume in the same period, this corresponds to 3.25 grams of H2O2per kg lw production. The average input of cleaner fish was 52 601 000 in the same period, and 95-99% of these were farmed. Farming in a closed land-based system is modelled based on data in (Philis et al., 2021), as well as a 500 km truck transport.

3.7 Processing

Processing refers to the transformation (e.g. filleting, freezing) of fish to seafood products. Several processing steps are performed, the first step being slaughtering. Products delivered from slaughter plants are mainly head-on and head-off gutted salmon, as well as minor quantities of fresh and frozen fillets. The share of fillet is typically 0-15% of the total production.

Data was collected from 13 salmon slaughter plants. Data on energy, water, chemicals and waste describe the consumption for all processes located at the facility in 2021. Data is given per tonne input into the slaughter plant. For energy use, which is the main factor contributing to the carbon footprint of processing, this will be a sufficient approximation, as energy use for filleting is a minor share of the total energy use at the facility (Nordtvedt, n.d.). For frozen fillets, energy use for freezing is included in addition to the inputs described in Table 3-7 (see section 3.9).

The table below shows the average energy, water and chemicals use. Building infrastructure is modelled using the same data as in Winther et al. (2020).

Table 3-7 Resource use of salmon slaughter plants (per input of 1 tonne of starved and bled salmon). Data on input of soap, detergent and building hall from (Winther et al., 2020)

Input/activity	Value
Electricity use	140 kWh
Freshwater consumption	3300 liter
Seawater consumption	4500 liter
Soap	0.3 kg
Detergent	0.3 kg
Building hall	0.0056 m2

For material use and waste (except biomass), the reported waste streams were used and matched with an equivalent input of the different materials.

Table 3-8 Material flows and waste of salmon slaughter plants (per tonne of starved and bled salmon to slaughter)

Materials	Kg/tonne salmon to slaughter
Plastics	0.1
Paper	0.09
Wood	0.14
Municipal waste	1.02
Metals	0.15

Chilled storing is included in the electricity consumption of the facility. Ammonia and CO_2 are commonly used as refrigerants at slaughtering facilities. As ammonia is a natural cooling medium and CO_2 has a low GWP, leakage of refrigerants from the slaughtering facility is excluded.

3.8 By-product utilization

98% of the by-products from salmon slaughter and processing in Norway is utilized,
based on a recent report analysing raw material flows used in the Norwegian seafood sector (Myhre et al., 2021)

3.9 Freezing of fish

Since a very minor share of the fillets are frozen, the overall energy use at the slaughtering facility can be assumed not to include energy use for freezing. Hence, this is added in addition to the energy use and other inputs described in section 3.7

Estimates for energy use for freezing is included based on expert judgements for energy systems for salmon processing facilities (Nordtvedt, n.d.). In a tunnel freezer, which is often used in the industry, the electricity use is 200 kWh/tonne product.

3.10 Transport to market

Products are distributed to the different markets by road transport, airfreight, sea freight and train.
One specific scenario is modeled per product. The routes and assumptions are displayed in Table 0-2.

A summary of emission factors for transport modes is given in Table 3-9 (data sources and assumptions are presented in the sections below). All transport modes except airfreight require refrigeration during transport. For shipping and rail freight, this is included based on ecoinvent data. For road transport, refrigeration during transport was not directly available in ecoinvent. The emission factors include refrigeration.

Table 3-9 Emission factors for transport to market. Refrigeration is included.

Transport	CF (kg CO_2e/t*km)
Road transport of fish	0.101
Road transport of other in- and outputs. See chapter 3.2.1	+63% compared to road transport of fish
Ferry (roll on roll off ferry). See chapter 3.5.4.	0.06
Sea transport Norway to Europe (feeder ship)	0.042
Sea transport Europe to Asia (large containership)	0.017
Sea transport Europe to USA (small containership)	0.034
Air transport, range dependent of type of flight, distance and load utilization, see chapter 3.5.3	0.57-1.34
Rail electric	-41% compared to road transport of fish
Rail diesel	-41% compared to road transport of fish

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 27 pallets weighing 25 kg. This results in 1.33 kg load/kg product for fresh fish and 1.13 kg load/kg product for frozen fish.

3.10.1 Road transport

Road transport is required at multiple stages in the value chain. For all inputs- and outputs except transport to market the ecoinvent dataset “Transport, freight, lorry 16-32 metric tonne, euro5 {RER}| market for transport, freight, lorry 16-32 metric tonne, EURO5 | Cut-off, U” is used.

For transport to market road transport is modeled using the dataset for a larger truck “Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric tonne, EURO5 | Cut-off, U”.

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 manufacturers of this kind of equipment (Thermo King) and literature, similar to Winther et al., (2020). A summary of the assumptions is included in Table 3-10. Details are available in Winther et al., (2020).

3-10 Data for refrigeration in road transport.

Parameter	Data
Type of refrigerant used	R452A. A mix of 30% R123yf, 11% R32 and 59% R125A (weight %). GWP of ~2000 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	200 days
Refrigeration system fuel use	2.5 liter/hour (Otten et al., 2015)
Carbon footprint (incl. production of refrigerant, emission and fuel use)	0.01 kg CO_2e/kg*day

The contribution of the refrigerant system to emissions per product transported is depending on the transport time. Number of days are calculated assuming an average speed of 50 km per hour (including obligatory stops etc.).

3.10.2 Airfreight

Several products are air freighted to markets in Asia and USA. 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. NTM was used instead of ecoinvent since ecoinvent only includes datasets for cargo flights and does not provide datasets for combined passenger and cargo flights.

Moreover, NTM provides more transparent information regarding key parameters for airfreight such as cargo load factor and capacity and aircraft type. Cargo flights of ecoinvent and NTM were earlier, and it was concluded that results were relatively similar, so that mixing data from both databases would not have a major influence on results.

Hence, it can be assumed 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 use. Goods can be transported both on 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 (IATA, 2022).

One transport route was established per product. Many different routes are used, depending on capacity and availability, lately influenced by the covid-19 pandemic. Based on information from the Norwegian seafood council and industry representatives it is common for products to USA to be transported by truck to London and thereafter airfreighted by passenger aircrafts to USA (some on cargo flights). For products to Asia direct cargo flights are used if available capacity, but a stopover in Doha/Istanbul/Seoul is common. From Doha/Istanbul/Seoul the flights can be continued by both passenger and cargo flights. Based on this information routes in Table 3-11 are established as representative cases.

Fuel use and tank-to-wheel emissions were extracted from the NTM database. Emissions for production of fuel (well-to-tank emissions) were modeled based on the ecoinvent dataset “Kerosene {Europe without Switzerland}| market for | Cut-off, U”.

Table 3-11 Data for air transport to market retrieved from NTM database. Distances are calculated from NTM.

Aircraft type	Route	Distance [km]	Cargo load factor [%]	Load capacity [kg]	Fuel use	Tank-to-wheel (TTW) Kg CO_2e
Belly freighter – cargo, range-based averages	London-NY	5716	65	20000	2093	6651
Freight aircraft, range-based averages	Oslo-Istanbul-Tokyo	11686	65	103873	2063	6558
Freight aircraft, range-based averages	Oslo-Istanbul-Seoul	10687	65	103873	1897	6028
Belly freighter – cargo, range-based averages	Oslo-Istanbul-Seoul	10687	65	20000	3924	12469
Freight aircraft, range-based averages	Oslo-Istanbul-Bangkok	10194	65	103873	1815	5767

3.10.3 Sea freight

Based on information from industry experts on logistics, three main size classes of ships are used. For products transported to Shanghai a feeder ship (100-200 TEU) is used for transport from harvest plant to the EU port, while a larger container ship (6000 – 16 000 TEU) are used for transport from EU port to Shanghai.

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).

All transport by sea was modeled using NTM data. Emission factors and data used are shown inTable 3-12.

Table 3-12 Data for transport to market by ship.

Type of ship	Ship size from NTM	Load factor (weight)	CF Kg CO_2e/tkm
Feeder ship	Container ship, inland waterways. 2000 DWT	70%	0.0417
Small container ship	Container ship, coastal. 5000 DWT.	70%	0.0342
Large container ship	Container ship, large ocean. 160 000 DWT	70%	0.0173
Ferry (truck on ferry)	Ro-Ro, regional ferry. 10 000 DWT	70%	0.060

Operation and emissions were modelled based on the ecoinvent dataset "Operation, reefer, cooling {GLO}| market for | Cut-off, U" and an assumed speed of 14 knots for all ship (which is similar to what is included in ecoinvent datasets)

3.10.4 Railfreight

Railfreight was modelled using the datasets "Transport, freight train {Europe without Switzerland}| electricity | Cut-off, U" and "Transport, freight train {Europe without Switzerland}| diesel | Cut-off, U" from ecoinvent. Based on ecoinvent, in Europe 40% of freight by rail is done by diesel trains and 60% by electric trains.

Operation and emissions were modelled based on the ecoinvent dataset "Operation, reefer, cooling {GLO}| market for | Cut-off, U. As for the ecoinvent datasets for train with reefer, 1.04 kg*day of operation of reefer is required per tonne*km.

3.11 Yield data

Data on edible yield is used for the conversion to the functional unit which is 1 kg edible seafood. The factors for yield are equivalent to Winther et al., (2020), and are based on the official conversion factors published by the Directorate of Fisheries (Fiskeridirektoratet, 2018), industry data and interviews with experts.

Table 3-13 Data on edible yield.

Product conversion	Yield
Whole fish to head on gutted	0.833
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
B-trim to edible	0.761
C-trim to edible	0.806
Head on gutted to edible	0.540
Whole fish to edible	0.833*0.54=0.45

3.12 Energy and Chemical inputs

Electricity used in the foreground system, or directly in the value chain of the seafood products, is modelled using the average European grid ("Electricity, medium voltage {Europe without Switzerland}| market group for | Cut-off" from ecoinvent). European electricity is used since use of electricity within Europe is linked physically, economically (e.g. through certificates of origin) and politically. Electricity grids in northern Europe are highly connected and the energy markets have a strong influence on each other, therefore it is considered more accurate to use the average European grid mix than one that reflects Norwegian energy production. 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 residual mix, which has a substantially higher carbon footprint.

Production and distribution of diesel fuel used by diesel aggregates, vessels and road transport is modelled using ecoinvent data "Diesel, low-sulfur {Europe without Switzerland}| market for | Cut-off,". The overall process of producing, distributing and combusting diesel results in a carbon footprint of 3.7 kg CO_2e/L. For conversion from liter to kg of diesel, a density of 0.84 kg/l is used.

At the feed mill, heat from natural gas, propane and LPG are also used in smaller amounts. These are modelled using ecoinvent market datasets for production of fuel and standard emission factors from the national emission inventories (Miljødirektoratet, 2022).

It is assumed that all oxygen is covered by purchased liquid oxygen. Oxygen is modelled using the ecoinvent dataset for European production “Oxygen, liquid {RER}| market for | Cut-off, U. Other chemicals are modelled by market datasets for European production from ecoinvent.

3.13 By-product utilization in market

The degree of by-product utilization after export has been used in the model to allocate the impacts to the by-products used in the market or to determine the amount of loss if by-products are treated as waste. The data on the degree of by-product utilization was obtained from Kontali Analyse AS. The percentages in Table 3-14 are estimated based on data collected by Kontali Analyse AS through desktop studies, interviews, consumer trends database by Norwegian Seafood Council, and trade statistics like EUMOFA. In addition, Kontali has collected supplementary information based on industry data collected in previous projects within these thematic areas: processing industry structures, value-chain analysis, market studies, and in-market product analysis.

Table 3-14 By-product utilization after export from Norway

	Product	Market	By-product utilization in % of non-edible part exported
1	Salmon, fresh head-on gutted	Paris	80%
2	Salmon, fresh head-on gutted	Oslo	75%
3	Salmon, fresh head-on gutted	New York	40%
4	Salmon, fresh head-on gutted	Tokyo	50%
5	Salmon, frozen head-on gutted	Shanghai	60%
6	Salmon, fresh fillet (B trim)	Paris	50%
7	Salmon, fresh fillet (B trim)	Germany	60%
8	Salmon, fresh fillet (C trim)	South Korea	20%
9	Salmon, fresh fillet (C trim)	Tokyo	40%
10	Salmon, fresh fillet (C trim)	New York	25%
11	Salmon, frozen fillet (C trim)	Paris	0%

3.14 Waste treatment

In this study waste treatment is included based on the “polluter pays” principle. This means that emissions related to waste treatment is allocated to the producer of the waste. A distinction is made between waste and by-products or co-products based on the definition given in ISO standards, see Chapter 2. Waste is output flows from the fish and fish products production system of no commercial value. If an output flow has a commercial value, it represents a by-product or a co-product and is not considered waste. In the cases where some waste flows are sent to recycling, for e.g. metal and plastic waste from aquaculture farms, the system is cut-off at the stage where the product becomes an input to the material recycling system. Similar principle is applied to the treatment of fish sludge and dead fish that is utilized as a substrate for biogas production. The emissions from handling and transport up to final treatment are included while emissions from final treatment i.e. biogas treatment are not included. This is because the biogas itself is a product with a market value and hence the fish sludge or dead fish is treated as a raw material for the production system for biogas. The aquaculture companies today pay a gate fee for delivering this material at the waste treatment facilities or pay for the service to collect the dead fish. However, products that are generated from mixed waste, such as energy and heat from municipal incineration, are not included in the system boundary and the upstream impacts are associated with the main product and heat from municipal incineration will be available without environmental burden.

Important waste flows in the foreground system and assumptions for waste treatment are:

Transport packaging: There are two types of transport packaging, EPS and cardboard boxes. 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, which implies that recycling is assumed.

Waste handling of dead fish (i.e. product losses): Modelled by ecoinvent data for municipal incineration of biowaste including transport to waste treatment facility.

Formic acid is used to treat co-products (biomass output) for ensilage. As this is regarded as a co-product instead of a waste flow the use of formic acid is attributed to the co-products and not the producer of the main product (salmon farmer). Formic acid has a fairly high carbon footprint per kg. If assuming 0.55 kg co-products per kg edible and 5% use of formic acid per kg biomass, the use of formic acid accounts for approximately 1% of the carbon footprint per kg edible product that are not air freighted.

Fish sludge: Treated at site up to a dry matter content of 30%, then transported (400 km) and delivered for biogas production.

4 Sensitivity analysis

4.1 Best / worst case

The variability in the Norwegian aquaculture industry is large, in terms of production as well as important parameters such as mortality and by-product utilization. A simple sensitivity analysis is performed to evaluate the effect of variability between different producers, as a best-worst case analysis. The parameters included, and their value, are shown in Table 4-1.

Allocation and dLUC emissions from soybean cultivation is handled separately.

Table 4-1 Overview of parameters for sensitivity analysis, best/worst case for *6) Salmon, fresh fillet (B trim) to Paris by Truck BUiM 50%.*

Parameter	Low GHG	Base case	High GHG
eFCR (grow-out)	0.91	1.30	1.70
Energy use at grow-out	Electricity by shore-supply Electricity: 0.09 kWh/kg lw produced Diesel: 0 litres/kg lw produced	Average; 60% electrified Electricity: 0.09 kWh/kg lw produced Diesel: 0.01 litres/kg lw produced	Diesel generator Electricity: 0 kWh/kg lw produced Diesel: 0.04 litres/kg lw produced
Juvenile energy use	5 kWh/kg lw produced	8.5 kWh/kg lw produced	13 kWh/kg lw produced
eFCR (juvenile)	0.91	1.00	1.30
By-product utilization at processing	90%	98%	60%
By-product utilization in market	100%	50%	0%

4.2 Economic allocation

As described in 2.4, mass allocation is chosen in this analysis, but as allocation is important for the results, economic allocation is included as a sensitivity. Allocation is required in the following steps in the value chain:

- In the production of the feed raw materials where multiple products are produced from one crop or one fish (e.g. meal and oil).
- In the production of salmon eggs, juveniles and grow out.
- In the processing of the fish where several co-products, e.g. guts, heads and fillets are produced.

In juvenile production and grow-out the output of biomass which is not utilized for production (human consumption) is an output without commercial value, which is regarded as a waste stream rather than a co-product. Hence, the choice of allocation method has no effect here.

The economic allocation factor, meaning how much of the environmental burden that is attributed to a product is expressed as (product A and product B):

$$A_a = \frac{M_a * V_a}{(M_a * V_a + M_b * V_b)}$$

Where V is the average economic value of product A and B over the study period, and M is the mass flow of product A and B. To model allocation in feed production and processing the following data and assumptions are used:

Feed production

Datasets from Agrifootprint is used to model feed either by mass or economic allocation.

For production of meal and oil from reduction fisheries a relative value of 1 is used for oil, and 0.75 for meal. The meal and oil yield depends on the species.

For production of oil and FPC from co-products (herring and whitefish ensilage) values and mass outputs from the industry is used. The relative value of oil and FPC is 11 and 6 respectively. Yield depends on the type of ensilage.

Processing at slaughtering facility and in the market

Economic value of products and co-products from harvest in Norway are estimated by industry data provided by Kontali Analyse AS.

For head-on-gutted products the value of the main product is 55 NOK/kg ($V_{HOG,main}$), while the value of co-products (used for ensilage and oil) is in the order of 2-2.5 NOK/kg ($V_{HOG,co-prod}$). At harvest plants in Norway all co-products apart from blood are utilized. Blood is 2 % in weight (Myhre et al., 2021). Other parts are used for ensilage and oil. The yield factors (section 3.11) are used, meaning that $M_{HOG,main}$ is 0.83 and $M_{HOG,co-prod}$ is 0.17. Using the formula above means that 99% is allocated to the main product, and 1% to the co-products.

For fillets, a share of off-cuts is used for other products for human-consumption, while the rest is used for ensilage and oil.

Values of products from human-consumption are higher than for co-products for ensilage and oil.

The value of processing trimmings is in the order of 16-30 NOK/kg, while coproducts for ensilage and oil have a value of 2-2.5 NOK/kg. Hence, the value of coproducts from fillet production is higher than coproducts from HOG. Based on the distribution of fractions of different coproducts from, 28% are co-products for human consumption and 72% are co-products for ensilage and oil (Myhre et al., 2021). Based on this, the average value of co-products from filleting is 8 NOK/kg ($V_{fillet,co-prod}$). For the main products, fillets, an average value for frozen and fresh fillets and all trims are used. The value is 88 NOK/kg ($V_{fillet,main\ prod}$). The yield factors (section 3.11) are used, meaning that $M_{fillet,main}$ is 0.58 (in the case of B-trim) and $M_{fillet,co-prod}$ is 0.42. Using the formula for allocation factors, this means that 94% is allocated to the main product and 6% to the co-product (for B-trim). For C-trim the value is 93% for the main product and 7% for the co-product.

Table 4-2 Allocation factors used for the main product and the co-product when economic allocation is applied at the processing in Norway and in market.

Main product	Allocation factor, main product	Allocation factor, co-product
HOG	99%	1%
B-trim fillet, fresh and frozen	94%	6%
C-trim fillet, fresh and frozen	93%	7%
Products in market	98-99%	1-2%

For allocation between the main products and co-products (defined by the share of by-product utilization in market) in the market after export the allocation values for fillets are used. This means that we assume that as in Norway, a share of the co-products is used for human consumption (with a higher economic value).

4.3 Emissions from land use change

The effect of dLUC emissions on the final results are evaluated by linearly reducing the effect of dLUC emissions from 100% to 0%. In the case of 100%, it assumed that soybeans are solely sourced in Brazil and have dLUC emissions associated as modeled by Agrifootprint data. In the base case, dLUC emissions are included based on this, but some of the soy is sourced from Europe, with lower dLUC emissions. Non-LUC emissions are fairly equal between different producer regions and are assumed constant.

5 Improvement measures

The potential of improvement measures were investigated quantitatively, in order to evaluate the potential GHG effect, while the economic costs were considered qualitatively.

Table 5-1 shows the list of measures evaluated. For the analysis, these measures were grouped, and each measure was evaluated for different functional units/product cases. In the end, results are normalized to the specific case of product 1 (fresh HOG, Paris) to be able to compare the effect of different measures.

The grouped measures are:

1. Changes in feed composition (feed)
2. Mortality and feed efficiency (loss) / By-product utilization and product losses (loss)
3. Production system
4. Transport to market (distribution) / Supercooling (distribution)
5. Energy efficiency and energy carriers (energy)

Table 5-1 Overview of measures evaluated

Main category	Measure	# Measure
1. Feed	Land-animal proteins (LAPs)	Measure 1
	More marine by-products	Measure 2
	No marine	Measure 3
	Salmon oil	Measure 4
	Novel feeds	Measure 5
	European soy	Measure 6
2. Loss	Mortality and feed efficiency	Measure 7
	By-product utilisation	Measure 8
3. Production systems	Increased smolt size	Measure 9
	Increased smolt size and offshore exposed	Measure 10
	Smolt size as today and closed pens	Measure 11
4. Distribution	Direct ship transport + processing at ship	Measure 12
	Train	Measure 13
	Ship	Measure 14
	Supercooling	Measure 15
5. Energy	Energy savings and electrification of feed barges	Measure 16
	Energy savings for land-based processes (juvenile production in RAS. harvest plant)	Measure 17

	New energy carriers for vessels	Measure 18
	New energy carriers for well boats	Measure 19

5.1 Changes in feed composition

As feed compose a large share of the carbon footprint for salmon production, the sourcing and use of low-GHG feed ingredients are an important strategy to reduce the overall carbon footprint. The goal has been to evaluate realistic changes in diets, which fulfil all required criteria for a balanced feed without increasing feed use. To achieve this, one of the feed companies have supplied data for feed ingredient composition for different scenarios. First, the average diet presented in 3.4 had to be adjusted, as this diet represented the average diet of different companies. This was done by using the nutrient contribution for the average diet as a base specification for the important nutrients (digestive protein, digestive energy, EPA+DHA etc.) and then reformulate the different scenarios considering these constraints, relaxing the ingredient constraints where needed. The scenario name describes the first change that is done, but as a consequence the composition of other ingredients are changed subsequently. The changes in carbon footprint may therefore be a result of different changes.

Table 5-2 yields an overview of the scenarios evaluated for changes in feed composition that are evaluated as improvement measures. The full overview of each scenario and changes in feed ingredient composition are included in the Appendixand Table 0-3.

Table 5-2 Overview of scenarios evaluated for changes in feed composition.

Scenario	Description
Land-animal protein (LAPs) by-products	SPC is to a large degree replaced by feather meal and poultry meal.
Marine by-products	Increased marine ingredients both meal and oil, but based on trimmings. SPC reduced to zero, while the share of wheat is increased.
No marine	Marine ingredients are replaced by algae oil, amino acids, and different types of crop-based proteins and oils.
Salmon oil	Salmon oil based on by-products from slaughtering waste Replacing other fish oils (?)
Novel feeds	Insects and algae oil are introduced. SPC reduced, rapeseed oil increased.
European soy/low LUC emissions)	Assuming that all soy is from European countries, where LUC emissions are low. This corresponds to the case of 10% LUC emissions presented in the sensitivity analysis for LUC emissions in Figure 6-7 and Figure 6-8.

5.2 Mortality and feed efficiency

Reducing mortality, efficient feeding and increasing nutrient retention are important factors for reducing the carbon footprint. The effect of this parameters is summarized in the eFCR. To quantify the net effect on GHG emissions from changes in eFCR, we use the same approach as in the sensitivity analysis (section 4.1). This means that the improvement measure is to change the eFCR from 1.30 (today's average) to 0.91 (today's best value observed).

5.3 By-product utilization

Case: 1 kg edible B-trim fillet in Paris (product 6), with economic allocation

The carbon footprint of the main product (salmon fillet) can be decreased by either increasing the share of by-products that are used for other purposes (mass allocation) or increase the value of the by-products (for economic allocation).

In the base case, the value ratio of the main product vs. by-products are 88:8. This means that a large share, approximately 95%, of the environmental burdens is attributed to the salmon fillet.

We evaluate the effect if by-product utilization is increased in the following steps (without increasing the value of by-products) as case A:

- Today 0% of the biomass output from grow-out that is not for human consumption (i.e. dead fish) is usedn. We assumed that this can be increased to 50%.
- Today 98% of the by-products are used from harvest plant. Assume that this is increased to 100%.
- BUiM is 50% for product 6, assume that this can be increased to 100%

Then we also evaluate the effect if the value of by-products is increased:

- The value ratio of by-products from grow-out is in the base case 28:1. We assume that this can be increased to 2:1 in case B and 1:1 case C.
- The value ratio of by-products from harvest plant and in market is in the base 10:1 in case 1. We assume that this can be increased to 2:1 in case B and 1:1 in case C.

5.4 Post-wholesaler supply chain

Case: 1 kg eaten B-trim fillet in Paris (product 6, but per consumed unit)

In the product cases the supply chain up until wholesaler is covered. Distribution from wholesaler to retailer, including processes and activities at retailer and consumer are not considered. Food waste in the value chain after wholesaler has not been accounted for as the results have been presented per unit edible food. Yet, food waste directly impacts the carbon footprint. Broadening the perspective to include the share of food that is consumed in the end, is important to pinpoint all potential improvement measures along the supply chain.

To evaluate the effect of these activities and product losses, the carbon footprint of a case that considers consumed fillet is included. Data on losses and packaging, retailer, transport to household and preparation are included based on default values for EU described in the PEF method (Zampori & Pant, 2019), and further used in the draft for the PEFCR for Marine Fish (Erik Hognes & Stenwig, 2022). In addition, a transport distance from wholesaler to retailer of 400 km is assumed.

The main assumptions are:

- Losses assumed along the value chain is 4% (in distribution), 4% (retailer) and 11% (consumer) so altogether 1*0.96*0.96*0.89= 0.82, so 18% post-wholesaler losses, as described in the PEF method (Zampori & Pant, 2019). As an improvement measure, we evaluate the effect of reducing product losses by 50% along the value chain.
- Transport from wholesaler to retailer 400 km by truck.
- Transport from retailer to consumer is modelled based on the assumptions that 2/3 of purchases are done by passenger car. The rest by foot or bike. It is assumed that each purchase includes 5 kg of goods and the impact of the transport activity is distributed on these by mass.
- Packaging: EPS box for consumer packaging is a box of 50 g EPS and 5 g PE packaging film holds 500 g fish. EoL of the EPS and the PE with market mix. A box of 30 g aluminium and 5 g PE packaging film holds 500 g fish. End of life for the aluminium is recycling and for the PE market

mix. The assumptions are based on the data used in the draft for PEFCR for Marine Fish (Erik Hognes & Stenwig, 2022).

- Retailer and use phase are included based on data described in the PEF method (section 4.4.5 and annex D) (Zampori & Pant, 2019).

5.5 Alternative production systems

Case: 1 kg live-weight equivalent at harvest gate entry

Different production systems for grow out are assessed together with change in smolt size and feed intensity. The following cases a), b), c) are compared. For all cases we assume that the new production system will be beneficial for mortality and feed efficiency, so that eFCR is reduced to the best in the industry today. For two of the scenarios smolt size is increased to 1000 g.

a) Smolt size 1000 g, open net pen as today
b) Smolt size 1000 g, grow out in offshore exposed cages
c) Smolt size 130 g, grow out in closed pens in sea

Feed intensity
For all cases compared, the feed efficiency is modelled using data from the Norwegian Directorate for fisheries and their annual survey on the profitability of the Norwegian salmon and rainbow trout aquaculture industry. The feed efficiency used is the best feed efficiency seen in the industry and an average value for the years 2018-2020 is used, yielding an eFCR of 0.91. The feed intensity is only changed for the grow out phase, not for the juvenile/smolt production.

Grow out infrastructure
For the grow out infrastructure for offshore exposed cages, data on the amount of steel and standing capacity from 2 exposed cages has been used. In addition, the same amount of plastic is assumed per kg production as for the open net pens. A lifetime of 25 years is assumed for the cages.

For the closed cages, data from one producer has been used including amount of steel, plastics and aluminum and standing capacity. The lifetime of the infrastructure is assumed to be 10 years.

For both closed and exposed cages, a production cycle of 1,5 years is assumed when calculating the total produced salmon over the lifetime of the infrastructure (standing capacity*lifetime of infrastructure/1,5 years)

Energy and oxygen use
For the exposed cages electricity use during grow out of 0.2 kWh/kg production is used, while fuel use is zero. Data is based on data from three exposed cages, as presented in the study by (Arntzen Nistad et al., 2021). For the closed cages electricity and oxygen use is based on one type of closed cages.

Vessels
The activities for vessels are likely to be different for a closed system in sea or at an exposed facility. For both closed and exposed facilities, one could assume that well boat activities will be less due to fewer lice treatment operations. The closed systems are likely to be placed in the same areas as today’s facilities, so the distances for boats from and to the facility is not likely to change substantially the fuel use for well boats. For exposed systems one could assume that fuel use for bringing smolt out , returning with harvest-sized salmon and feed transports will be higher. Dimensions and rough conditions will also likely be factors that increases fuel consumption. As data for how much of the fuel that is used for lice treatment operations vs. transit is not known it is hard to make a qualified estimate for changes in fuel use when production systems are changed. It is assumed that the vessel fuel use, both for smaller vessels and well boats, are similar as per today.

Table 5.3 summarizes the parameters used for exposed and closed system in sea. A production cycle of 1,5 years is assumed for all production methods.

Table 5-3 Parameters for evaluation of exposed aquaculture and closed systems in sea.

Parameters	Exposed aquaculture	Closed systems in sea
Electricity use for grow-out (kWh/kg lw produced)	0.2	1
Fuel use for grow-out (litre/kg lw produced)	0	0
Oxygen for grow-out (kg/kg lw produced)	Same as open net pen	0.78
Equipment and investment (gram material per kg produced)	Steel: 105,1 Plastic: 22.3	Steel: 16,8 Nylon: 1,5 Aluminium: 0.2 Plastics: 4,46 Fibre-reinforced plastics: 0,8
eFCR grow-out	0.91	0.91
eFCR smolt	1	1

5.6 Energy efficiency and energy carriers

Case: 1 kg live-weight equivalents at open-net pen gate exit.

Three measures were quantified for energy use based on the following assumptions:

Energy savings and electrification of feed barges
Based on Arntzen Nistad et al., (2021), the potential for reducing energy use at feed barges during grow-out was evaluated to 25%. Additionally, a measure for reducing GHG emissions is to replace diesel generators by electricity delivered from shore. Electricity demand is 0.09 kWh/kg lw produced (section 3.2) if only electricity is used, which is reduced to 0.07 kWh/kg lw produced assuming 25% reduction in energy use due to energy efficiency measures such as feeding under water, heat pumps for living quarter and energy management.

Energy savings for land-based processes (juvenile production in RAS, feed mill, harvest plant)
Based on Arntzen Nistad et al., (2021), the potential for reducing energy use in land-based RAS facilities was evaluated to 30%. We assume a similar potential for feed mills and harvest plants.

New energy carriers for vessels
Replacing marine fuel oil by battery-, hydrogen or ammonia-powered vessels have the potential to reduce life-cycle emissions per vessel. In the study carried out for ENOVA (Arntzen Nistad et al., 2021) it was assessed that electric work boats and smaller service vessels could reduce emissions by 75-85%, while larger service vessels and well boats could potentially replace marine fuel oil by ammonia or hydrogen which could yield a 65% reduction (if ammonia and hydrogen is produced based on a large share of renewable energy (Nordic electricity mix)).

5.7 Transport to market

Case: 1 kg fresh HOG in Paris by road.

For transport to market alternatives for conventional road transport are assessed. A specific case is developed assuming transport of fresh HOG from the middle of Norway (Frøya) to processing/retailer in Paris. The following cases are compared:

a) Transport by road (as base case)

b) Transport by small containership (0-999 TEU) from Frøya to Rotterdam. Road transport from Rotterdam to Paris.

c) Transport by road from Frøya to Trondheim. Train from Trondheim to Paris. Assume that 80% of the distance occur by electric trains, the rest by diesel.

d) Processing on ship and transport with the same ship to Rotterdam. Road transport from Rotterdam to Paris.

   We assume that the energy use for processing is equivalent to harvest plants on land, but diesel aggregates are used instead of electric supply from grid. Fuel use for the vessel apart from processing is modelled using the same container ship as in case b). As there is no need for transport from open net-pen location to the harvest plant, it is assumed that fuel use for well-boats per kg fish produced is 30% lower.

Modeling of emissions per tonne-km for different transport modes are included using the emission factors in chapter 3.10

5.8 Supercooling

Super-cooling of salmon can contribute to a lower carbon footprint because of lower amount of ice, transport and packaging materials (Iversen et al., 2022). Based on (Iversen et al., 2022), the following assumptions are made to evaluate the potential for improvement:

- Energy use for ice production is reduced by 21 kWh/tonne, while cooling demand is increased by 7 kWh/tonne. In total, this yields a net reduction of 14 kWh/tonne.
- Water use is increased by 1500 litre/tonne and 52,5 kg salt/tonne.
- Ice in EPS boxes are replaced by fish. In (Iversen et al., 2022), it was assumed 21,5 kg fish in a standard box with ice and 26 kg in the case of supercooling. In this report 20 kg fish was assumed in the base case, with 5 kg of ice. 25 kg fish and 0 kg ice are assumed for supercooling.

6 Results

The first part of the results section presents the carbon footprint of the products delivered to wholesaler in the market, as defined in section 2.2. Thereafter, the contribution from different inputs and activities are shown. It is important to again underline that results are not comparable with previous reports on the carbon footprint of Norwegian seafood products due to various differences in methodology and data (see section x-x). Thereafter, the results of the sensitivities assessed are presented.

The second part shows the results of the evaluation of the improvement measures. Finally, the results for carbon footprint over time are presented.

6.1 Carbon footprint of products in market

Figure 6-1 shows the carbon footprint of the supply chains and products analysed. The main factors contributing to differences in carbon footprint across the products are 1) whether products are air-freighted and 2) the share of by-products that are utilized in market, with airfreight being the most important factor.

Generally, airfreighted products to Asia or USA have a carbon footprint in the range from 16-28 kg CO_2e/kg edible product delivered to wholesaler. For these supply chains, airfreight is accounting for 68-82% of the carbon footprint. Products 4 and 9 to Tokyo are assumed to be transported by a dedicated freight aircraft, while the other products are transported by a combined freight-passenger aircraft (a so-called belly freighter). Based on the NTM calculator, emissions per tonne*km freight are approximately 50% lower for freight by a freight aircraft than a passenger-freight aircraft.

Products that are shipped by road or sea have a carbon footprint between 5-6 kg CO_2e/kg edible product deliver to wholesaler. In contrast to airfreighted products, the contribution from export is less than 10% of the total emissions (see Figure 6-2).

Products with a lower BUiM generally have a higher carbon footprint as indicated in Figure 6-1 and Figure 6-2. This is because by-products that are further utilized (e.g. to produce feed) 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. However, the difference between products with different BUiM are not substantial, as most products are C and B-trim fillet where a high share of the product is edible. For HOG, where ca. 50% of the product is non-edible, the BUiM is a more important factor for the carbon footprint.

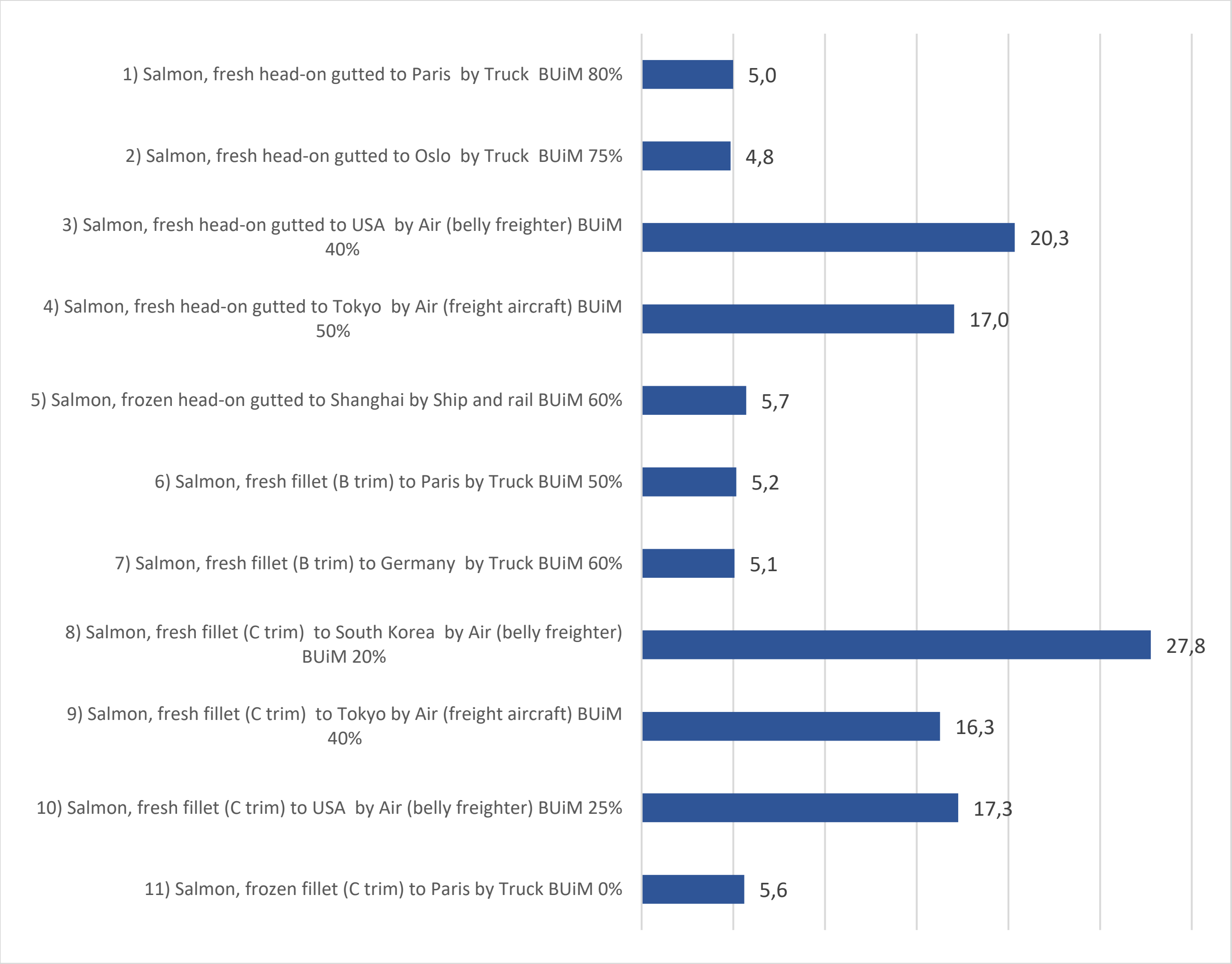

Figure 6-1 Total greenhouse gas emissions of all salmon products (kg CO_2e/kg edible product delivered to wholesaler) BUiM = By-product use in market.

Packaging and processing only have a minor influence on the final results of products delivered to the market, as shown in Figure 6-2. For frozen products, an additional electricity consumption related to freezing of products is accounted for, but the contribution is negligible when evaluating the edible products in market. Slaughtering and processing contributes to less than 2% of the total carbon footprint for all products, while packaging accounts for 1-5% of the carbon footprint.

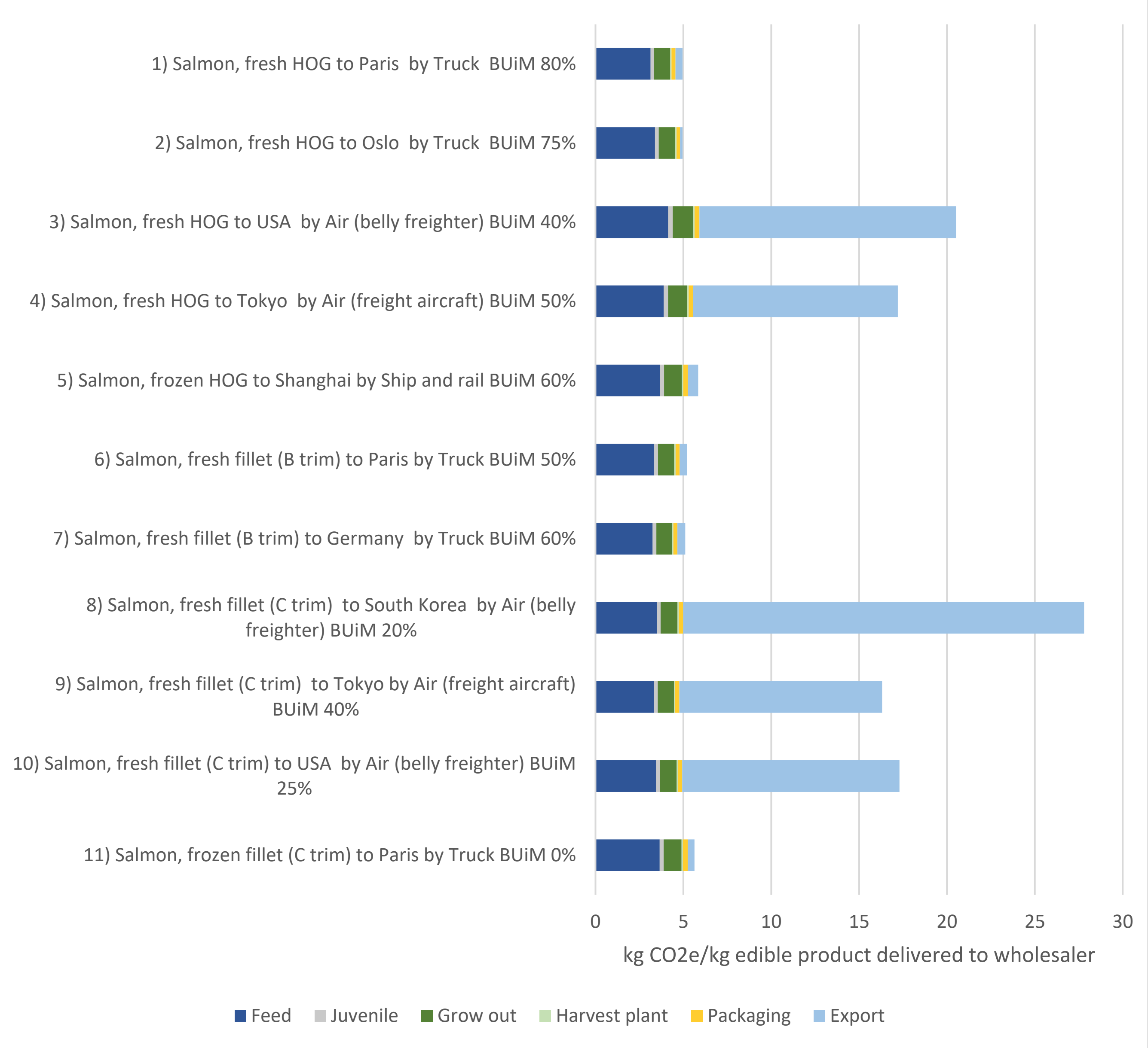

Figure 6-2 Greenhouse gas emissions per life cycle phase of all salmon products (kg CO_2e/kg edible product at wholesaler) BUiM = By-product use in market.

6.2 Results at farmgate

The result for farmgate salmon (salmon delivered to harvest plant entry) is 3.8 kg CO_2e/kg LW salmon, of which 0.8 is due to LUC (i.e. 3.0 kg CO_2e/kg without LUC).

For products in market, except airfreighted products, the contribution from feed to the total carbon footprint is in the range of 63 to 68%. At the farmgate, 75% of the carbon footprint is attributed to production of feed including LUC, leading to an “upscaling factor” from feed-related to total farmgate emissions of 1.3 instead of 1.2 (Ziegler et al. 2021). The proportion of emissions represented by feed is hence slightly lower than previously (Winther et al. 2020, Ziegler et al. 2021). The reduced relative contribution of feed is due to changes in feed composition as well as in the climate intensity of the feed inputs resulting in a lower footprint per kg feed used than previously reported. The importance of emissions from land use change to the total carbon footprint is also slightly lower than previously calculated, but still in the same range (25-30% of total carbon footprint). This is described more in section 6.2.1.

As shown in Figure 6-3, the overall picture for contribution of different activities and inputs to the carbon footprint for farmgate salmon confirms findings in previous assessments, although the contribution from feed is slightly lower. Except for feed, vessel activities are the main contributor to emissions in production. The detail and quality of data on fuel use by vessels in the industry is improved compared to previous assessments (Winther et al. 2020). The finding that well boats are important for the final carbon footprint of salmon production in Norway is thereby strengthened, yet better data from more companies is required to further investigate their use profiles and variability in fuel use etc.

Around 4% of the carbon footprint at farmgate is caused by juvenile production (including salmon egg production). Feed, electricity and oxygen are the main inputs causing GHG emissions in this phase. Egg production was excluded from previous assessments (Winther et al., 2009; Winther et al., 2020), but was now included based on a LCA carried out for Aquagen AS Production of eggs is negligible for the overall carbon footprint and maximum ~0.2% of emissions. The contribution from juvenile production to the total carbon footprint is directly related to the smolt size. The smolt size has increased the last years, and several actors are now producing post-smolt, which is smolt of 250 to 500 grams when released to sea. Still the average size in the sector is 130 gram, which is assumed in the analysis. The effect of having a longer production cycle on land is evaluated as a measure for different production systems (section 6.4).

A range of different chemicals are used during grow-out. The use of H_20_2 is included in the assessment, as the quantity is substantially higher than for other chemicals and medicines in use. For the carbon footprint, only the production of chemicals is of importance for the results. For other environmental indicators, chemicals and medicine is of higher importance. In addition to the use of $H_20_{2,}$ some of the well boat activities are related to lice treatment but the share of well boat activities related to lice treatment is not known based on the available data. Even though lice treatment and medicine are not directly shown to be of high importance to the carbon footprint, the more important effect of lice and disease is decreased growth and increased mortality. Mortality in the industry is estimated to 6-9% of the biomass produced, which increases the use of all other input factors per unit production. Decreasing mortality will reduce the carbon footprint, and the effect is quantified in the assessment of measures presented in section 6.4.

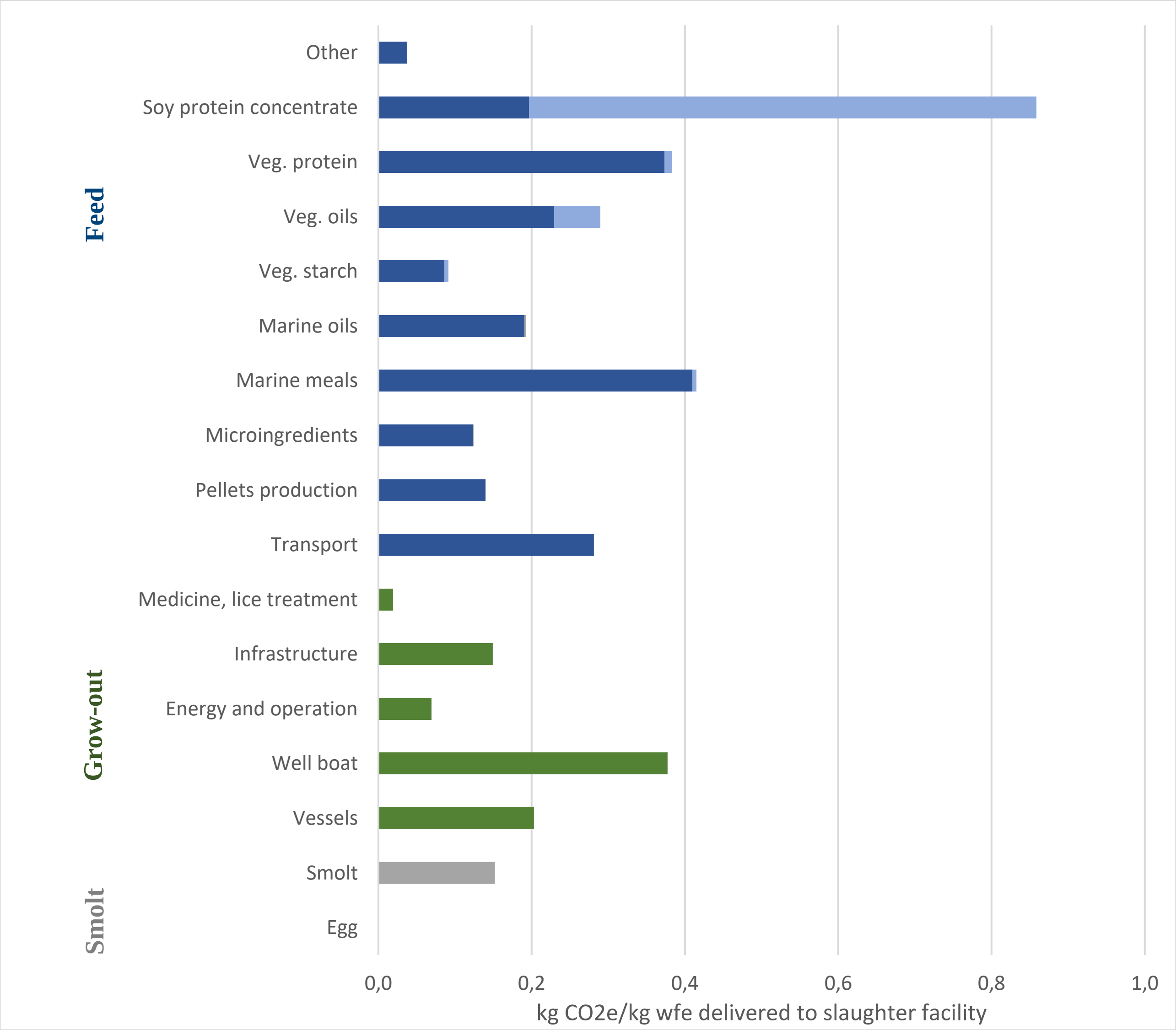

Figure 6-3 Detailed greenhouse gas emissions per kilo farmgate salmon of different activities and feed inputs. Solid colors indicate fossil GHG emissions, lighter colors indicate emissions from land use change.

6.2.1 Feed

Looking closer at feed production, the carbon footprint per kg feed is 2.3 kg CO_2e per kg feed delivered to fish farmer using mass allocation. Of this 0.6 kg CO_2e per kg feed is LUC emissions. Soy protein concentrate, marine protein, crop proteins and oil are the main input groups contributing to the carbon footprint of feed. The sum of all transports of feed ingredients from production region to the feed factory in Norway is also represents an important source for emissions.

As presented previously, the production of soy protein concentrate is modelled using the dataset for production of SPC from Brazil in Agrifootprint “Soybean protein-concentrate, at processing {BR} Mass, U” and a modified dataset for the European mix. 19% of the soy is of European or US origin, while the rest is from South America. A range of different emission factors for soy can be found in LCA-databases and a suppliers have also carried out own LCA-studies including or excluding land use change. Moreover, different frameworks and modeling choices can be made related to how LUC emissions should be attributed to a specific production batch. To handle this, a sensitivity analysis for LUC are presented in section 6.3.3, and the effect of different emission factor or shares of LUC emissions can be read from those results.

The proportion of mass of feed ingredients versus emissions are shown in Figure 6-4. For micro ingredients, soy and marine protein the contribution to emissions is higher than the contribution in terms of mass. In the previous assessments (Ulf Winther et al., 2020), soy and micro ingredients stood out with a disproportional contribution in terms of emissions compared to mass. This is also observed in this study, but not to the same degree as in 2017.The mass proportion of carbohydrates is also substantially higher than previously (Ulf Winther et al., 2020), but this is caused by a different classification of some of the feed ingredients. The category other includes algae oil and insects, and compose 0.6% of the total mass, and 2.9 % of emissions.

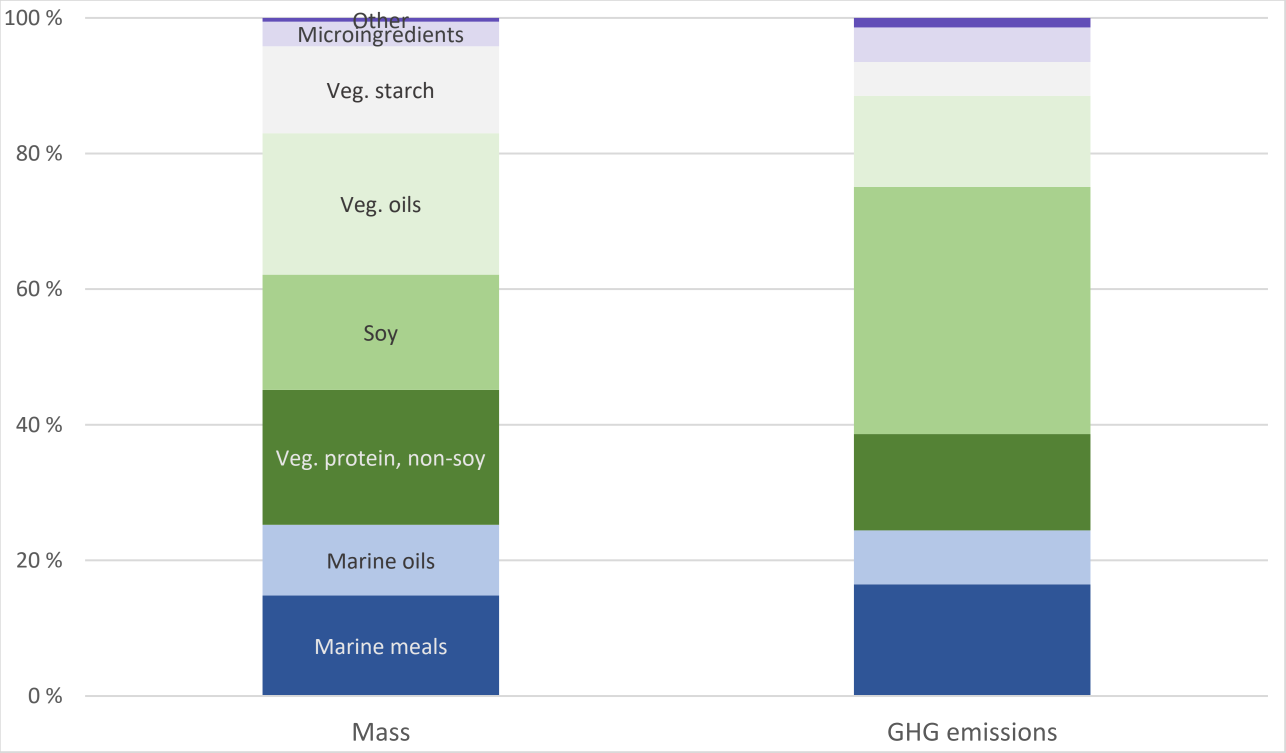

Figure 6-4 Relative contribution to mass and greenhouse gas emissions, respectively, of different components of salmon feed (per kg feed).

6.2.2 Impact of services and investments estimated with an environmentally extended input-output (EEIO) model

6.2.2.1 The use of services for aquaculture producers

We collected accounting data from two large aquaculture producers in Norway. All economic expenditures that were captured in the LCA analysis with an equivalent material flow, was eliminated in the EEIO analysis. Examples of service expenditures that's included here is accommodation, IT services and other business activities. Table 6-1 shows how the service expenditures are distributed with a following estimation of greenhouse gas emissions in tonnes CO_2e. Service industries do not have large Scope 1 emissions themselves. However, they demand inputs from other industries that have higher Scope 1 emissions intensities in production. By taking into account (which is the essence of the EEIO method) such indirect GHG effects of the service demand, the numbers become significant also for service demand.

These two aquaculture producers used about 437 mill NOK on services whereas their total expenditures were about 6.5 billion. Then only ~7 % of the average expenditures from aquaculture producers did not have an equivalently covered material flow in the LCA. Results from the EEIO shows that the 437 mill. NOK expenditures of services generated a total emission on 4.000 tonnes of CO_2e. Although the monetary flows and related demand and expenditures not covered by the LCA are relatively high, GHG emissions related to these purchases are relatively small. Total production from these two producers was 130.000 tonne.

Emissions from services represents 0.03 tonnes CO_2e per tonne processed. Service purchases then represent less than ~1 % of the total carbon footprint of salmon at farmgate.

Table 6-1 Service purchases from of two aquaculture producers and related carbon emissions

Service	GHG (tonnes CO_2e)	Sum expenditures (mill NOK)
Accommodation	119	7
Publishing	148	12
Communication	169	16
IT	193	23
Financial services	331	88
Real estate	197	31
Business activities	2 152	195
Public	133	14
Education	12	2
Health	12	2
Recreation	562	45
Sum service expenditures	**4 029**	**437**
Total expenditures (mill NOK)	6 500	
Total production (tonne)	130.000 tonne	

6.2.2.2 The role of investments for aquaculture producers

In this section we have mapped investment data from one aquaculture producer to the EEIO model. Table 6-2 shows how GHG emissions are distributed among the investments products of suppliers. Investments products bought from metal, machinery, textiles, trade, construction and other manufacturing industries contribute the most to the total GHG emissions from investments. Total purchases of investments were 160 mill. NOK and transformed into 3 100 tonne CO_2e. In relation to total production of the aquaculture producer, emissions from investments represents 0.06 tonne CO_2e per tonne processed. Emissions generated from investments represents ~2% of the carbon footprint of salmon at farmgate. These numbers reflect investments from one producer not having large investments in the particular year we got the data from the accounting system. Obviously, data covering more years and several producers would have made this estimate more robust.

Table 6-2 Emissions from investment products used by an aquaculture producer.

Supplying industries	Industry codes	GHG (tonnes CO_2e)
Agriculture, fisheries and aquaculture	D01T03	58
Energy Mining	D05T06	0
Non-Energy Mining	D07T08	0
Mining support	D09	0
Food products	D10T12	0
Textiles	D13T15	374

Wood products	D16	0
Paper	D17T18	0
Petroleum products	D19	0
Chemicals	D20T21	77
Plastics	D22	0
Nonmet minerals	D23	152
Basic metals	D24	0
Metal products	D25	755
Computers etc	D26	0
Electrical Equipment	D27	22
Machinery	D28	400
Motor vehicles	D29	0
Other transp Equipment	D30	14
Other manufacturing	D31T33	301
Utilities	D35T39	0
Construction	D41T43	351
Trade	D45T47	349
Transportation	D49T53	2
Accomodation	D55T56	2
Publishing	D58T60	1
Communication	D61	0
IT	D62T63	8
Financial services	D64T66	2
Real estate	D68	32
Business activities	D69T82	191
Public	D84	1
Education	D85	0
Health	D86T88	0
Recreation	D90T96	18
Total		3 110

6.3 Sensitivity analysis

Sensitivity analyses are performed to evaluate the effect on results and conclusions of variability in important data and assumptions. Changes in three main parameters (best-worst case), choice of allocation method and impact of land use change emissions.

6.3.1 Best/worst case

Figure 6-5 shows the results for the base case, best and worst case for salmon at farmgate and for product 6 (fresh B-trim fillet, Paris) at wholesaler. The best case reflects the lowest eFCR in the industry (0.91 instead of 1.30), an electrified feed barge, low energy use for juvenile production and high by-product utilization. In the worst case, the salmon is produced with an eFCR of 1.7 instead of 1.3, diesel generator at the feed barge, high energy use for juvenile production and low by-product utilization. The results in Figure 6-5 show that farmgate salmon can be produced with a carbon footprint of 3 kg CO_2e/kg wfe salmon at slaughter (best case) or up to 5 kg CO_2e/kg wfe salmon (worst case). Fuel use for vessels and contribution to LUC emissions from feed ingredients are additional parameters that are important for the carbon footprint, and were treated separately.

The variation from best to worst case is larger for the fresh fillet delivered to the market, as the factor for BUiM is an important factor for the final results. In the base case BUiM is 50%, while it is 100% in the best case and 0% in the worst case. This illustrates the potential for reducing the carbon footprint by increasing by-product utilisation across the value chain, and most importantly in the market where the lowest by-product utilisation is seen per today (50%). The impact on the carbon footprint of increasing by-product utilisation along the value chain is also quantified in the evaluation of improvement measures (section 6.4).

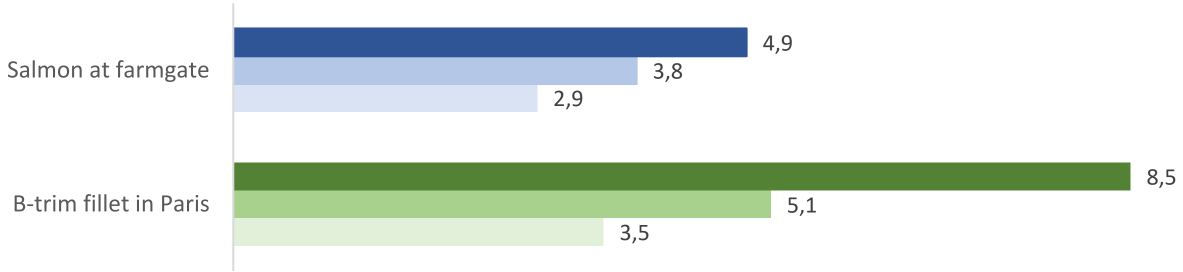

Figure 6-5 Carbon footprint of products at farmgate (kg CO_2e/kg lw at farmgate) and product 6 fresh fillet (B trim) to Paris by Truck BUiM 50% (kg CO_2e/kg edible product at wholesaler) in the base (light colour), best (medium colour) and worst case (dark colour) (based on parameters in Table 4-1).

6.3.2 Economic allocation

Results so far have been presented using mass allocation, based on the rationales presented in section 2.4. The two different allocation methods are acknowledged by different standards can yield very different results. The methods offer different perspectives, with economic allocation taking into account that the economic value differs between the co-products. When economic allocation is used, the footprint is to a higher degree attributed to the most commercial valuable parts, which today are the products for human consumption. This has different effects on multiple stages in the value chain. For the salmon products, it implies that a larger share of the carbon footprint is attributed to the edible products and their carbon footprint is increased, as seen in Figure 6-6. On the other hand, off-cuts and trimmings from salmon processing will seem to have a lower environmental burden, based on their lower relative economic value.

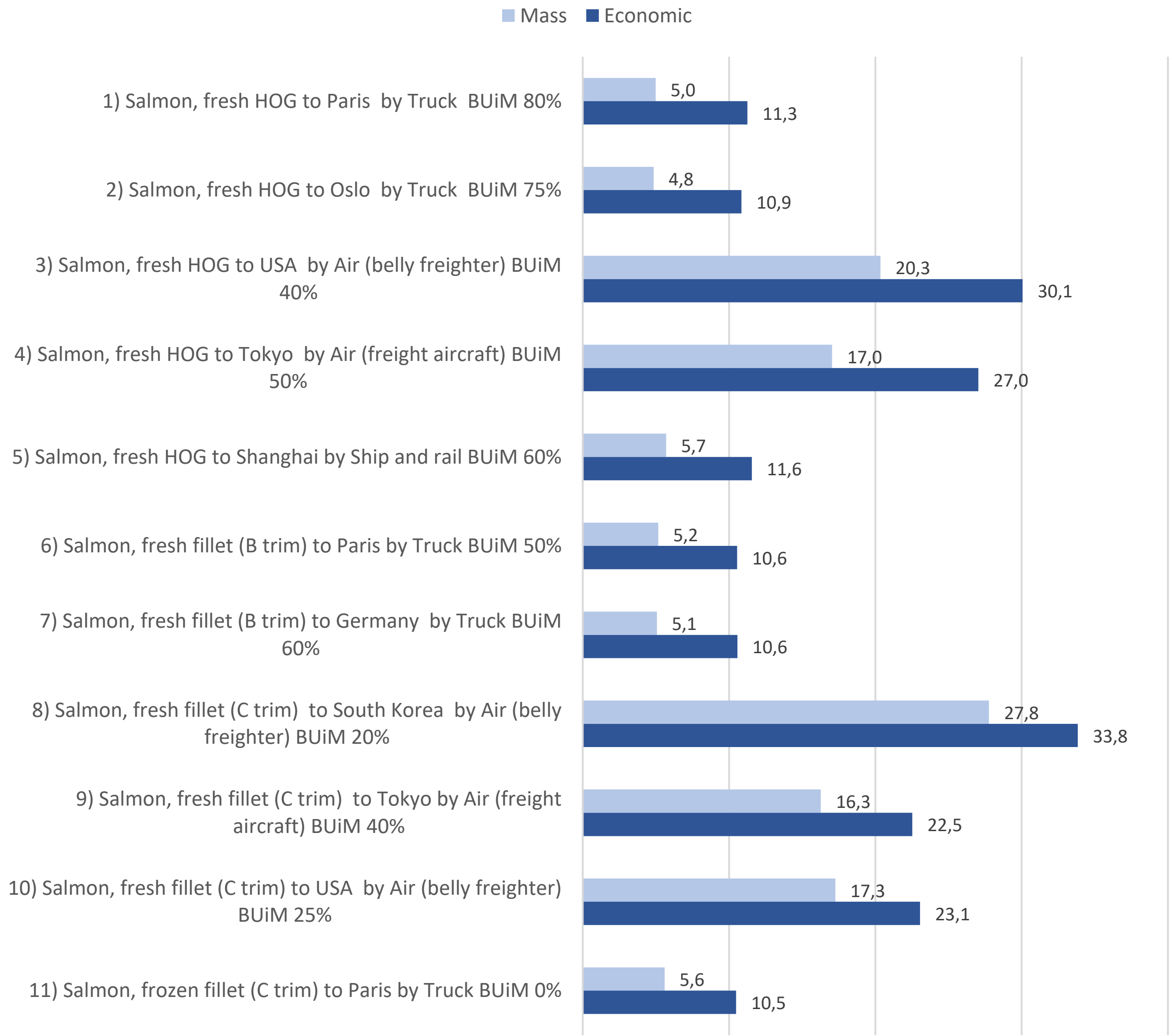

Figure 6-6 Greenhouse gas emissions of all studied products (kg CO_2e/kg edible product delivered to wholesaler) by using mass allocation (light blue) and economic allocation (dark blue). BUiM = By-product use in market.

The choice of allocation method is also an important factor for the carbon footprint of feed ingredients. In the production of feed ingredients by-products are in some cases used as an input, while in other cases production of one feed ingredient leads to one or multiple by-products. In both cases allocation is required. The impact of allocation method on the carbon footprint per feed ingredient can be observed in Figure 3-1 and Figure 3-2.

For most crop ingredients the carbon footprint is higher for economic allocation compared to mass allocation. Taking SPC as an example, SPC is one of multiple outputs from the extraction process that uses ethanol and energy to extract products from the soybeans. The outputs are SPC (70%), fines (8%) and molasses (22%). When using mass allocation, the impacts are attributed according to the shares above, and the carbon footprint per kg output will be equal. If economic allocation is used, 97% of the upstream carbon emissions will be allocated to SPC, instead of 70%, due to the higher economic value of SPC.

For marine by-products/trimmings, an opposite pattern can be observed. In this case, economic allocation leads to a lower carbon footprint for the feed ingredients as a lower share of the upstream environmental impact is allocated to the by-products used for ensilage production. By-products into ensilage production, which are by-products from slaughtering of whitefish and herring, have a lower commercial value than the main product, which is HOG fish. The same principle is applicable for by-products from salmon slaughtering that are used for ensilage production or other purposes.

For economic allocation, the carbon footprint of feed is 3.0 kg CO_2e/kg feed delivered to fish farmer (including LUC emissions). As a result, the carbon footprint for farmgate salmon is 4.8 kg CO_2e/kg lw delivered to slaughter or harvest plant entry.

6.3.3 Land use change emissions

Close to 30% of the carbon emissions for production of salmon are caused by emissions from land use change. As shown in Figure 6-3, nearly all emissions from land use change are caused from cultivation of SPC, mainly from Brazil, but to some degree also from Europe. As a result, the carbon footprint for Norwegian salmon is sensitive to dLUC emissions attributed to soybean production. To explore the sensitivity to dLUC emissions and emission factors used for SPC, a simple sensitivity analysis is carried out.

In Figure 6-7, the share of dLUC emissions included and the effect on the carbon footprint of farmgate salmon is seen. To the right, 100% of the soy is assumed to be sourced from Brazil and dLUC emissions are modeled according to Agrifootprint. To the left, 0% of dLUC emissions are included. The result shows in this case the carbon footprint of farmgate salmon if one can be sure that the cultivation of soybeans did not cause land use change. If soybeans are cultivated in Europe, the share of dLUC emissions will be ca. 10%. If economic allocation is used, the emission factor for SPC is higher, and the effect of dLUC emissions on final results for farmgate salmon is thereby larger, as indicated by the steeper slope in Figure 6-7.

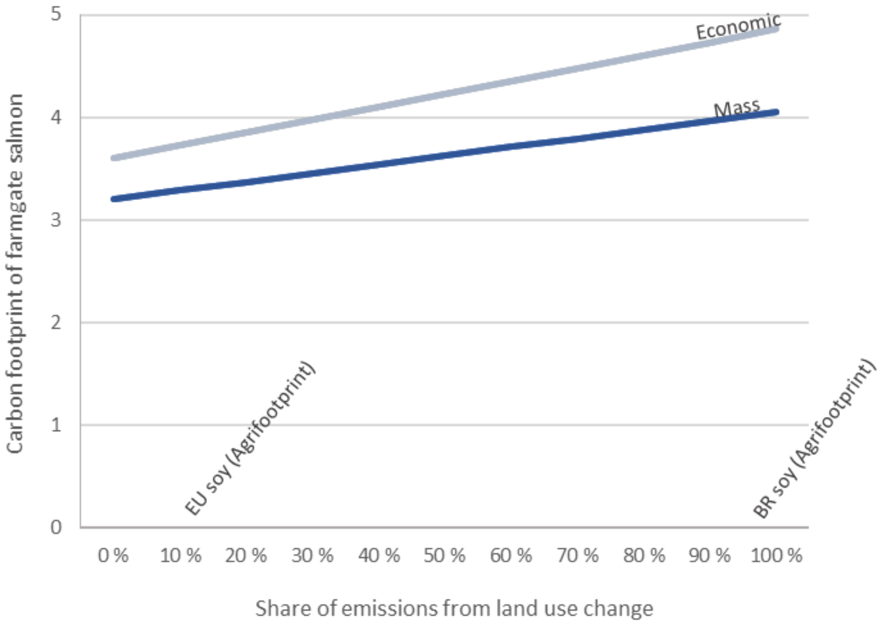

Figure 6-7 Carbon footprint of farmgate salmon (kg CO_2e/kg lw at harvest plant entry) as a function of the share of emissions from dLUC. 100% is the share of dLUC emissions from SPC, with soybeans farmed in Brazil based on Agrifootprint data. 0% indicate that dLUC emissions are zero. Results are shown for allocation by mass and economic allocation.

In Figure 6-8, the results are shown with different emission factors on the horizontal axis, instead of the share of dLUC emissions. The horizontal axis is extended to include emission factors up to 7 kg CO_2e/kg SPC at feed mill entry. An emission factor close to 1 kg CO_2e/kg SPC reflects the case where dLUC emissions are zero, and only transport and processing is required throughout the supply chain from farming to extraction.

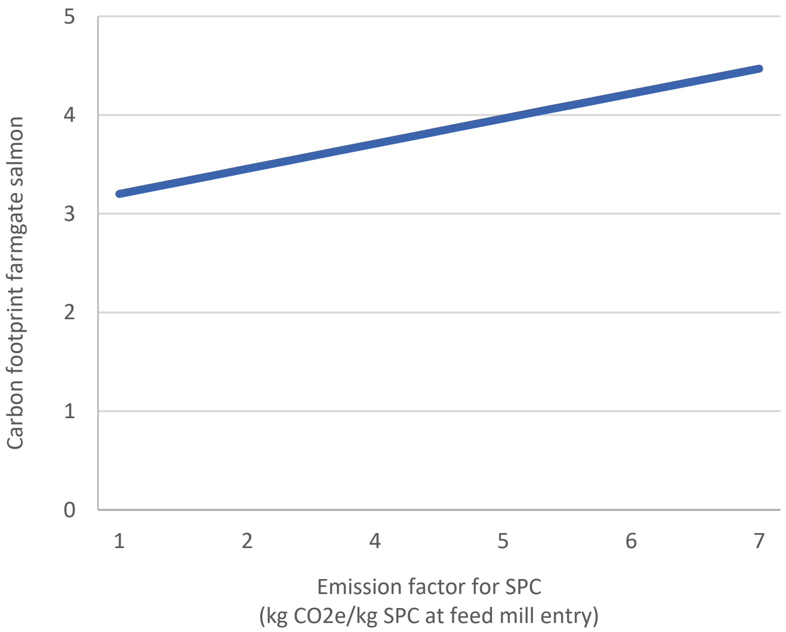

Figure 6-8 Carbon footprint of farmgate salmon (kg CO_2e/kg lw|- at harvest plant entry) as a function of different emission factors for SPC (shown as kg CO_2e/kg SPC at feed mill entry). Results are shown for allocation by mass.

6.4 Improvement measures

6.4.1 Greenhouse gas emission reduction effect per measure

Five measures with 19 sub-measures were evaluated. First, results are presented for the cases described in section 5. To be able to compare the measures the results are thereafter calculated for product 1) fresh HOG in Paris (using allocation by mass).

6.4.1.1 Changes in feed composition

In Figure 6-9, the change in carbon footprint of product 1 is shown both for allocation by mass and economic value. As described in section 5.1, different scenarios for changes in feed composition were described by a feed supplier. The scenarios were named after the initial change made to the feed composition (for instance introduction of novel feed ingredients or increasing the share of marine by-products), but these changes lead to subsequent changes that will have additional effects on the carbon footprint, so the result does not entirely depend on the change indicated in the name of the measure. All changes are shown in the Table 0-3 Scenarios for changes in feed composition attached in the Appendix.

Land-animal proteins (LAPs): The initial change in the feed composition in this scenario is introduction of feather and poultry meal. As a consequence, the use of SPC is reduced from 17% to 5.5% and the share of wheat is increased from 15% to 17.5%. The result for the carbon footprint depends on the allocation perspective that is applied. If mass allocation is used, the carbon footprint of feather and poultry meal per mass unit is equal to the production of poultry meat for human consumption. The average European poultry production and processing datasets from Agrifootprint is used to model the poultry by-products. As poultry has a higher carbon footprint than SPC, the replacement of SPC will in this case increase the carbon footprint of product 1 by about 15%. On the other hand, if economic allocation is used instead, the carbon footprint of poultry by-products will be substantially lower than that of SPC, which results in a 15% reduction of the carbon footprint of product 1.

Marine by-products: In this scenario marine protein and oil from reduction fisheries are replaced by marine by-products and trimmings. The content of SPC is reduced to zero, wheat is increased (from 15 to 35%), while rapeseed oil is decreased. Figure 3-2 shows that the carbon footprints of ingredients from marine by-products are lower than many of the fisheries, independent of allocation method. Combined with the elimination of SPC, the carbon footprint is reduced. The reduction is larger when applying economic allocation, because then the trimmings are viewed as almost free from upstream environmental burden due to their low economic value.

No marine: The initial change in feed composition is the removal of all fish oil and meal. Marine ingredients are replaced by algae oil, corn gluten, rapeseed oil and wheat. SPC is reduced to 14%, compared to 17% in the original feed. For algae oil, confidential data is retrieved from one company, but allocation methods are not known. The sum of changes is very small, with a slight increase for mass allocation and slightly larger for economic allocation.

Salmon oil: In this scenario, some of the fish oil in the base scenario is replaced by salmon oil. Subsequently, the content of rapeseed oil is decreased (from 18% to 13%). Salmon oil is modelled with the results from this study for farmed salmon in Norway. Again, the allocation perspective is important. If mass allocation is used, the carbon footprint of salmon oil is high. If economic allocation is used instead, the carbon footprint is low, as salmon by-products like all type of by-products carry a minor share of the upstream carbon emissions, as the economic value is low compared to the salmon fillet exported for human consumption.

Novel feeds: The main changes in this scenario is that insect meal and algae oil is introduced. Rapeseed oil will consequently increase slightly, while SPC is slightly decreased. For insect meal, LCA-data is collected from literature. The allocation methods used are mainly economic allocation. As seen, the effect on the carbon footprint of the final product in the market is minor.

European soy: in this scenario, all soy from South America is replaced by soy from Europe. This will reduce emissions related to dLUC as shown in Figure 6-7. The carbon footprint is reduced independently of the allocation method applied, for product 1 by 15-20%.

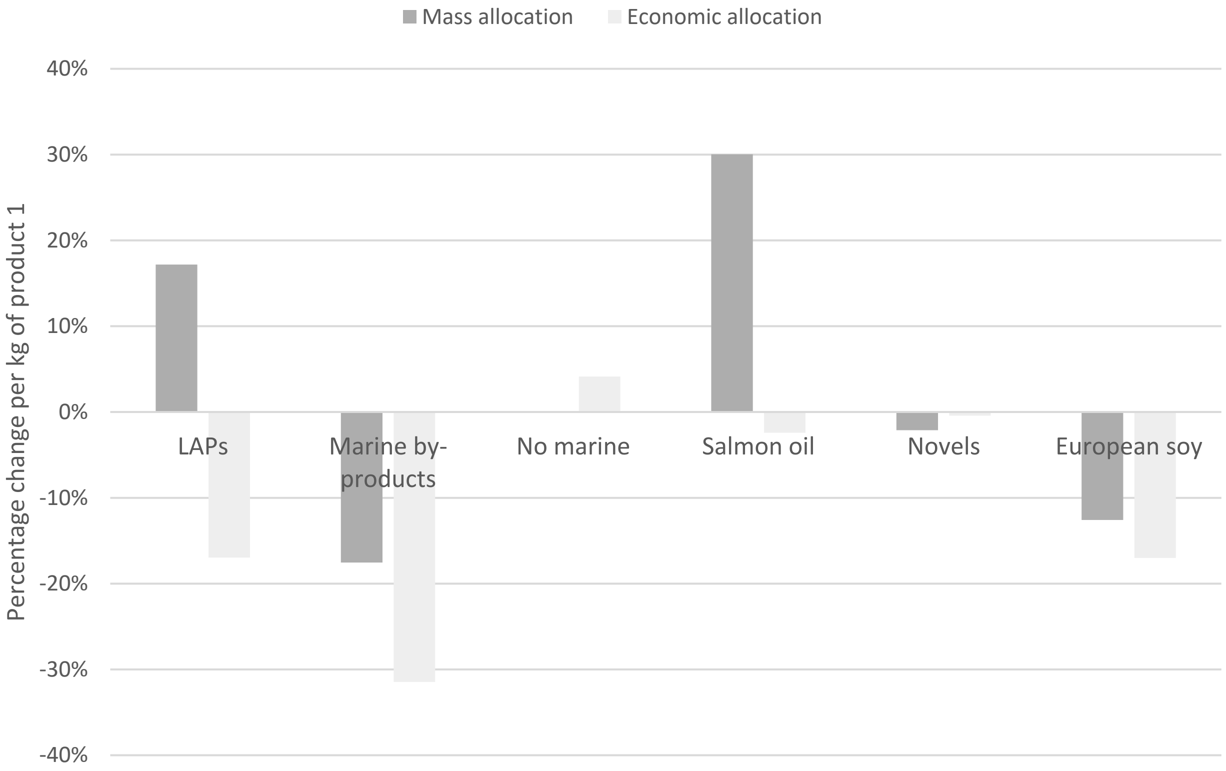

Figure 6-9 Results for changes in carbon footprint of fresh HOG in Paris (product 1) for the different scenarios for feed composition. Results are shown for mass and economic allocation.

6.4.1.2 By-product utilisation

Figure 6-10 shows the carbon footprint of product 6, fresh B-trim fillet in Paris assuming different levels of by-product utilization and values of by-products presented in section 5.3, in the case of mass allocation (left) and economic allocation (right).

When mass allocation is used, the value of co-products vs. main products does not influence the results. Still, increasing utilization of biomass output from grow-out (from 0% to 50%), harvest plant (from 98% to 100%) and in the market (from 50% to 100%) decreases the carbon footprint by 17%.

If economic allocation is applied, the effect of increasing the value of by-products used is prominent. In this case, more of the environmental burden will be attributed to the co-products instead of the fillet. In this case, the combined effect of increasing utilization and value of by-products reduces the carbon footprint of the fillet by 30% if the value of by-products are half the value of the fillet. If an equal value is assumed for the fillet and the co-products, the carbon footprint is decreased by 50%. This means that in a future scenario, when by-products have a higher economic value in relation to the fillet, it will seem like the emissions of the fillet have decreased, while the resource use of the supply chain can be exactly the same.

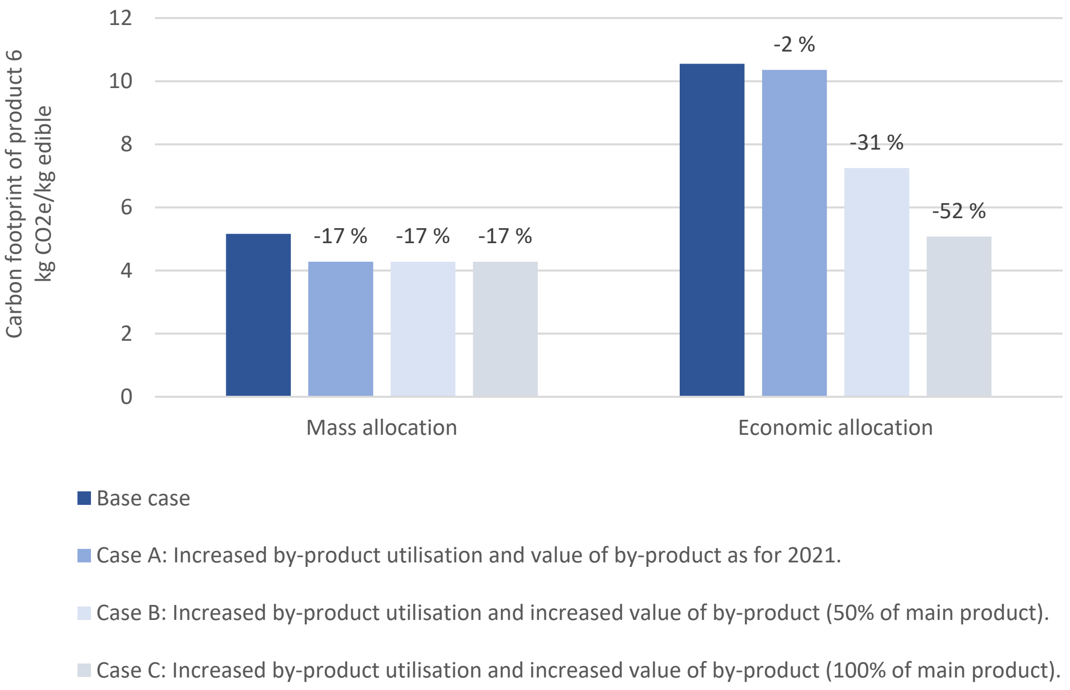

Figure 6-10 Carbon footprint of fresh B-trim fillet in Paris (product 6), kg CO$_2$e per kg edible at wholesaler. Left bars show results if allocation by mass is used, right bars if economic allocation is applied.

6.4.1.3 Post-wholesaler supply chain and losses

Food waste occurs both in the value chain before the consumer buys the product and after. To capture the effect of losses, results for the carbon footprint per unit of consumed product are shown in **Figure 6-11**. As seen, the post-wholesaler steps of the value chain, i.e. product losses (in addition to packaging) compromise a notable share of the carbon footprint per consumed product. It is assumed that 19% of the product delivered from the retailer ends up as food waste. The carbon footprint per *eaten* fresh B-trim fillet in Paris is 7.7 kg CO$_2$e/kg (compared to 5.2 kg CO$_2$e/kg at the wholesaler). If the product losses in distribution, retailer and for the consumer were reduced by 50% compared to average loss rates assumed in the PEF method, this would reduce the carbon footprint by 9%.

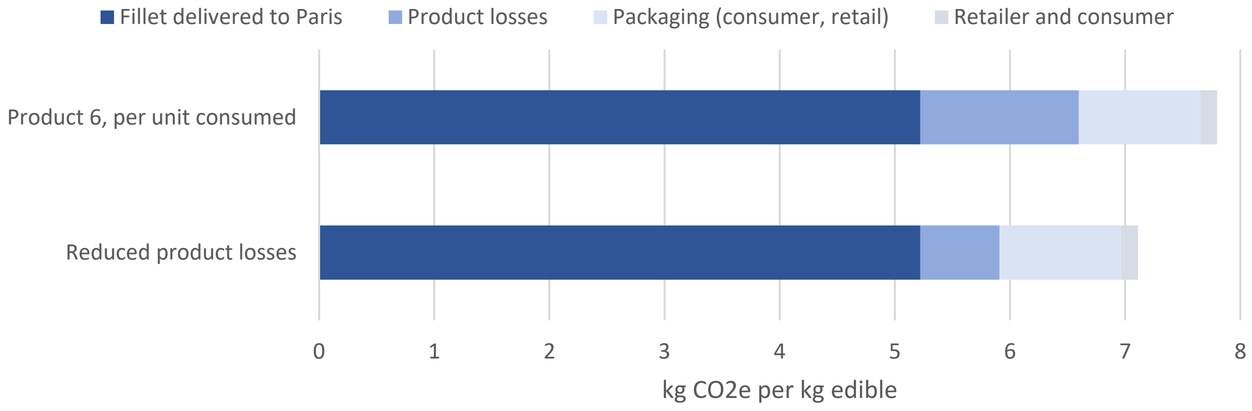

Figure 6-11 Carbon footprint per kg consumed product 6 (fresh B-trim fillet in Paris), kg CO_2e per kg eaten. In the upper case the default product losses are assumed (18% in total), while in the second case the losses are reduced by 50%, to 9%.

6.4.1.4 Alternative production systems and energy sources

Results for three scenarios are shown in Figure 6-12, in addition to the today's production (base case). Results are shown for two different electricity mixes, which as shown largely influences the carbon footprint as the alternative production systems are more energy intensive than today's open net pen systems. As shown in Figure 6-12, the benefit of better feed efficiency is outweighed by increased emissions from energy use and infrastructure investments. Only scenario closed pens (scenario c) is evaluated to lower the carbon footprint of production somewhat, and only if the pen is powered by low-GHG energy sources. Exposed aquaculture shows the largest increase in carbon footprint.

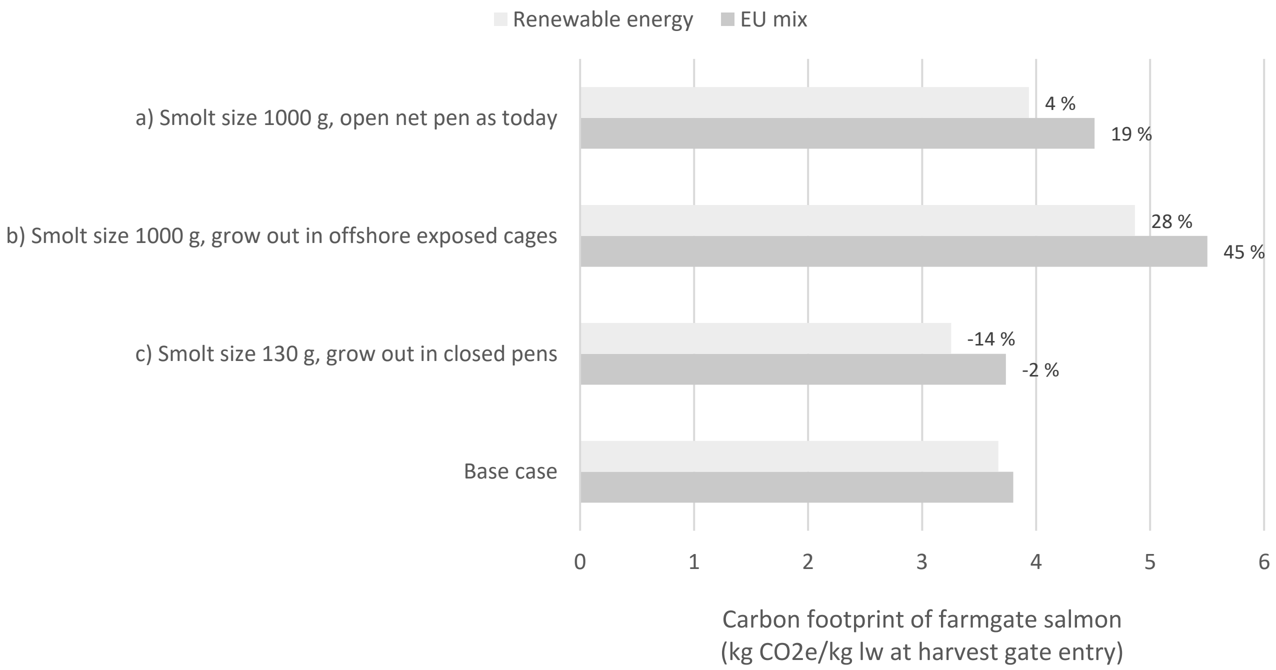

Figure 6-12 Carbon footprint of scenarios including new technology for production systems. Results are shown both for a mix with only renewable energy (Norwegian grid mix) and the EU grid mix, which is used in the base case.

Figure 6-13 shows the carbon footprint for the different inputs and activities in the scenarios. As seen, emissions from feed are decreased while emissions from juvenile production and infrastructure are increased. The shaded area of the energy and juvenile bars show the increase in emissions with EU grid mix. When EU grid mix is used the carbon footprint from juveniles and energy use are highly increased, especially for post smolt production.

For production in offshore cages the increase in carbon footprint is both due to infrastructure and post smolt production. Reducing the amount of steel in the infrastructure as well as reducing post smolt size will reduce emissions from offshore production. It should be underlined that the estimate for infrastructure contribution for exposed aquaculture is based on few systems, and the material demand of those vary considerably. How the pens are designed is important for how exposed aquaculture compares to today's production.

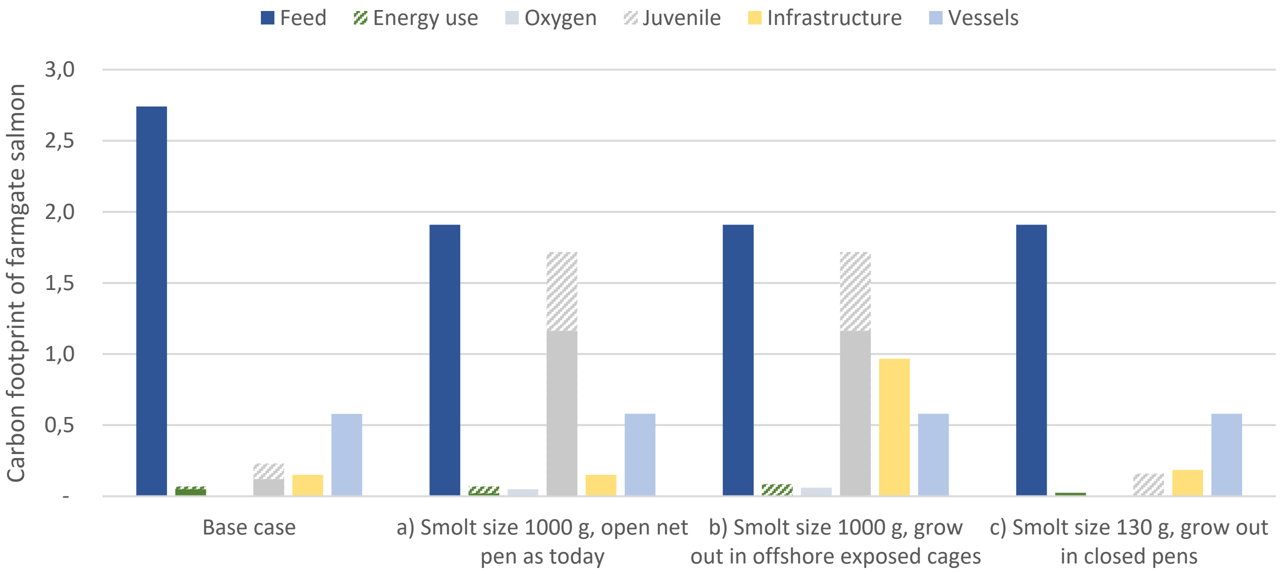

Figure 6-13 Carbon footprint distributed by activity for the different scenarios for changes in production systems.

6.4.1.5 Supercooling

Supercooling reduces the carbon footprint due to elimination or at least lower amounts of ice, which again reduces energy use for ice production, transport and packaging demand. Energy use for cooling is however slightly increased.
Post-harvest emissions are reduced by around 15% for fresh HOG in Paris (product 1), accounting for about 13% of the carbon footprint. This results in 5% lower emissions of HOG salmon in Paris (product 1)

6.4.2 Combined GHG and cost effect of improvement measures

By combining the reduction potential in terms of GHG emissions and economic costs, the different improvement measures are categorized according to their effectiveness an feasibility. Details regarding assumptions and results for the carbon footprint of different cases are presented in the section above. Here, a summary of the effect of the measures quantified as well as the related qualitative costs are presented when evaluated for product 1) fresh HOG in Paris. Costs of implementing measures have been evaluated using a qualitative approach.

The measures with high GHG reduction potential and low costs will have highest effectiveness. Still, a range of different measures are evaluated, and the level of detail for the carbon footprint assessment and the applicability of each measure should also be considered. It is important to note that both assumptions and methodology used for evaluating the measures are important for the outcome of the analysis, and these are further presented and discussed in section 5 and section 7.

Figure 6-14 and Table 6-3 show a summary of the GHG effect and economic cost of the measures evaluated. Figure 6-14 shows the measures evaluated and their effect on the carbon footprint per 1 kg edible fresh HOG in Paris. As seen, selected measures for feed composition, mortality, by-product utilization and distribution by ship to the market have the highest reduction potential in terms of GHG emissions. Costs are measured qualitatively by considering reference literature and comments from the reference group.

It is important to note that both assumptions and methodology used for evaluating the measures are important for the outcome of the analysis, and these are further presented and discussed in section 5 and section 7.

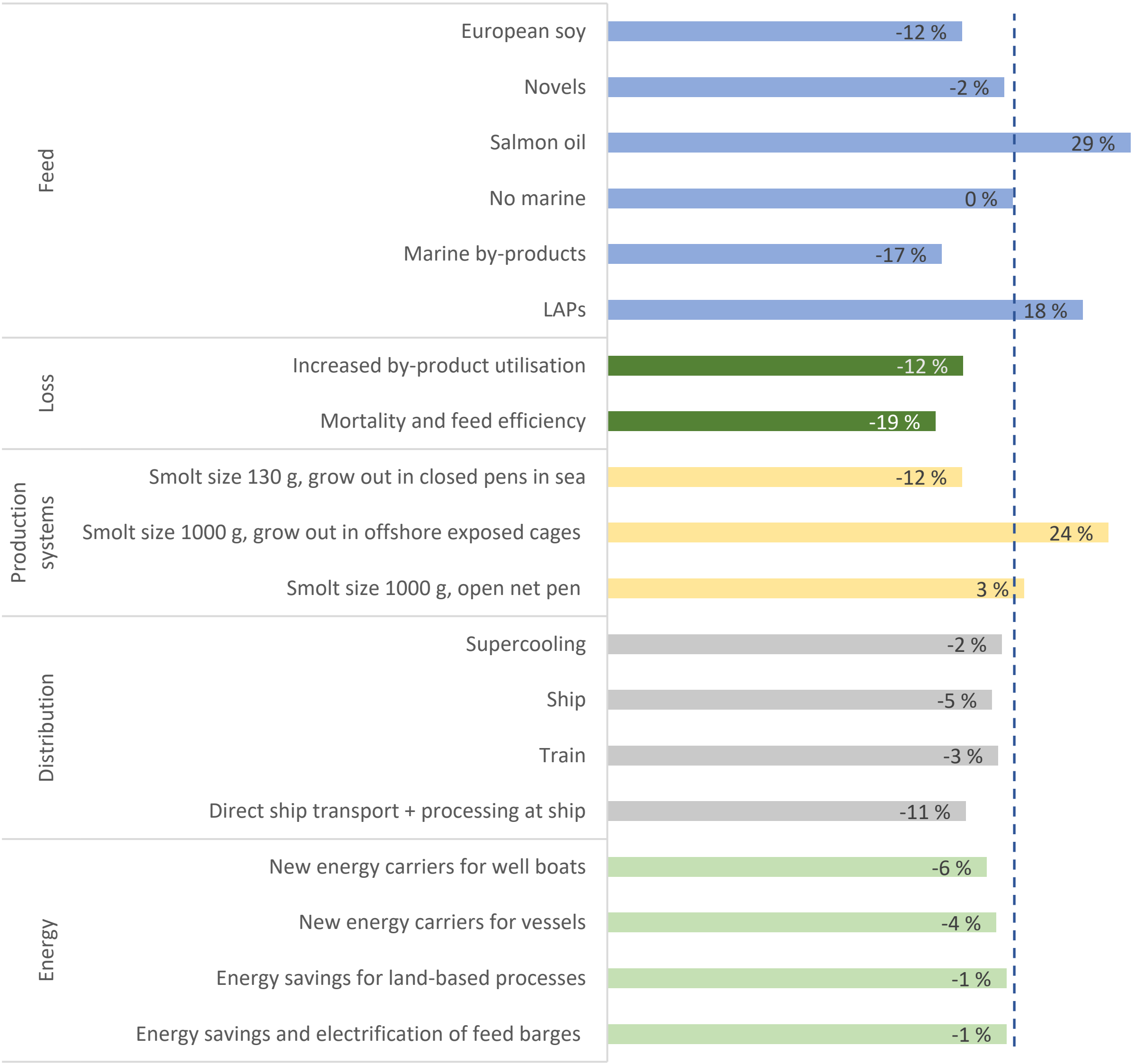

Figure 6-14 Changes in carbon footprint for fresh HOG in Paris (product 1, kg CO_2e per kg edible at wholesaler) for different measures compared to base case (dashed line, 5 kg CO_2e per kg edible at wholesaler)

Table 6-3 GHG effect and costs of implementing measure

Main category	Measure	# Measure	% effect on GHG emissions per kg edible at wholesaler	Short-term	Long-term	Costs (qualitative measure -10 / +10)
Feed	LAPs	1	18%	x		0
	Marine by-products	2	-17%	x		3
	No marine	3	0%	x		0
	Salmon oil	4	29%	x		-1
	Novel feeds	5	-2%	x		1
	European soy	6	-12%	x		0
Loss	Mortality and feed efficiency	7	-19%		x	NA
	By-product utilisation	8	-12%	x		NA
Production systems	Increased smolt size	9	3%	x		-9
	Increased smolt size and offshore exposed	10	24%	x		8
	Smolt size as today and closed pens	11	-12%	x		10
Distribution	Direct ship transport and processing at ship	12	-11%	x		0
	Train	13	-3%	x		0
	Ship	14	-5%	x		0
	Supercooling	15	-2%	x		-1
Energy	Energy savings and electrification of feed barges	16	-1%	x		0
	Energy savings for land-based processes (juvenile production in RAS, harvest plant)	17	-1%	x		0
	New energy carriers for vessels	18	-4%	x		0
	New energy carriers for vessels (well boats)	19	-6%		X	NA

Feed

Measures for feed were evaluated as five scenarios for how feed composition can change. The diets are delivered by a feed supplier. The scenario name describes the first change that is done, but as a consequence the composition of other ingredients are changed subsequently. The changes in carbon footprint may therefore be a result of different changes.

The scenarios named “Marine by-products”, “Novel feeds” and “European soy” are evaluated to reduce the carbon footprint of the feed.

The scenario “LAP”, which introduces by-products from poultry, and “Salmon oil” both increases the CF of feed, as the results are calculated using allocation by mass. If economic allocation had been used, the CF of the feed would have been decreased also in these scenarios (with the market values for co-products in poultry production as per today).

Costs of each scenario for changes in feed composition were evaluated by the feed producer based on today’s market values. Costs were given as %-change from today’s feed price. On average the feed cost represents a major proportion of the total costs for an aquaculture producer, thus changes in the feed price will have a large impact on the total production costs of salmon. Using "Marine by-products" is expected to have large impact on production costs for the feed supplier and the following price, while the "Novel feeds" scenario will have small effects on price and cost for the producer. The “LAPs” scenario will only have minor effects on costs, and "No marine" and the "Salmon oil" scenario reduces the feed price level. For the "European soy" scenario we expect the feed price to in line with the price of the Brazilian soy, thus no changes in costs are expected in this scenario.

Loss

Improving feed efficiency and reducing mortality, full utilisation of by-products and decreasing losses all along the value chain to the end consumer are all important measures for lowering the carbon footprint. Losses along the value chain cannot be compared against the other measures but are as illustrated for the case.

Costs of improving feed efficiency and reducing mortality are hard to measure. These measures are considered as measures with effects on a longer time horizon, and therefore not considered in the cost evaluation of the measures.

Production systems

Changes in production systems, by increasing smolt size and grow-out in either closed systems or exposed offshore systems are evaluated to increase the carbon footprint slightly, despite an assumed improvement in eFCR from 1.3 to 0.9 due to an assumed reduction in mortality. Shortly summarized, the increase in energy costs (for land-based production) and increased investments in infrastructure compared to today’s open net-pens outweighs the improved feed efficiency. In this assessment, vessel operations had to be assumed equal, in lack of better data on how this is changes when grow-out happens either in a closed system fairly close to the shore or in exposed systems further away from the coast. The need for lice treatment related operations will be reduced for closed systems while it can be assumed that longer distances for exposed systems will result in increased energy use for the vessels.

The cost estimates for the different production systems is based on the estimates given by Lie et al. (2021). They estimate the current value of the improvement measures i. e. different production systems compared to traditional production systems. Production cost of one kg salmon was estimated to 34.67 NOK pr. kg in the base case. The cost of having smolt size of 1000 g is estimated to 31.60 NOK pr. kg salmon. In this case it is economically beneficial to implement the measure to increase smolt size for salmon producers. The marginal cost is positive at 41.7 NOK. Grow out farming in offshore cages is expected to be more expensive than traditional production in terms of investment costs but not in operating costs. The marginal cost is set to net –43.3 kroner. Grow out in offshore cages is therefore less economically beneficial production system both in terms of investment and production by comparing these economic numbers with changes in GHG emissions of farmgate salmon. The marginal cost is set to net -222.6 kroner for this production system.

Distribution

All measures for transport are evaluated to decrease the carbon footprint per kg product delivered to Paris. Transport by ship is evaluated as the most effective measure. Processing on ship and transport on the same vessel directly to the market is shown as the measure that can reduce GHG emissions the most. This is because it is assumed that by direct processing and transport on a processing vessel, the fuel use for well boat will be lower as one can avoid transport to a slaughter facility. It is assumed that all other consumption values related to the processing is equivalent to a slaughtering/processing facility on land, with the exception that the energy required is delivered by a diesel aggregate. The rest of the fuel use is assumed to be equal of the vessels transporting fish to the market.

It is assumed that there is no need to make large investments for aquaculture producers for the improvement measures focusing on alternative transport. In the case of rail freight disadvantage costs for the consumers may be apparent because of the uncertainty associated with train transport and transport time to the market which could in turn compromise the quality of the salmon product. Also, capacity constraints on the train network may lead to enormous investments costs for Norway as a society.

Energy

The measures include new energy carriers for vessels (battery, ammonia, hydrogen), energy efficiency and electrification and energy savings for feed barges. As well boats and other vessels account for the largest share of the carbon footprint, these measures have the largest potential for reduction.

The data on costs associated with the improvement measures on energy is based on data from Nistad et al. (2021). Electrification of feed barges on onshore power projects that has received ENOVA support investment cost has varied from NOK 1 to 9 million, with an average of NOK 3 million. For new energy carriers for vessels it is reported there is a need of 30-60 % higher investment costs for the boats that have been built with electric operation (Arntzen Nistad et al. 2021). All energy efficiency and energy carriers reported here have some initial investment costs due to shift from current technology to new. The operating cost after implementation of the measure will depend on the relative price of the energy carriers to determine if higher costs will occur or not. Additional disadvantage costs for the user of the product are not relevant here. The measure of new energy carriers for well boats are also hard to quantify with costs and considered more as a measure for the long run.

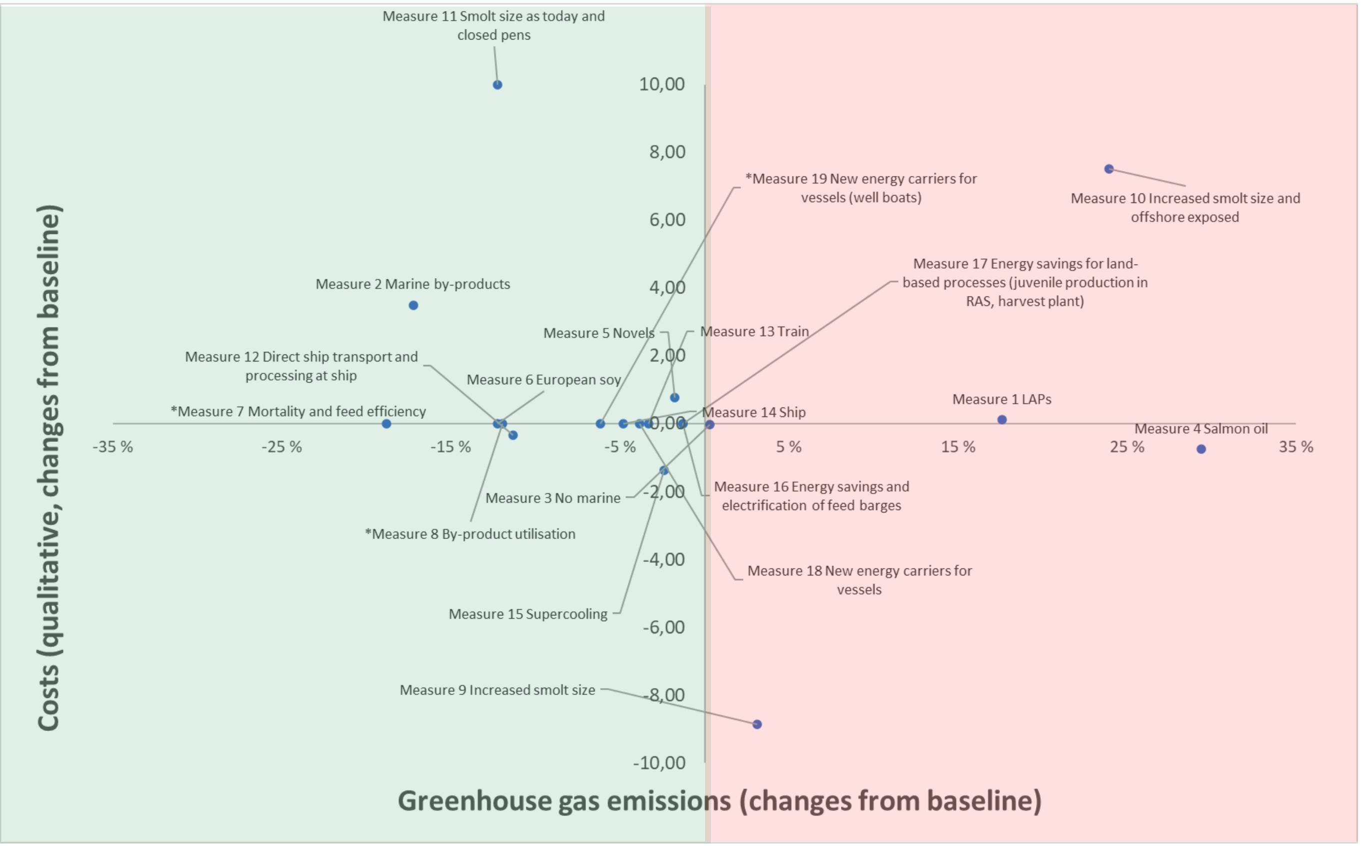

Figure 6-15 Combined GHG and cost effect for measures evaluated. Positive values are associated with higher emissions and costs compared to baseline, while negative are lower values compared to a baseline. Measures with * have not been evaluated with a cost level but included in the figure with a zero-cost level. Green area in the graph shows the measures that have a negative GHG effect while red area shows the measures that has positive GHG effect.

6.5 Analysis over time

The simplified method developed in the previous assessment for Norwegian seafood products (Winther et al. 2020) has been used to evaluate changes in carbon footprint of farmgate salmon over time. Figure 6-16 shows the development of the key parameters for the industry, including the carbon footprint. Emissions appear to have decreased since 2010, mainly because the carbon footprint of feed and reductions in eFCR. In the last years (2017 and 2021), the eFCR has again increased. In 2017, the carbon footprint was only slightly increased, despite a higher eFCR, compared to the previous years. This was due to a reduction in GHG emissions of the feed and of other inputs. In 2021, the eFCR was stable compared to 2017, but the GHG emissions of salmon decreased due to lower GHG emissions of the feed. The changes in feed in 2021 compared to 2017 are discussed in section 6.2.1 and section 7.

The changes in feed composition between 2017 and 2021 happened mainly within rather than between the feed input groups defined in Ziegler et al. (2021). Applying the simplified method suggested in Winther et al. (2020) and developed further in Ziegler et al. (2021) means assuming that the feed input groups are composed as in the most recent version and then simply applying the feed conversion ratio and the composition of the feed input groups. This obviously represents a tradeoff between simplicity and accuracy. Since important changes were observed in the crop protein group, a switch from soy to other plant proteins, it was decided that the simplified method needed to be adjusted. SPC was separated from other crop proteins, and was modelled based on data on soy content in 2007, 2012, 2013, 2017 and 2021.

The upscaling factor to go from feed-related to total farmgate-GHG emissions for salmon was adjusted based on the current results, with 75% of the carbon footprint caused by feed and the factor increased from 1.2 to 1.3.

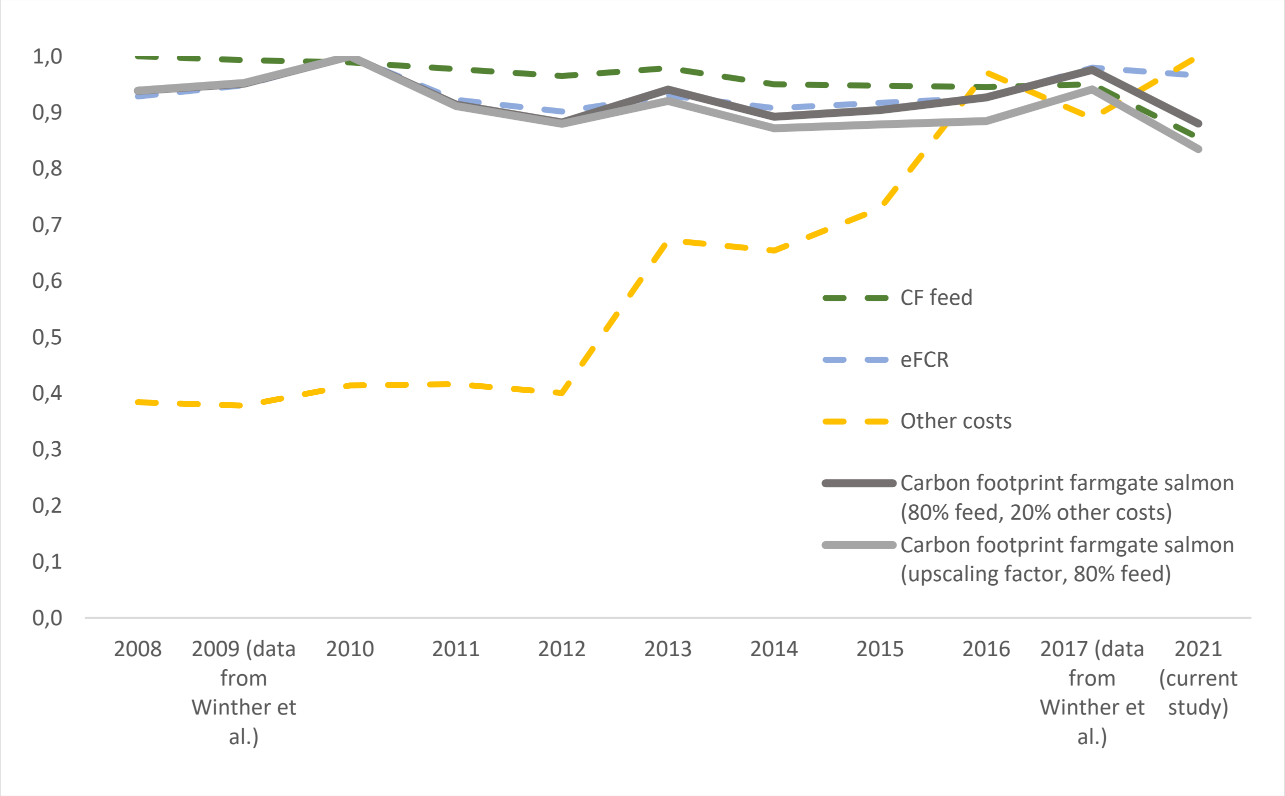

Figure 6-16 Development for key parameters and greenhouse gas emissions of salmon at slaughter 2008 to 2021. All values are normalized against the highest value during the period.

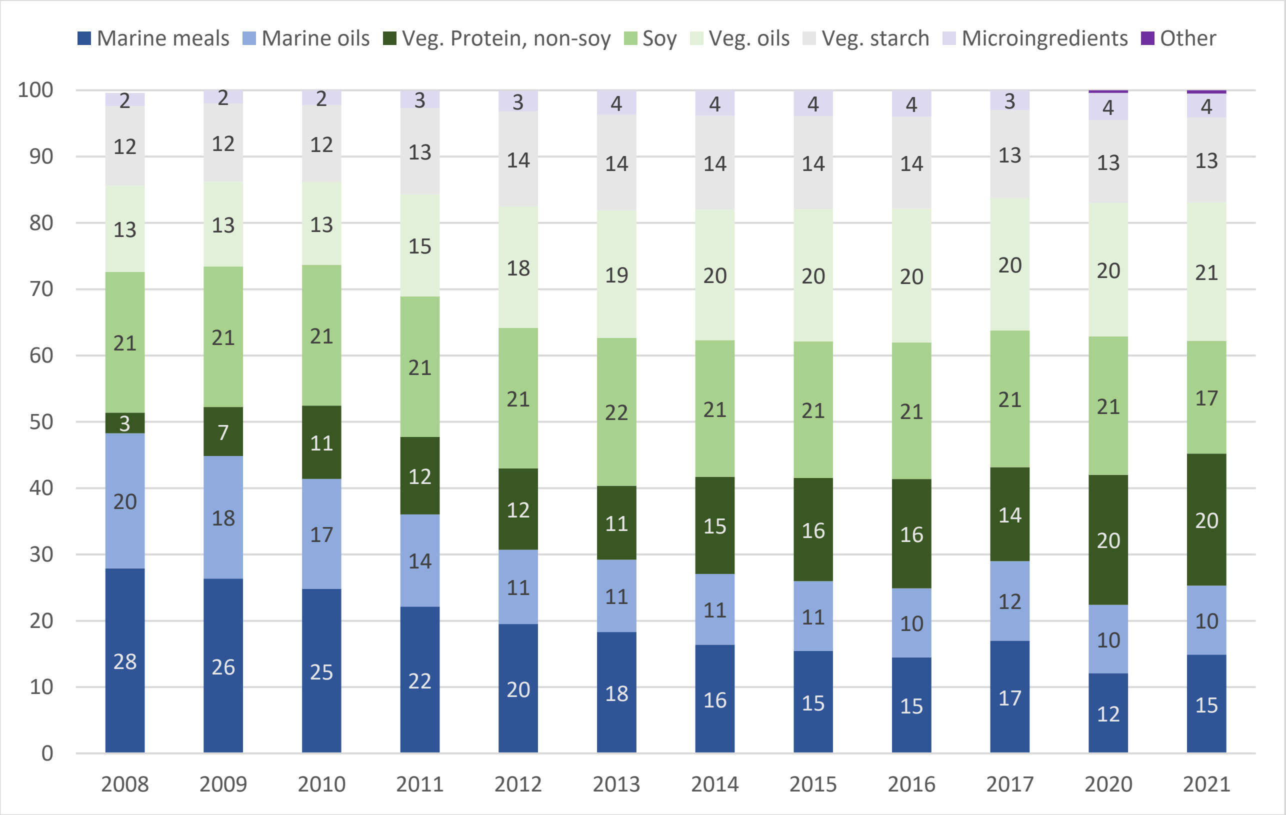

Figure 6-17 Changes in composition in main feed groups from 2008 to 2018. Data from Aas et al., (2022) and Ziegler et al., (2021)

6.6 Data quality assessment

The data quality is assessed according to the framework presented in the PEF method (Zampori & Pant, 2019), as well as ISO 14044 section 4.2.3.6.2 (ISO, 2022b). Data quality is addressed based on the scoring from the PEF method, which include *excellent*, *very good*, *good*, *fair* and *poor*. Completeness and methodological appropriateness and consistency are evaluated according to yes/no.

Table 6-4 Assessment of data quality.

Data quality criteria	Assessment	Comments
Completeness Quantification shall include all environmentally relevant material/energy flows and other environmental interventions as required for adherence to the defined system boundary, the data requirements, and the impact assessment methods employed. Percentage of flow that is measured/estimated.	Yes	All main material flows and energy flows are included in the assessment. Where disregarded, an evaluation of the contribution to the overall carbon footprint is performed. EEIO-method is used to evaluate the exclusion of services and investments by process-based LCA. Results from this analysis indicate that the exclusion of these flows in process based LCA have minor impact on results. Yet, economic data for these flows are based on a single year, from two companies. Including multiple years and more companies are needed to make a robust conclusion.

Methodological appropriateness and consistency *Whether methods are applied uniformly to the various components in the analysis*	Yes	The analysis is performed by experienced, trained LCA-practitioners and researchers. Methodological choices are critically evaluated and transparent documented in section 2. Methods for allocation, inclusion of land use change emissions and waste treatment are consistently modelled throughout the analysis. Allocation methods are applied to all processes consistently, except for a few processes where data for both mass and economic allocation is not available.
Geographical representativeness *Geographical area from which data for unit processes should be collected to satisfy goal of study*	Very good	Foreground system: Data collected describes the production in the Norwegian aquaculture sector. Specific data is collected for all relevant inputs from producers representing a large share of production in the industry. For feed, data was collected from all feed producers. Scenarios for distribution describes plausible alternatives for the selected markets. Best available information is retrieved regarding by-product utilisation in markets (BUiM), however, these data are associated with moderate uncertainty. Background data: ecoinvent, Agrifootprint and NTM are the databases used. Inputs are mainly modelled using market processes, which represents the average European market. Geographic representativeness is especially critical for feed inputs where there is large variation between the production of the same feed ingredient based on production location. Data from feed suppliers were to a large degree tagged with origin of feed ingredients. Region specific data from Agrifootprint and datasets for fishing were used were appropriate. For others, where specific data on origin were not available or evaluated to not be important for the outcome of the analysis, market mixes for Europe were used.
Technological representativeness *Specific technology or technology mix*	Very good	Technological representativeness may be described in two ways; representativeness of the raw material input, and representativeness of data used for production. Regarding raw material input generic data is used where technology specific information is not available or important for the outcome of the analysis. Technology specific information is used for fuel use in fishing and production of marine feed ingredients. The representativeness is considered to be good/very good. For production the technological representativeness is regarded as excellent/very good, as detailed information were gathered and included in the model based on the in-depth knowledge and information about common practices in the Norwegian aquaculture industry today. The reference group was used to review representativeness regarding technology and common practice.
Temporal representativeness	Very good	Specific data is collected for the three last years (2019-2021). Where considered relevant, the average of three years is used.

Age of data and the min length of time over data should be collected		In cases where one year was considered to have better data than other, a single year is used. For example: feed ingredient composition (2021), fuel use and energy use for boats and feed barges (2019-2020). Some data from the carbon footprint assessment of Norwegian seafood products in 2017 was used, in these cases it was evaluated that no better data has become available since. The age of generic and specific data is within a 10- and 3-year cut-off respectively.

7 Discussion

Main results

Greenhouse gas emissions of Norwegian farmed salmon products in 2021 were between 4.8 and 28 kg of CO_2e/kg edible salmon at wholesaler. In terms of important emission drivers, the results confirm previous findings. When airfreight is involved it dominates emissions, irrespective of market, distance, product form and type of airfreight (belly or dedicated freight). In the previous reports (Winther et al. 2009, 2020) only one case of airfreight was included (gutted salmon to Tokyo) while here five airfreighted supply chains of both gutted salmon and salmon fillet were modelled both to North American and Asian markets. The conclusion about airfreight as an emission hotspot is valid for all five cases and although slight improvements of airfreighting are possible (e.g. by using dedicated airfreight rather than belly freight and avoiding stopovers and empty inflights and returns) the main improvement potential is to use other means of transport. If limited shelf-life of fresh products makes that non-feasible shifting towards products with a longer shelf-life (e.g. frozen products), which allows slower transportation would be beneficial. Excluding the airfreighted products, the other products were all between 4.8 and 5.7 kg CO_2e/kg, even when shipped to Shanghai (product 5). The by-product use after export is important and a low utilization translates into higher emissions per kg edible salmon, which is why increased by-product utilization represents an important improvement option.

Feed composition and modelling

After airfreight feed production is the main impact driver and up to the farmgate, it dominates emissions (representing 75% of total farmgate emissions). The feed composition has changed slightly between 2017 and 2021, the inclusion of soy has been reduced and instead other plant proteins have increased. The inclusion of marine inputs was similar and the proportion of these that originated in trimmings was lower than before. The data for yield of oil and meal from ensilage was updated based on new data from the Norwegian industry, which lead to a lower carbon footprint of marine ingredients from trimmings. Microingredient inclusion has increased slightly and their composition changed with lower inclusion of astaxanthin, previously identified as a high-emission feed input. The inclusion of astaxanthin in Winther et al. (2020) was overestimated due to a misinterpretation of the data. Salmon oil, made from salmon trimmings. also had a high impact previously and was used to a very limited degree in Norwegian salmon feeds in 2021 and is not shown in the feed mix. In this study higher inclusion of salmon oil was modelled as an improvement measure, however, it turned out to lead to a considerable increase in emissions, but that result depended on the choice of allocation method.

In addition to lower inclusion. soy protein was in 2021 to a larger extent sourced from other regions than South America (Europe and US) but with the current geopolitical events. a certain backlash is likely to happen. at least temporarily. On the long-term. it is important that capacity for both production and processing of protein crops like soy is increased in Europe increases to avoid the expansion of agricultural land in countries like Brazil and Argentina to fulfil European needs. European and US soy has considerably lower emissions due to less land use change taking place in these countries. However, also the emissions of Brazilian soy are lower today according to the updated data that was used in the model which adds lower land use change emissions of about 19% lower. Prices of soyabean meal and oil have also changed and more impacts are arrtibuted to soya meal compared to last time. Also emissions of other protein crops like broad/horse beans and pea protein and the main crop-based lipid used rapeseed oil have been significantly reduced in recent version of AgriFootprint. Altogether these changes in feed composition and feed input LCI data leads to a lower footprint of the feed and, due to the importance of the feed, also for farmgate salmon than reported in 2020.

It has been a long discussion whether or not certified soy from Brazil should be counted as free from land use change or not. The arguments for are that producers and buyers are trying to improve the situation in Brazil by creating demand for soy from land that was not deforested or converted from other land use after 2008, the reference year of the ProTerra standard widely used in soy sourced for Norwegian salmon feeds.

More than 95% of the Brazilian soy used was certified by a standard. The arguments against counting it as free are 1) that the time horizon is too short and that consumers would not agree that land that was deforested in 2007 should count as deforestation free and 2) that increased demand for soy (certified or not) will lead to expansion of the area farmed with frontiers moving into ecosystems. To avoid going too far into that discussion. to which there is no objective answer results were presented with and without LUC with a gradient between the two. If land use change emissions had been excluded fully or partly in the base case, farmgate emissions would have been around 25% lower (Fig 4-6). When a higher data resolution is available, in terms of origin of Brazilian soy by state or municipality, which robustly can justify accounting the crops as free from land use change, this diversity could be taken into account applying e.g. the BRLUC model (Garofalo et al., 2022). At this point, however, the data resolution does not allow this kind of fine-tuned assessment.

Sensitivity analysis

The sensitivity analysis showed that the method for accounting for land use change has a large influence on results and emissions of farmgate salmon would be around 25% lower if the soy was accounted for as not causing any land use change. Except, land use change, another highly debated topic in LCA methodology is how to split environmental burden between co-products- allocation. The sensitivity analysis on economic allocation showed that this has a major influence on results, emissions of the studied supply chains increased to 11-34 kg CO_2e/kg edible salmon at wholesaler, mainly because a larger portion of upstream impacts was placed on the fillet compared to the by-products. It should be mentioned that adding this economic layer is an additional task that requires more data collection and adds uncertainty. Prices of food and feed resources are always volatile, but have lately increased rapidly in unpredictable and non-linear ways. Using economic allocation. the results. conclusions and recommended improvement options will depend on such values, which is particularly problematic when monitoring performance over time. A change in relative prices between main and by-product will result in an improvement in environmental performance of a product or co-product without any change in resource use of the supply chain.

Comparison over time

Monitoring performance over time is challenging. Impact assessment methods (i.e. IPCC indicators for different greenhouse gases) change over time, as well as smaller or larger other methodological details of each study and therefore, it is rarely possible to take two reports of the same or different products and simply comparing them. It is more relevant to identify key input data and compare these, or use these to calculate comparable results, as done in the simplified method. The method shows a reasonably stable footprint of farmed salmon, with a slight reduction since 2017.

Input-Output analysis

Compared to Hognes et al., (2011); Winther et al., (2009) and Ziegler et al., (2021), this the first time a hybrid LCA approach has been applied to these analyses for Norwegian seafood products. To challenge the system boundaries of the LCA inventory, an input-output approach was applied to estimate the additional GHG emissions from purchases of services and investments based on economic data, which may give important contributions total emissions (Ward et al., 2018, Agez et al., 2020). The results show that although service inputs represent about 7% of all purchases from aquaculture producers, they represent less than 1% of the GHG emissions of farmgate salmon. The most interesting findings from these numbers is that we do not need to speculate whether there are any unaccounted emissions in the LCA. This analysis splits the data on service purchases and leave the remaining emissions to be considered by LCA data. However, more sensitivity on the where the separation between LCA and the MRIO model should be placed, to limit the truncation error in the LCA, are welcome for future analyses to investigate.

Improvement measures

The evaluation of the different improvement measures shows that they affect the GHG emissions both positively and negatively compared to the base case. The measures on board processing and distribution by ship show a reduction in the carbon footprint as these modes of transport have lower emissions than road transport to the same destination. Using alternative energy sources like hydrogen, battery and ammonia on service vessels and well boats also leads to emission reductions. On the other hand, the improvement measures for larger smolt size and farming in exposed localities leads to higher emissions. These measures are evaluated based on several factors including mortality, infrastructure, energy source and energy demand that all affect both the cost and the emissions. Larger smolt produced on land has a higher energy and infrastructure demand compared to the regular smolt as it spends more time on land where energy intensive Recirculating aquaculture systems (RAS). The infrastructure requirement for exposed cages is also large, which explains the higher emissions. The use of a large amount of steel in particular increases the emissions from infrastructure. The lifetime of the infrastructure is an important parameter for the outcome of this analysis, the longer the lifetime, the lower the carbon footprint will be. The lifetime of exposed cages was estimated as 25 years and 10 years of that of closed systems, but it is possible that facilities can be used longer than that. closed systems that have a higher share of emissions from infrastructure compared to open net pens show a significant reduction in emissions only when the energy is from renewable sources in comparison to the energy from EU electricity grid (Fig 4-6). Hence the source of energy too in addition to the lifetime, is an important factor that will determine the improvement potential of several measures.

Switching the feed composition from Brazilian soy to European, provides a huge emission cut, without affecting the costs according to the feed producers. The feed measure on marine by-products also provides large emission cuts (mainly from reducing soy) but implies large cost increases. On the distribution side particularly shipping the products directly including processing at sea has a high potential to reduce emissions without necessarily leading to higher costs. The rest of the measures on distribution also leads to large emission reductions with no expected cost increases. For the energy savings measures there are emission reduction opportunities in all case, against without necessarily leading to higher costs. For example, new energy carries for service vessels give a high drop in emissions, and investments for this measure have a relatively short payment period. From the analyses undertaken, there seem to be plenty of opportunities for the industry to work on reducing the greenhouse gas emissions of farmed salmon, even without the need for major investments. Even if only implementing current “best practice” in terms of eFCR, energy source of feed barge, energy efficiency in juvenile production and by-product utilization, the greenhouse gas emissions of farmgate salmon would be 24% lower than the average in 2021.

Having said this,it should be noted that the carbon footprint and cost assessment of potential future production systems is simplified and based on crude estimates for production parameters. For eg. it is assumed that the vessel fuel use, both for smaller vessels and well boats, are similar as per today due to lack of data. Moreover, it is important to remember that only the carbon footprint is evaluated in this study, whereas the changes in production systems are largely motivated by other environmental aspects such as reducing escapees and lice. improving resource efficiency (N and P recycling) and reducing eutrophication and negative biotic impacts. These environmental aspects are not reflected in the evaluation of GHG emissions only and an environmental footprint in contrast to carbon footprint must be conducted in the future to compare the overall effects of the improvement measures. It can also be argued that in practice, implementation of the reduction measures depends on many factors like technology readiness for onboard processing, availability of marine by-products and European soy, reconstruction of vessels to new energy carriers and consumer demand.

In this project, as well as in previous projects, it has been a goal to include trout products and considerable effort was spent on trying to disentangle statistics and resource use for salmon and trout. But as the feed producers were unable to specify differences between trout and salmon feed, and official statistics on feed use and edible yield do not differentiate between the two species, it had to be concluded that it is not possible to assess them separately at this point.

Acknowledgements

We are most grateful to all the fish farmers, equipment producers and industry representatives in various positions in the Norwegian seafood industry, who spent time and effort on finding data and make the best assumptions. Sofie Møller from Asplan Viak for her contribution to the modelling and calculation of the results. Ulf Winther was also a part of the project and contributed during the start phase before he retired. The reference group and external reviewer of the project have provided very useful feedback and questions all along the way which helped improve the outcome of the work. Finally, we are grateful to the Norwegian Seafood Research Fund (FHF) or funding the work for the third time.

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A APPENDIX - Additional Data Sources

Table 0-1 Composition of salmon feed per ingredient with source of LCA data used indicated (AFP= AgriFootprint v6. AB=Agribalyse v3. WFD= World Food Database. EI = Ecoinvent v.3.8) Country-specific versions of the processes were used (e.g. for sunflower protein) to represent flows when the country of origin was known and the more general process (market mix) stated below when the specific origin was not known.

Table 0-1 Separation of marine feed inputs into proteins and oils from targeted reduction fisheries and from fish processing trimmings

Ingredient group	Ingredient	Volume (tonne)	Fuel use (l/tonne)	Data source for fuel use	Yield (kg/1000 kg of raw material processed) Data source Winther et al.
Marine oil - Trimmings 2%	Atlantic cod (*Gadus morhua*)	435	189	Winther et al. (2020)	87
	Atlantic herring *(Clupea harengus)*	26275	86	Winther et al. (2020)	87
	Whitefish mix	4747	189	Winther et al. 2020	87
Marine oil - Reduction fishery 8%	Anchoveta – Peruvian (*Engraulis ringens*)	15968	18	Cashion et al., (2017)	50
	Anchovy (*Engraulis encrasicolus*)	11172	18	Cashion et al., (2017)	50

	Blue whiting (*Micromesistius poutassou)*	1528	93	Winther et al. (2020)	19
	Atlantic herring *(Clupea harengus)*	8408	86	Winther et al. (2020)	110
	Atlantic horse mackerel (*Trachurus trachurus)*	180	270	Iribarren et al., (2010)	70
	Atlantic mackerel (*Scomber scombrus*)	258	88	Winther et al. 2020	186
	Gulf menhaden (*Brevoortia patronus)*	47631	37	Cashion et al., (2017)	160
	Norway pout (*Trisopterus esmarkii*)	5239	75	Winther et al. 2020	115
	Sandeel (*Ammodytes sp.*)	8271	84	Winther et al. 2020	42.4
	Chilean sardine (*Strangomera bentincki*)	4386	18	Cashion et al., (2017)	42.4
	European pilchard (*Sardina pilchardus*) "Sardine"	2657	18	Cashion 2017	42.4
	European sprat (*Sprattus sprattus*)	12869	93	Winther et al. 2020	79
	Unknown	44542			
Marine protein - Trimmings 5%	Capelin (*Mallotus villosus*)	1019	93	Winther et al. 2020	165
	Atlantic cod (*Gadus morhua*)	1982	189	Winther et al. 2020	380
	Atlantic herring *(Clupea harengus)*	34651	86	Winther et al. 2020	380
	Unknown	23947	NA		
	Whitefish mix	30928	189	Winther et al. 2020	380
Marine protein - Reduction fishery 10%	Anchoveta – Peruvian (*Engraulis ringens*)	13870	18	Cashion 2017	240
	Anchovy (*Engraulis encrasicolus*)	4673	18	Cashion 2017	240
	Blue whiting (*Micromesistius poutassou*)	38559	93	Winther et al. 2020	197
	Capelin (*Mallotus villosus*)	1245	93	Winther et al. 2020	
	Atlantic herring *(Clupea harengus)*	7949	86	Winther et al. 2020	200
	Atlantic horse mackerel (*Trachurus trachurus)*	255	270	Iribarren 2010	230
	Krill/Calanus protein	9456	NA	NA	NA

	(*Euphausia superba/Calanus finmarchicus*)				
	Atlantic mackerel (*Scomber scombrus*)	849	88	Winther et al. 2020	194
	Gulf menhaden (*Brevoortia patronus*)	6660	37	Cashion 2017	210
	Norway pout (*Trisopterus esmarkii*)	11197	75	Winther et al. 2020	204
	Sandeel (*Ammodytes sp.*)	33052	84	Winther et al. 2020	197
	Chilean sardine (*Strangomera bentincki*)	185	18	Cashion 2017	240
	European pilchard (*Sardina pilchardus*) "Sardine"	34	18	Cashion 2017	240
	Silver smelt *(Argentina sphyraena)*	32			240
	European sprat (*Sprattus sprattus*)	18740	93	Winther et al. 2020	188
	Unknown	54188			

Table 0-2 Overview of routes and transport from harvest plant to market. Distance data from NTM (NTM, 2022)

No.	Product	Market/ Destination	Road (km)	Sea (km)	Rail (km)	Air (km)
1	Salmon. fresh head-on gutted to Paris by Truck. By-product utilisation in market: 80%	Paris	2642	95		
2	Salmon. fresh head-on gutted to Oslo by Truck. By-product utilisation in market: 75%	Oslo	942			
3	Salmon. fresh head-on gutted to USA by Air (belly freighter). By-product utilisation in market: 40%	New York	942+1550	95+168		5716
4	Salmon. fresh head-on gutted to Tokyo by Air (freight aircraft). By-product utilisation in market: 50%	Tokyo	942			11686

5	Salmon. frozen head-on gutted to Shanghai by Ship and rail. By-product utilisation in market: 60%	Shanghai	50	1400+19630	200	
6	Salmon. fresh fillet (B trim) to Paris by Truck. By-product utilisation in market: 50%	Paris	2642	95		
7	Salmon. fresh fillet (B trim) to Germany by Truck. By-product utilisation in market: 60%	Germany	2740	95+320		
8	Salmon. fresh fillet (C trim) to South Korea by Air (belly freighter). By-product utilisation in market: 20%	South Korea	942			10674
9	Salmon. fresh fillet (C trim) to Tokyo by Air (freight aircraft). By-product utilisation in market: 40%	Tokyo	942			11673
10	Salmon. fresh fillet (C trim) to USA by Air (belly freighter). By-product utilisation in market: 25%	New York	942+1550	95+168		5716
11	Salmon. frozen fillet (C trim) to Paris by Truck. By-product utilisation in market: 0%	Paris	2642	95		

Table 0-3 Scenarios for changes in feed composition.

Feed ingredients	**As Is**	**Scenario A - LAPs**	**Scenario B - Marine By-products**	**Scenario C - No Marine**	**Scenario D - Salmon Oil**	**Scenario E - Novels**
Microingredients	3,6	3,6	4,7	5,6	3,6	3,6
Other	1,0	1,0	1,0	6,5	1,0	6,5
Camelina Oil	0,2	0,2	0,2	0,2	0,2	0,2
Corn gluten	0,2	0,2	0,2	5,0	0,2	0,2
Feather meal	0,0	5,0	0,0	0,0	0,0	0,0
Faba bean dehulled	4,9	4,9	4,9	4,9	4,9	4,9
Fish meal	14,2	14,2	14,2	0,0	14,2	14,2
Fish Oil	10,3	10,3	13,0	0,0	6,0	3,9
Guar meal	5,8	5,8	5,8	10,0	5,8	5,8

Linseed oil	0,6	0,6	0,6	0,6	0,6	0,6
Pea Protein Concentrate	1,6	0,0	0,0	0,0	1,6	1,6
Peas	2,6	2,6	2,6	2,6	2,6	2,6
Poultry meal	0,0	6,7	0,0	0,0	0,0	0,0
Lecithin	0,3	0,3	0,3	0,3	0,3	0,3
Rapeseed oil	19,8	18,8	14,6	24,9	14,7	23,5
Salmon oil	0,0	0,0	0,0	0,0	9,4	0,0
Soya oil	0,3	0,3	0,3	0,3	0,3	0,3
SPC	16,7	5,4	0,0	13,8	16,7	13,3
Sunflower meal	2,6	2,6	2,6	4,5	2,6	2,6
Wheat	5,8	7,4	14,7	5,8	5,8	6,4
Wheat gluten	9,5	10,0	20,3	15,0	9,5	9,5
Total	100	100	100	100	100	100
Share of fish meal - trimmings	35 %	35 %	100 %	35 %	100 %	35 %
Share of fish oil - trimmings	25 %	25 %	100 %	25 %	25 %	25 %

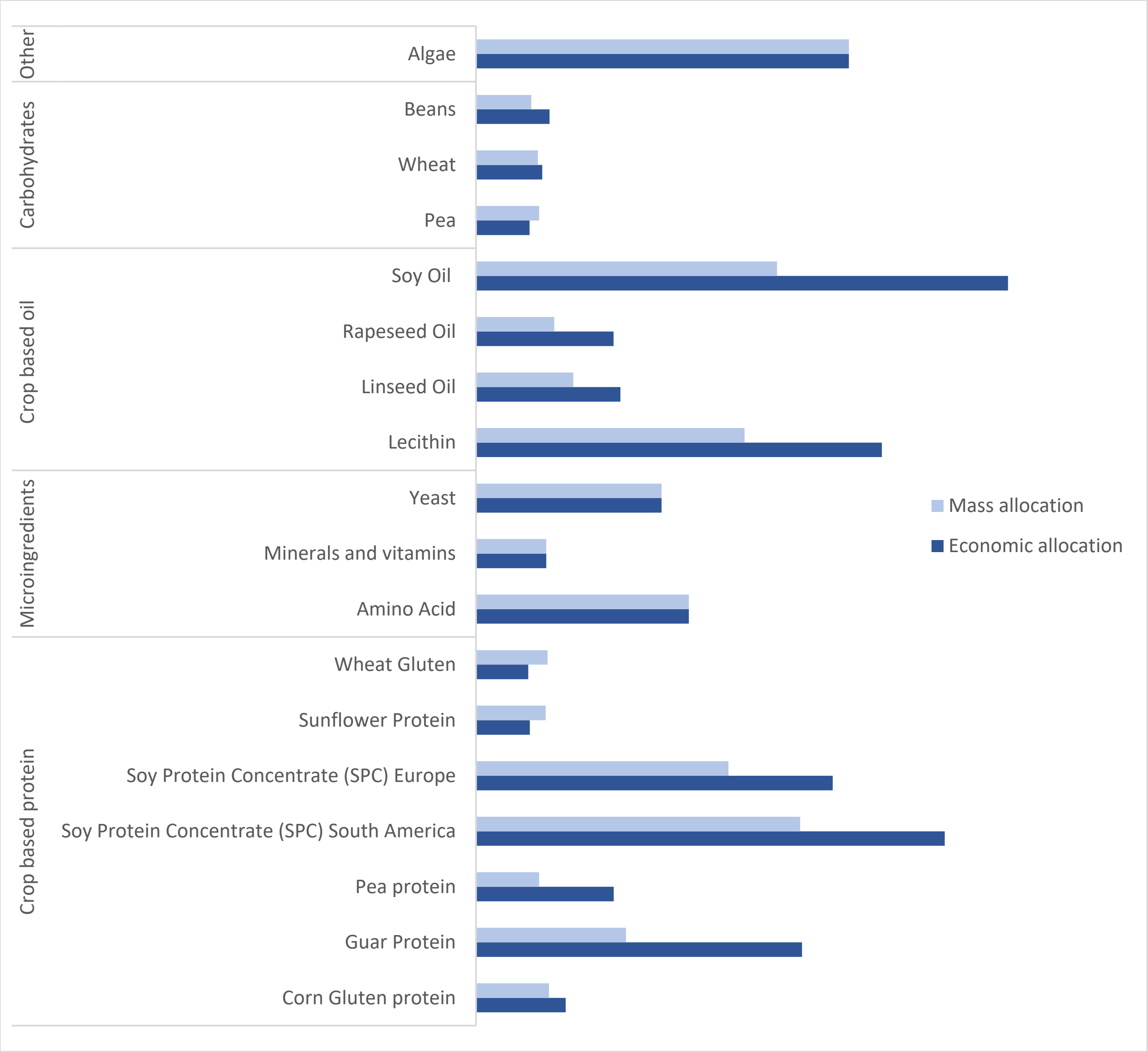


Figure 0-1 Relative greenhouse gas emissions per tonne non-marine feed ingredient (tonnes CO_2e/tonne feed ingredient at feed mill entry) presented relative to each other. Astaxanthin is not shown in the graph but is modelled with a carbon footprint 15 times higher than SPC and algae oil. Dark blue indicates economic allocation, light blue allocation by mass.

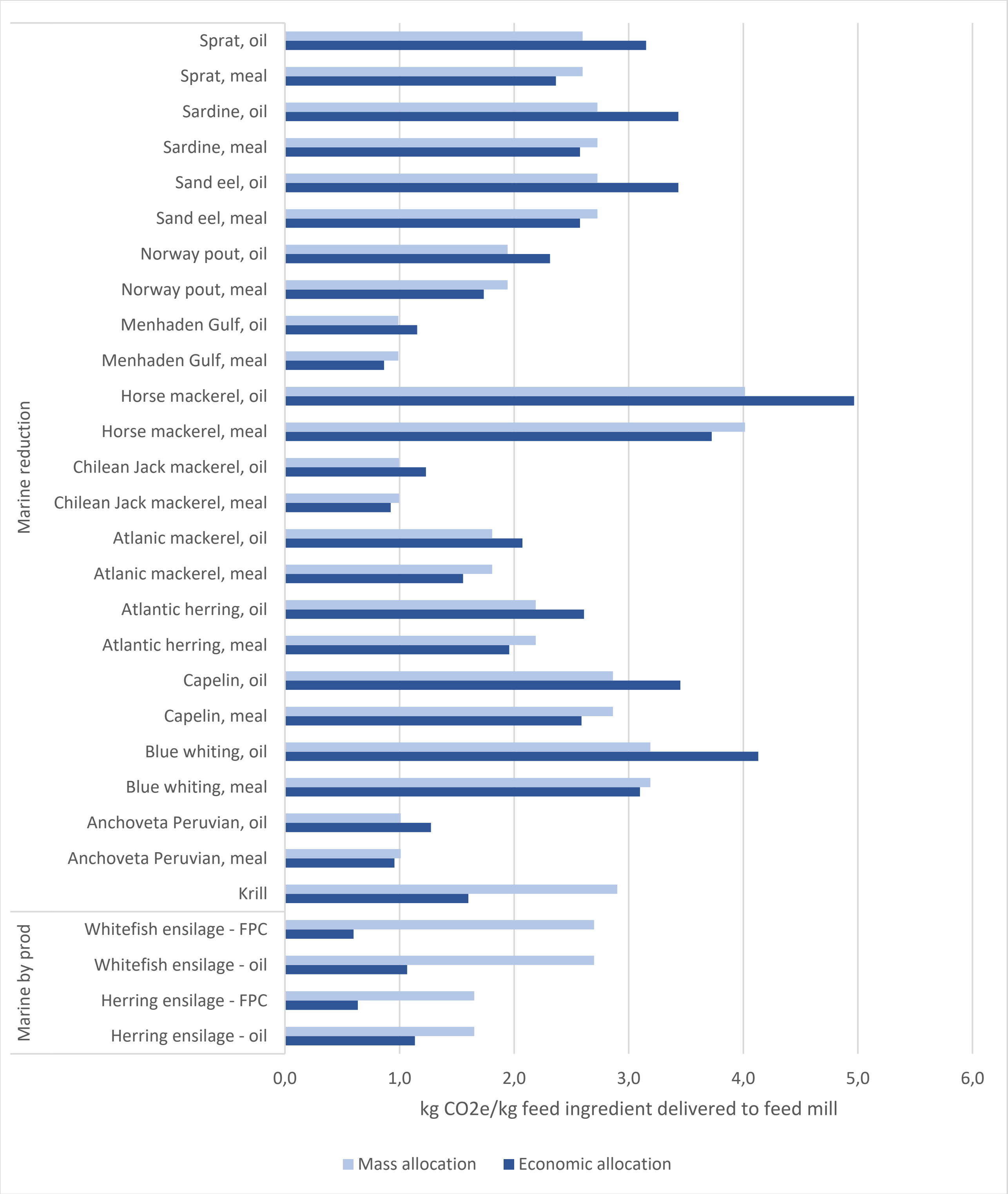
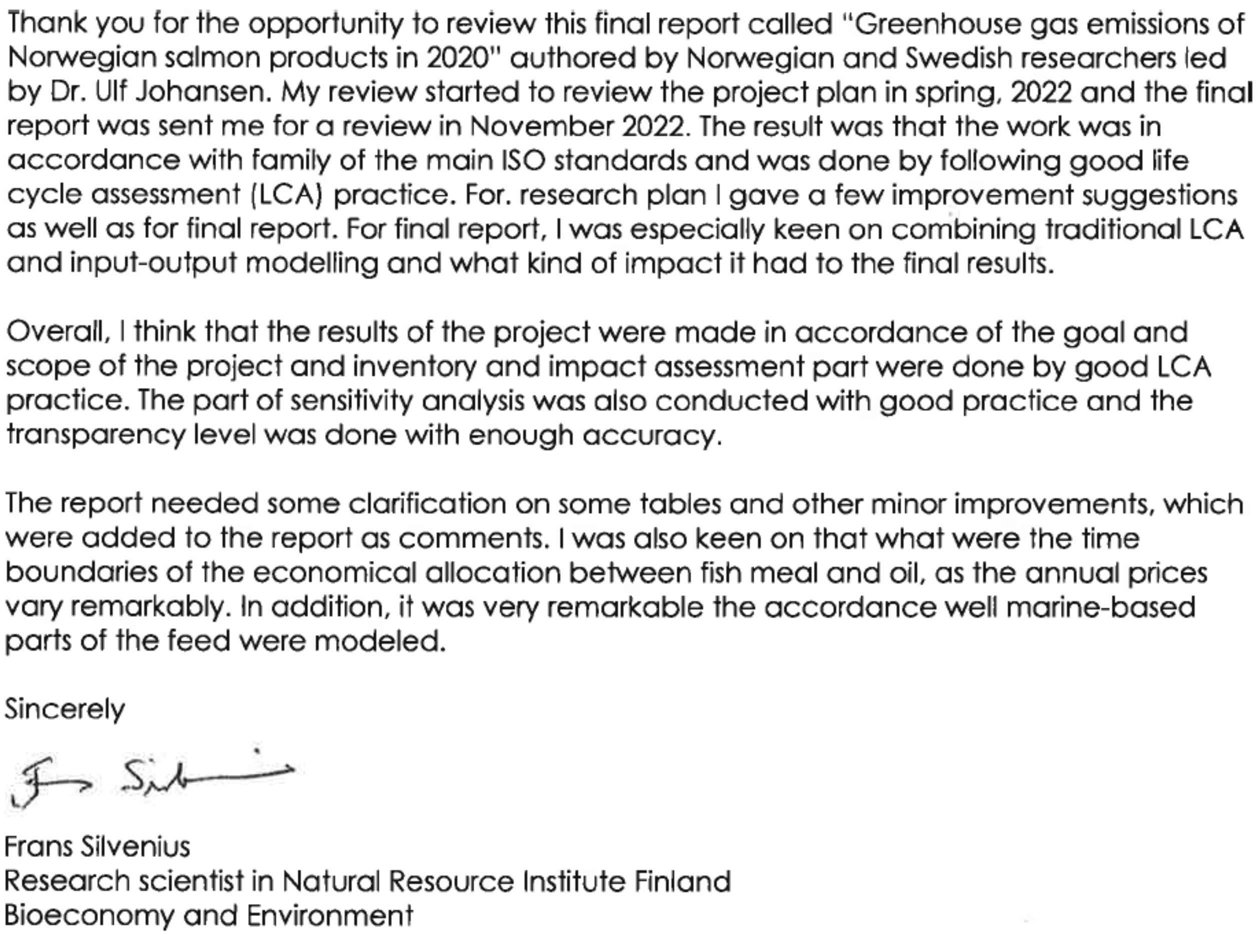


Figure 0-2 Greenhouse gas emissions per tonne marine feed ingredient (kg CO_2e/kg feed ingredient at feed mill entry).

B APPENDIX - External review



Thank you for the opportunity to review this final report called "Greenhouse gas emissions of Norwegian salmon products in 2020" authored by Norwegian and Swedish researchers led by Dr. Ulf Johansen. My review started to review the project plan in spring, 2022 and the final report was sent me for a review in November 2022. The result was that the work was in accordance with family of the main ISO standards and was done by following good life cycle assessment (LCA) practice. For. research plan I gave a few improvement suggestions as well as for final report. For final report, I was especially keen on combining traditional LCA and input-output modelling and what kind of impact it had to the final results.

Overall, I think that the results of the project were made in accordance of the goal and scope of the project and inventory and impact assessment part were done by good LCA practice. The part of sensitivity analysis was also conducted with good practice and the transparency level was done with enough accuracy.

The report needed some clarification on some tables and other minor improvements, which were added to the report as comments. I was also keen on that what were the time boundaries of the economical allocation between fish meal and oil, as the annual prices vary remarkably. In addition, it was very remarkable the accordance well marine-based parts of the feed were modeled.

Sincerely

Frans Silvenius
Research scientist in Natural Resource Institute Finland
Bioeconomy and Environment