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Report

Carbon footprint and area use of farmed Norwegian salmon

Author(s)
Erik Skontorp Hognes (SINTEF Fisheries and aquaculture)

Other authors
Friederike Ziegler and Veronica Sund (Swedish Institute for Food and Biotechnology, SIK)

SINTEF Fisheries and Aquaculture
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SINTEF

SINTEF Fiskeri og havbruk AS
SINTEF Fisheries and Aquaculture

Address:
Postboks 4762 Sluppen
NO-7465 Trondheim
NORWAY

Telephone:+47 40005350
Telefax:+47 93270701

fish@sintef.no
www.sintef.no/fisk
Enterprise /VAT No:
NO 980 478 270 MVA

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ABSTRACT

This report presents the carbon footprint and area use of Norwegian farmed salmon that is fed five different diets. It also compares the carbon footprint and occupation of agricultural land of Norwegian farmed salmon from 2010 with Swedish pig and chicken.

All results are calculated according to LCA methodology where the functional unit is 1 kg edible product and the system boundaries from fishing/growing of feed ingredients and until the products are at the farm gate.

A salmon that is fed the average Norwegian feed diet in 2010 has a carbon footprint of 2.6 kg CO_2e; it occupies 3.3 m^2 agricultural land and requires 115 m^2 of sea primary production area. Although only 40 % of the diet was of marine origin, the area needed to produce those inputs was much larger than the area used for farming. Results show that changes in the content of marine ingredients can change the final carbon footprint per kilo edible product with ± 7 %.

The comparison with pig and chicken concluded that salmon has the lowest carbon footprint and occupies least agricultural land. Even an almost "vegetarian" salmon can occupy less agricultural land than chicken. Pig had the highest carbon footprint and the highest occupation of agricultural land.

PREPARED BY Erik Skontorp Hognes	SIGNATURE Erik Skontorp Hognes
CHECKED BY Ingunn Marie Holmen	SIGNATURE Ingunn M Holmen
APPROVED BY Ulf Winther	SIGNATURE Ulf Winther

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APPENDICES

No Appendices

1 Introduction

This project is a delivery to Nofima AS to their project "Ressursregnskap og SWOT analyse fôrråvarer" (FHF prosjektnr 900568) and has been performed as a collaboration between SINTEF Fisheries and aquaculture, Trondheim, Norway, and the Swedish Institute for Food and Biotechnology (SIK), Gothenburg, Sweden.

The goal of this project is to calculate the carbon footprint (potential climate impact through greenhouse gas emissions) and area use to produce one kilo of Norwegian Salmon that is fed different diets. These results are compared to results from similar studies of Swedish pig and chicken production. The results will be used to study how changes in the salmon feed diet affect the results and to study how Life Cycle Assessment (LCA) can be used to evaluate the sustainability of salmon feed production.

2 Methodology

All results come from LCAs performed in accordance with the ISO standards for LCA (ISO, 2006a, ISO, 2006b). The chapter in this report follow the four iterative stages of an LCA illustrated in Figure 2-1. The basics of LCA methodology is not explained here. For a more detailed description of LCA methodology we recommend the book "The hitchhikers guide to LCA" (Baumann and Tillman, 2004) and "General guide for Life Cycle Assessment – Detailed guidance" by the European Commission Joint Research Centre (JRC-IES, 2010). The report "Carbon footprint and energy use of Norwegian seafood products" (Winther et al., 2009) gives a more thorough description of carbon footprint of seafood and references to articles etc.

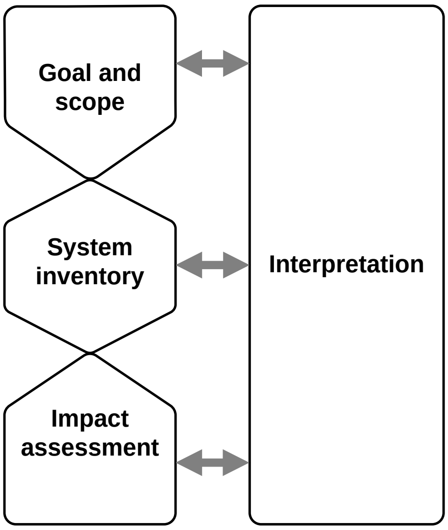

Figure 2-1 Iterative phases of LCA

2.1 Goal and scope

Functional unit

The functional unit of these analyses are 1 kilo edible product at farm gate.

System boundaries

These analyses include carbon footprint (referred to as the carbon footprint or greenhouse gas emissions of the products) and three types of resource use; occupation of agricultural area, requirement of sea-primary-production-area and cumulative energy demand.

The processes that are taken into account reach from production/catch of feed ingredients to animal ready for slaughter: From field and sea to farm gate. Figure 2-2 illustrates the system boundaries for the salmon.

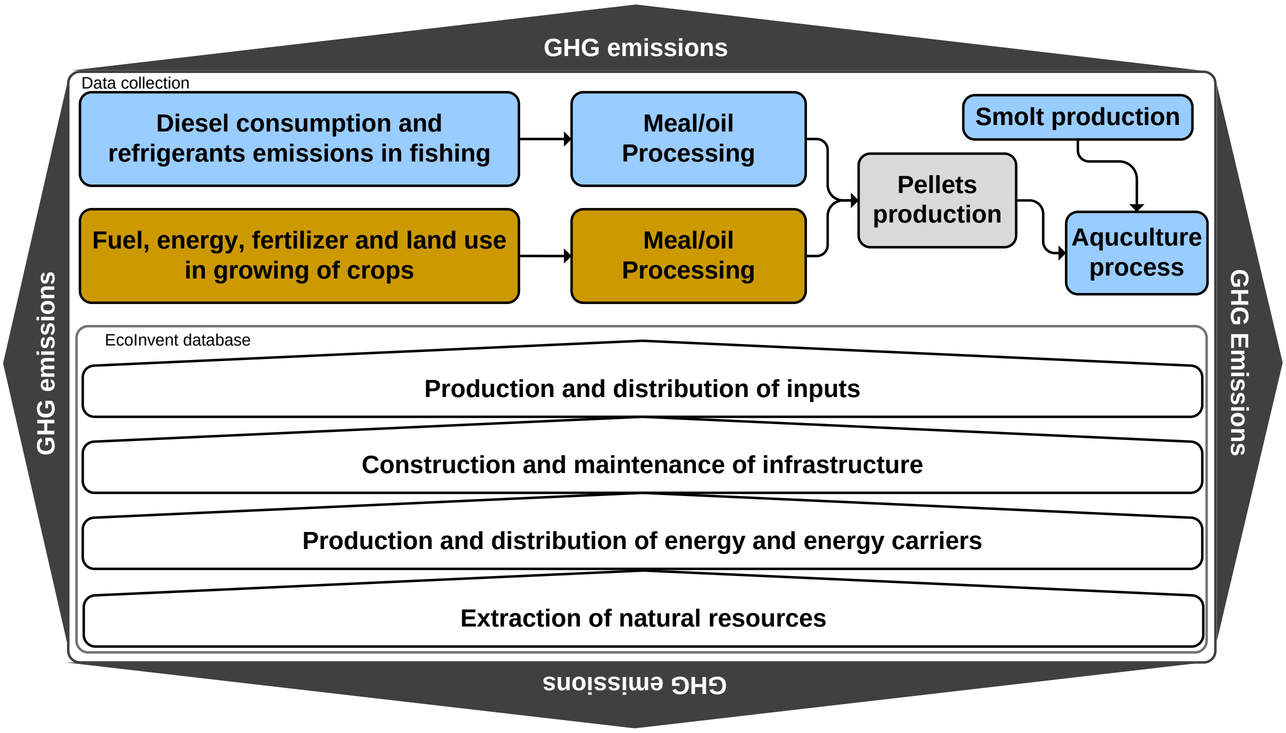

Figure 2-2 System boundaries for the impact assessment (carbon footprint and energy- and area use) for the salmon

Allocation

Allocation is done when processes have several outputs (e.g. fillet, trimmings and guts from processing of salmon) and the environmental impact from that process and previous processes need to be shared among these outputs. In these analyses allocation is done based on the mass of the outputs, this is called "mass allocation".

Allocation is a methodical choice that can have considerable impact on the final results. In the following analyses allocation is of special importance when by-products from fisheries and poultry production is used, with mass allocation they will carry the same amount of carbon footprint and area use as the main products.

For a thorough discussion on different allocation procedures we point to Appendix B in the report "Carbon footprint and energy use of Norwegian seafood products" (Winther et al., 2009). The article "An Ecological Economic Critique of the Use of Market Information in Life Cycle Assessment Research" also give a good insight into economic vs. mass allocation (Pelletier and Tyedmers, 2011). Allocation methods and their effects are also studied in the article "Effect of different allocation methods on LCA results of products from wild-caught fish and on the use of such results" (Svanes et al., 2011). Torrisen et. Al. argue for economic allocation in their article "Atlantic Salmon (Salmo salar): The “Super-Chicken” of the Sea?"

2.2 Impact assessment methodologies

Impact assessment is the phase of an LCA where the in and outflows that are mapped and quantified in the life cycle inventory phase are assigned into different impact categories and calculated into impact category reference substances.

Carbon footprint

The carbon footprints are calculated using the impact assessment method ReCiPe and its mid point indicator (ReCiPe, 2010). The ReCiPe method for climate impact assessment is based on the IPPC guidelines for climate impact assessment of GHG emissions in a 100 years perspective (IPCC, 2007): Emission of Green House Gases (GHG) are calculated into CO_2 equivalents (CO_2e) based on their chemical and physical properties.

Occupation agricultural land

The land occupied by the growing of crops is calculated as the direct land use, i.e. land use per kg of crop per year. Data on land occupation in agriculture is collected when inventorying production or yield. Neither the area used for spreading manure from animal production, nor the area occupied by the farm itself is included, so land use, in this case, is solely the direct use of field area.

Sea primary-production-required

Area used by fisheries is less evident than that of agricultural processes. Basically there are two types: sea area primary-production-required (PPR) to sustain the fish used in the salmon feed and benthic area that is influenced by the fishing gears. The species used in the feed ingredients of this report are mainly fished with pelagic gears that are not in contact with the bottom and thus benthic impacts from fishing gears are not included. The whitefish trimmings probably originate from fisheries that include bottom trawls, but this area use is then neglected (this is treated further in chapter 4).

The area of primary production required (PPR) to sustain the fish catch, was calculated using trophic levels for the species together with levels of primary-production-per-area in the Large Marine Ecosystem (LME) in which they are caught.
The primary-production-per-area factors are based on the average primary production for that LME found on the site of the Sea Around Us Project (seaaroundus.org, 2011). This can give a rough indication of the area required to produce the marine part of the feed. Primary production in the LME’s is estimated from satellite measurements of concentration of chlorophyll (in phytoplankton). The chlorophyll pigment concentration is measured from radiation, which during the measurements regularly was disturbed by clouds. Certain calculation methods were used to make probable assumptions for these areas. The model used for assessing the primary production is based on monthly estimates of chlorophyll and sunlight for any spatial cell of the oceans. The variation within an LME and over the year is considerable, but it was considered beyond the scope of this work to go more into details on this matter. The uncertainty in the measurements is not stated with standard error. More details about the data on primary production can be found on the sea around us web page (seaaroundus.org, 2011).

The formula used for calculating the PPR for the marine ingredients originates from a study by Pauly & Christensen (Pauly and Christensen, 1995):

$$PPR=(catches/9)*10^{(TL-1)}$$

The trophic level occupied by a fish species was retrieved from the internet database (fishbase.org, 2011), where trophic levels are given based on diet studies or based on food items. Trophic level calculations are not precise but are rather estimates of which place the species occupies in the marine food web and there is variation e.g. between juveniles and adult and between stocks. The value that has been used here is the single average value as decided by FishBase and the primary production of the LMEs is equally the single average as indicated on the website. The standard error for the trophic levels is given on Fish Base, and using the minimum and maximum values for trophic level gives a large span in PPR for each fish species.

Cumulative energy demand

The cumulative energy demand (CED), i.e. primary energy use meaning not only the direct energy used in the production chain is included but also the energy that was used to produce various supply materials, measured in MJ equivalents, is calculated with the "Cumulative energy demand method v1.08" as provided by SimaPro 7.3.2. This method is also explained in the report "Implementation of Life Cycle Impact Assessment Methods"(Frischknecht et al., 2003)

2.3 Data sources

The data for the inventory of the feed ingredients and the farming, processing and transport processes are derived from databases and published reports and journal articles.

For the fisheries fuel consumption is calculated from the annual profitability survey of Norwegian fisheries from 2007 (Fiskeridirektoratet, 2008) and refrigerants emissions from the project "Carbon footprint and energy use of Norwegian seafood products"(Winther et al., 2009). For some species fuel consumption is retrieved from articles (specified in the inventory chapter).

The agricultural ingredients inventory data are mainly from a feed database built by SIK. Most of these data are already published (Flysjö et al., 2008), but some data are not published yet. These data will be published on www.sikfeed.se during winter 2012. Where the SIK feed database doesn't cover the ingredients data has been retrieved from supplementary material to the article "Not all salmon are produced equal" (Pelletier et al., 2009) and the life cycle database EcoInvent 2.3 (PRé, 2011).

2.4 Cut offs

As in all LCAs some processes and inputs can not be included due to restraints on data and/or the resources available to do the LCA. In this project some important cut offs are:

- Capital investments are in general not included in the modelling of the foreground processes, e.g. fishing vessels and farming buildings.
- Area occupied by buildings and infrastructure and area influenced by fishing gears are not included.
- Micro ingredients, for an example vitamin, minerals and pigments, are not included even though they form 2.2 to 2.5 % (in weight) of the different diets. The main reason that they were left out is that it was not possible to find data on the resource use and environmental impacts to provide these ingredients and neither did we find data on the average composition of these "micro ingredients".

3 System inventory

The following chapter presents the data that was used to model the production systems.

3.1 Feed composition scenarios

Five different diet scenarios are analysed Table 3-1 presents the content of each diet. The scenarios and their purpose are:

- 2010: Average Norwegian diet in 2010. This diet forms the base case for the comparing changes to the other diet scenarios.
- 2010 HMI (High level of marine ingredients): Diet with a much higher content (same as in 1990) of marine ingredients. Composition of marine ingredients the same as for 2010.
- 2010 NAMI (North Atlantic Marin Ingredients): Same composition as the 2010 diet, but all American fish oil and meal (from Anchoveta, Menhaden and Chilean Jack Mackerel) is replaced with European marine ingredients.

- 2020 LAP (Land Animal Protein): Content of fish meal is reduced to 10 % and fish oil to 5 % by replacing them with poultry by-products.
- 2020 VEG (Vegetarian): Content of fish meal is reduced to 10 % and fish oil to 5 % by replacing them with agricultural products.

Table 3-1 Composition of the different diets in percentage of total mass. Comments in brackets.

Ingredient	Diet				
	2010	**2010 HMI**	**2010 NAMI**	**2020 LAP**	**2020 VEG**
Marine meal	24.8	64.0	24.8	10.0	10.0
Marine oil	16.6	23.5	16.6	17.5 **[1]**	5.00
Rape seed oil	12.5		12.5		24.0
Soy Protein Concentrate (SPC)	19.6		19.6	15.0	26.5
Pea Protein Concentrate (PPC)	4.50		4.50	10.0	16.0
Wheat gluten	6.40		6.40	5.00	6.00
Wheat grain	8.50	10.0	8.50	9.50	5.00
Sunflower meal	4.90		4.90	5.40	5.00
Poultry by-product fat				10.5	
Poultry by-product meal				7.00	
Poultry blood meal				3.80	
Chicken feather meal				3.80 **[2]**	
Vitamins, minerals and micro ingredients	2.20	2.50	2.20	2.50	2.50
Total	**100**	**100**	**100**	**100**	**100**

[1] This marine oil was modelled as purely from herring trimmings

[2] This was modelled identical to "poultry by-product meal

3.2 Composition of marine ingredients in 2010 Norwegian salmon feed

Table 3-2 presents the composition of the marine ingredients based on data from the three main Norwegian feed producers.

Table 3-2 Composition of marine oil, in percentage og total mas of meal and oil in 2010 feed diet

Reduction fisheries	**Share of meal**	**Share of oil**	**Share of total marine inputs**
Anchoveta, Peruvian	25 %	11 %	19 %
Blue Whiting, North Atlantic	6.8 %	1.0 %	4.5 %
Atlantic herring - Norwegian spring-spawning **[1]**	4.5 %	5.0 %	4.7 %
Atlantic herring - North Sea **[1]**	1.3 %	3.1 %	2.0 %
Atlantic herring - Icelandic summer-spawning **[1]**	3.3 %	5.0 %	4.0 %
Sandeel	13 %	11 %	12 %
Norway Pout	4.6 %	2.1 %	3.6 %
Sprat	6.7 %	21 %	12 %
Capelin - Barents Sea **[2]**	2.6 %	0.4 %	1.7 %
Capelin – Icelandic **[2]**	3.9 %	0.7 %	2.6 %
Menhaden	0.0 %	9.6 %	3.9 %
Atlantic mackerel - North East Atlantic **[2]**	1.1 %	1.9 %	1.4 %
Atlantic horse mackerel **[2]**	0.0 %	0.0 %	0.0 %
Chilean jack mackerel	1.5 %	0.0 %	0.9 %
Boar fish	3.7 %	0.0 %	2.2 %
Pearlside	0.0 %	0.5 %	0.2 %
Pilchard	0.6 %	2.5 %	1.4 %
By-products and ensilage			
Atlantic herring - Norwegian spring-spawning **[1]**	7.5 %	10 %	8.6 %
Atlantic herring - North Sea **[1]**	1.9 %	4.5 %	3.0 %
Atlantic herring - Icelandic summer-spawning **[1]**	2.7 %	2.2 %	2.5 %
Capelin - Barents Sea **[2]**	1.1 %	0.0 %	0.6 %
Capelin – Icelandic **[2]**	1.0 %	1.4 %	1.1 %
Atlantic mackerel - NE Atlantic	0.3 %	0.0 %	0.2 %
Fish Protein Concentrate (ensilage from herring cuttings)	5.0 %	2.4 %	4.0 %
Whitefish trimmings **[3]**	1.7 %	3.7 %	2.5 %
TOTAL	**100 %**	**100 %**	**100 %**

[1] Some of the companies did not divide their use of herring into "Norwegian spring-spawning", "North Sea" and "Icelandic Summer spawning", these tonnages were distributed among these three different types of herring according to the data from the one, and biggest company, that gave the most detailed data. This was done both for by-products from herring and whole herring.

[2] Just as with the herring some companies did not give detail data on their use of capelin and mackerel and also for these tonnages was distributed to "Capelin Barents Sea" and "capelin Icelandic" and to "Atlantic mackerel - North East Atlantic" and "Atlantic horse mackerel" according to the detailed data from the largest producer.

[3] Two of the companies had a post called unknown trimmings. These tonnages was assumed to be whitefish trimmings on the basis that a considerable tonnage of Norwegian whitefish trimmings go to feed production and that all the pelagic products are defined in detail

3.3 Salmon aquaculture process, Feed Conversion Ratio (FCR) and product yield

Carbon footprint from the salmon aquaculture process is modelled with data used in the project by Winther et. al., 2009. The feed conversion ratio (FCR) that is used is the economic FCR given in the 2010 environmental report from the Norwegian Fisheries and Aquaculture Association (FHL, 2010): 1.3 kg feed per kilo salmon to slaughter in live weight. The FCR is identical for all the different diets.

The marine area occupied by the aquaculture process is also derived from the FHL environmental report (FHL, 2010): The area occupied by the Norwegian aquaculture industry in 2010 was 420 km^2 when restrictions of fishing and other activities and anchoring is included, at the same time they had an output of 991 000 tonne, this gives an "occupied area" factor of 0.424 m^2/kg salmon

In the calculation from living salmon to the functional unit; 1 kg edible part, it is assumed that 1.74 kg living salmon yield 1 kg edible fillet (Winther et al., 2009).

3.4 Area of primary production required by marine ingredients

Table 3-3 Catching area, trophic level and primary production area required by the marine inputs

Species (fish)	Species (latin)	Catching area	Trophic level	LME PP [mg/(m^2*day)]	m^2/kg fish
Anchoveta - Peruvian northern-central stock	*Engraulis ringens*	Humboldt current	2.70	876	17.4
Blue whiting - Northeast Atlantic	*Micromesistius poutassou*	North sea	4.01	1115	279
Atlantic herring - Norwegian spring-spawning	*Clupea harengus*	Norwegian sea	3.23	491	105
Atlantic herring - North Sea	*Clupea harengus*	North sea	3.23	1115	46.4
Atlantic herring - Icelandic summer-spawning	*Clupea harengus*	Iceland shelf	3.23	551	93.8
Lesser sand-eel - North Sea	*Ammodytes marinus*	North sea	2.71	1115	14.0
Norway pout - North Sea	*Trisopterus esmarkii*	North sea	3.24	1115	47.4
European sprat - North Sea	*Sprattus sprattus*	North sea	3.00	1115	27.3
Capelin - Barents Sea	*Mallotus villosus*	Barents sea	3.15	414	104
Capelin - Icelandic	*Mallotus villosus*	Iceland shelf	3.15	551	78.0
Gulf menhaden - Gulf of Mexico	*Brevoortia patronus*	Gulf of Mexico	2.19	570	8.3
Atlantic mackerel - NE Atlantic	*Scomber scombrus*	North sea	3.65	1115	122
Atlantic horse mackerel	*Trachurus trachurus*	North sea	3.64	1115	119
Chilean jack mackerel	*Trachurus murphyi*	North sea	3.49	1115	84.4
Boarfish	*Capros aper*	Celtic-Biscay Shelf	3.14	956	44.0
Pearlside/Silvery lightfish	*Maurolicus muelleri*	Iceland shelf	3.01	551	56.5
Pilchard	*Sardina pilchardus*	Canary current	3.05	1196	28.6
Whitefish (Cod)		North sea	3,73	1115	147

3.5 Carbon footprint from energy use and refrigerant emissions in fisheries

Data on the fuel consumption in the fisheries providing the marine ingredients are derived from the 2007 profitability by Fiskeridirektoratet (Fiskeridirektoratet, 2008); personal communication with vessel owners and published reports. The calculation method of fuel factor from the Profitability survey is explained in Winther et al. (2009).

Table 3-4 Carbon footprint and cumulative energy demand per kilo at landing

Fishery	**Carbon footprint [kg CO_2e/kg landed]**	**Cumulative energy demand [MJ/kg landed]**
Blue whiting **[1]**	0.33	4.38
Boar fish **[1]**	0.33	4.38
Capelin **[1]**	0.33	4.38
Herring **[1]**	0.33	4.38
Mackerel. *Atlantic* **[1]**	0.33	4.38
Mackerel, Atlantic Horse **[4]**	0.87	12.5
Mackerel, Chilean Jack **[3]**	0.10	0.88
Gulf Menhaden **[2]**	0.13	1.29
Norway Pout **[1]**	0.33	4.38
Pearlside **[1]**	0.33	4.38
Anchoveta, Peruvian **[3]**	0.10	0.88
Pilchard **[4]**	0.50	6.92
Sand eel **[1]**	0.19	2.24
Sprat **[1]**	0.33	4.38
Whitefish/demersal **[5]**	1.71	19.4

[1] Fuel consumption and refrigerants emission assumed to be equal to Norwegian Pelagic fisheries. Fuel consumption calculated based on the annual profitability survey of 2007 (Fiskeridirektoratet, 2008).
[2] Calculated from Table 1 in (Ruttan and Tyedmers, 2007)
[3] Average for Peruvian fishing vessels with a load capacity from 100 - 600 cubic metres. Personal communication with Peruvian vessel owner.
[4] Calculated from table 1 in (Iribarren et al., 2010). To convert from kilos to litre an density of 0.855 kg/l is used[1]
[5] Fuel consumption and refrigerants emission assumed to be equal to Norwegian demersal fisheries. Fuel consumption calculated based on the annual profitability survey of 2007 (Fiskeridirektoratet, 2008)

3.6 Yields in oil and meal production

Yield of oil and meal from fish is based on confidential data from major feed producers (Winther et al., 2009).

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[1] Statoil product sheet: http://www.statoil.no/file_archive/produktdatablader/2008_11_Marine_lavsvovel.pdf

3.7 Transports of feed ingredients

It is assumed that all the ingredients are transported to Norway as meal, oil, grains or concentrates. These transports are modelled with EcoInvent transport processes except Ro-Ro (roll on - roll off) ferries between Denmark and Norway that are modelled based on data from the project "Carbon footprint and energy use of Norwegian seafood exports" (Ellingsen et al., 2009). To calculate the transport distances it was assumed that the pellets factory was situated close to Bergen.

3.8 Agricultural ingredients

GHG emissions, land use and energy demand for the vegetable ingredients are presented in Table 3-5. Information about the origin of data, as well as system boundaries in these studies, is presented in the text below.

Table 3-5 Data agricultural ingredients

Ingredient	**Carbon footprint [kg CO_2e/kg]**	**Occupied agricultural area [m^2/kg]**	**Cumulative energy demand [MJ/kg]**
Wheat grain, dried	0.35	1.65	2.20
Soy Protein Concentrate (SPC)	3.09	4.06	4.01
Wheat gluten	Confidential data		
Pea Protein Concentrate (PPC)	0.69	9.54	10.8
Sunflower meal	1.01	12.1	8.78
Rape seed oil	0.87	3.60	6.54
Poultry blood meal	5.70	NA	63.0
Poultry fat	5.28	NA	59.1
Poultry by-product meal	3.05	NA	34.1
NA= Not Available			

Pea Protein Concentrate (PPC)

Data on carbon footprint from production of French Pea Protein Concentrate (PPC) were found in an article: 0.69 kg CO_2e/kg of PPC (Pelletier et al., 2009). Land use is not included in these data and calculated with data on feed pea production in the SIK database: 3.78m^2a/kg (Flysjö et al., 2008). This was for peas with a water content of 14%. This was combined with data on the protein content in such peas: 21.8 % protein, from the website of the National Food Administration in Sweden[2]. Then 1 kg 55 % PPC needs 2.523 kg of peas. Hence, the land use for production of pea protein concentrate is 3.78 m^2 * 2.523 kg peas = 9.54 m^2a.

Soy Protein Concentrate (SPC)

Carbon footprint from Soy Protein Concentrate (SPC) from Brazil is assumed to be equal to soy meal found in the SIK database (SIK-feeddatabase-v2, 2011).

For soy production the climate impact from land use change is of special importance since soy production contributes to deforestation both directly and indirectly. The reason that this type of climate impact is only included for soy is, that among the crops that are used in this analysis, soy is to a higher extent grown on newly deforested land than the others. Here the climate impact is calculated using a method developed by the Joint Research Centre of the European Commission for calculating climate impact from land use change:

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[2] http://www.slv.se/en-gb/

3.09kg CO_2e/kg (based on mass allocation). The direct land area used for soy farming is 4.06 m^2a per kg of soy meal (mass allocated).

To give an example of how much the climate impact values changes according to how land use change is taken into account the SIK database provides three different values (these values are based on economic allocation):

- 0.62kg CO_2e/kg. A scenario where land-use-change was not included.
- 2.75 kg CO_2e/kg. A moderate scenario, where all new agricultural land in Brazil was assumed to originate from forest, scrubland or grassland ((Leip et al., 2010), scenario II). The actual expansion for each land type was split between all expanding crops in the region (the region including Brazil and a couple of other South American countries).
- 7.35kg CO_2e/kg. A worst case scenario for Brazilian soy, where all expansion of cropland for soy cultivation was assumed to directly or indirectly lead to clearing of forests (Gerber et al., 2010).

The assumption that SPC is comparable with soy meal was checked by looking at the data on climate impact in Pelletier et. al 2009 with the data from the SIK database on soy meal, and when climate impact from land use change is excluded these are close to identical.

Wheat Grains/Fodder Wheat

Climate impact from wheat is modeled with data from the SIK feed database for wheat grains (SIK-feeddatabase-v2, 2011). Data represents average Swedish production of wheat during 2008-2010, based on winter wheat production. The system starts in the field, including production of and emissions from fertilizers and other agricultural inputs. The system ends after drying of wheat. No allocation is needed for the fodder wheat since there are no co-products produced.

Wheat gluten

The wheat gluten is modeled as produced from wheat flour from the same wheat farming data that are used to model the "wheat grains" input (see above). Data on wheat flour production comes from a confidential project at SIK where a bread product was assessed. The processing from wheat flour to wheat gluten is based on mass allocation between wheat gluten and wheat starch, and this data is also derived from a confidential dataset. The production plant for wheat gluten is located in the Netherlands, and Dutch electricity production (including electricity imports) is used in the processing. The system ends at factory gate in the processing plant in the Netherlands.

Rape seed oil

Rape seed oil is modelled based on data from the SIK feed database (SIK-feeddatabase-v2, 2011) for production of rape seed meal, where oil is the main product. The data where calculated from economic allocation to mass allocation. The data on rape seeds represents Swedish cultivation from field, with all inputs included (e.g. fertilizer and diesel), to oil/meal factory gate.

Sunflower meal

Sunflower meal production is modeled based on data from Skretting (Winther et al., 2009). These data did not include the area occupied so this was retrieved from the EcoInvent process "Sunflower conventional, Castilla-y-Leon, at farm/ES U" (PRé, 2011).

3.9 Poultry by-product fat and meal

All the poultry ingredients: Blood meal, fat and by-product meal are modelled based on data found in the supplementary data to the article "Not all salmon are created equal" (Pelletier et al., 2009). These data are based on Canadian poultry production and with allocation based on gross energy content (in most cases identical with mass allocation due to lack of information on energy content).

3.10 Pellets production

Data on the pellets production process was derived from Skretting's environmental report for 2010 and their report to the Carbon Disclosure Project(CDP) (Skretting, 2010)

3.11 Swedish chicken and pig meat

The results for the chicken and pig meat is derived from a study of Swedish production by SIK (Cederberg et al., 2009). This study was based on national accounts and statistics, which makes the results representative for Swedish chicken production in 2005. Complementary data was used where the statistics were not sufficient, e.g. in the form of information from advisory services and research reports etc. The results for 1 kg edible product were:

- For pig: 3.9 kg CO_2e and occupation of 8.35 m^2 agricultural land
- For chicken: 3.4 kg CO_2e and occupation of 6.95 m^2 agricultural land.

In these calculations of these results mass allocation was used and it was assumed that all by-products where used. For the use of soya land-use-change is included in the climate impact in the same way as it is for the salmon. The following feed factors and yields were used for the pig and chicken:

- Pig: 4.04 kg feed/kg CW (carcass weight). Yield from carcass weight to edible part: 0.59 kg/kg.
- Chicken: 3.07/kg CW (carcass weight). Yield from carcass weight to edible part: 0.75 kg/kg

The composition of the feeds that are used for the pig and the chicken are given in the report by Cederberg et. al. on pages 72-73 and 74-75.

Since the study by Cederberg et. al. used economic allocation some alterations in data were needed to make them comparable to the salmon results, who are based on mass-allocation: The feed used on the farms was calculated on mass instead of economic basis and the allocation between edible products and by-products was changed. These alternations are also explained and used in the project "Carbon footprint and energy use of Norwegian seafood products" (Winther et al., 2009).

The land use for the pig and chicken include only the land use for farming of the feed inputs and not area occupied by pig stables and broiler houses, which were left out since the small areas coupled to the direct rearing of chickens and pigs (house areas), are negligible compared to the land use for farming of the feed inputs.

4 Results

4.1 Carbon footprint

The overall carbon footprint for the different diets are presented in Figure 4-1.The details of the different diets and their climate aspects are treated in the following sections. The different diets and their abbreviations are presented in Table 3-1. Results in numerical values are presented in Table 4-2.

The carbon footprint of the 2010 diet salmon (2.6 CO_2e/kg edible) is similar to the results in the project by Winther et al., 2009, where the 2007 diet was used; the carbon footprint back then was around 2 kg CO_2e/kg edible, when the assessment stopped at the farm gate and it was assumed that all by-products were used. These two values are not directly comparable since the data quality and granularity has been improved since the assessment in 2009.

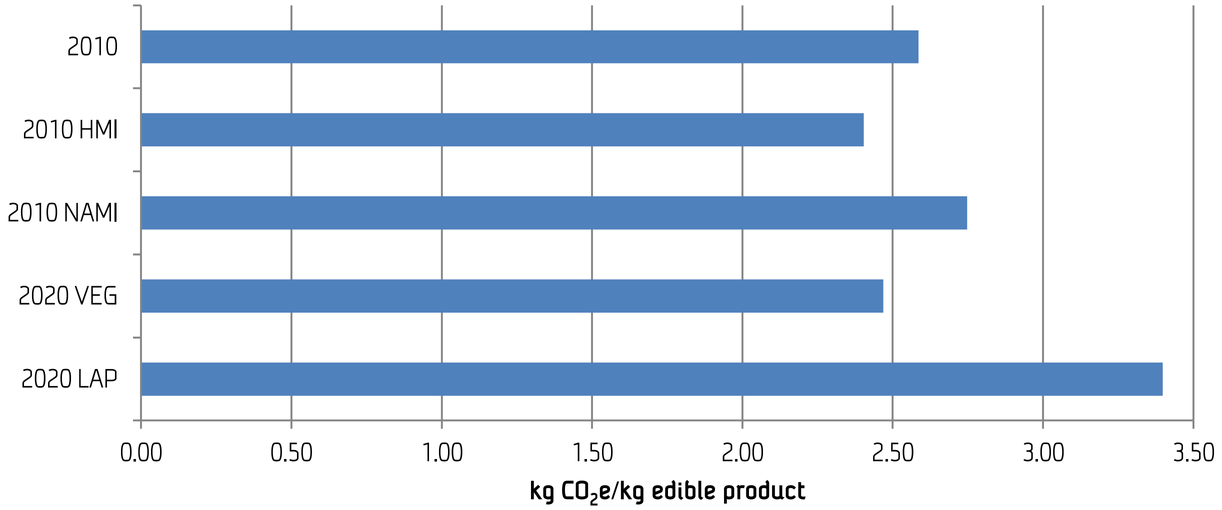

Figure 4-1 Total carbon footprint per kilo edible product for each diet

The feed conversion ratio[3] (FCR) is a key factor in the carbon footprint. The 2010 diet salmon show that production and distribution of the feed and its ingredients explain 96 % of the total, and thus changing the FCR 1 % will change the overall result with 0.96 %. By reducing the FCR from 1.3 (as it was in 2010) to 1.2 (as it was in 2007) the total carbon footprint would be decreased by 11 % to 2.30 kg CO_2e/kg edible product. In the analysis performed here the same FCR is used for all the diets, but it is reasonable to believe that the FCR will change according to the diet. On another side the FCR is influenced by many other factors than the diet, e.g. feeding technology, diseases, escapes and other types of stress that is put onto the salmon,.

Climate aspects in the 2010 diet.

Figure 4-2 presents how much (expressed as percentage of total) the different processes in the production system contribute to the total.

"Production Marine Oil" and "Production Marine Meal" are identical to the carbon footprint from fuel combustion and refrigerants emissions from the fisheries behind these ingredients. Fisheries cause 28 % of the total carbon footprint for the 2010 salmon. Processing of fish to oil and meal contribute with 9 % of the total and transport of marine ingredients with 3 %. In total the marine ingredients contribute with around 39 % of the total carbon footprint when fishing, processing and transports are taken into account. Growing, processing and transports of the crops ingredients cause 47 % of the total. Growing of soy beans and processing to soy protein concentrate on its own cause 30 % of the total. This is because SPC is an important part of the diet and attributed with the highest carbon footprint per kilo ingredient of the different crops (Table 4-1). The processing of marine and agricultural meal, oil and binders into pellets and transport of these pellets contribute with 5 %. Transports (both agricultural and marine ingredients) to the pellets factory contribute with 8 % (not including transport of pellets).

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[3] Economic feed factor: kilo feed per kilo slaughtered salmon in live weight

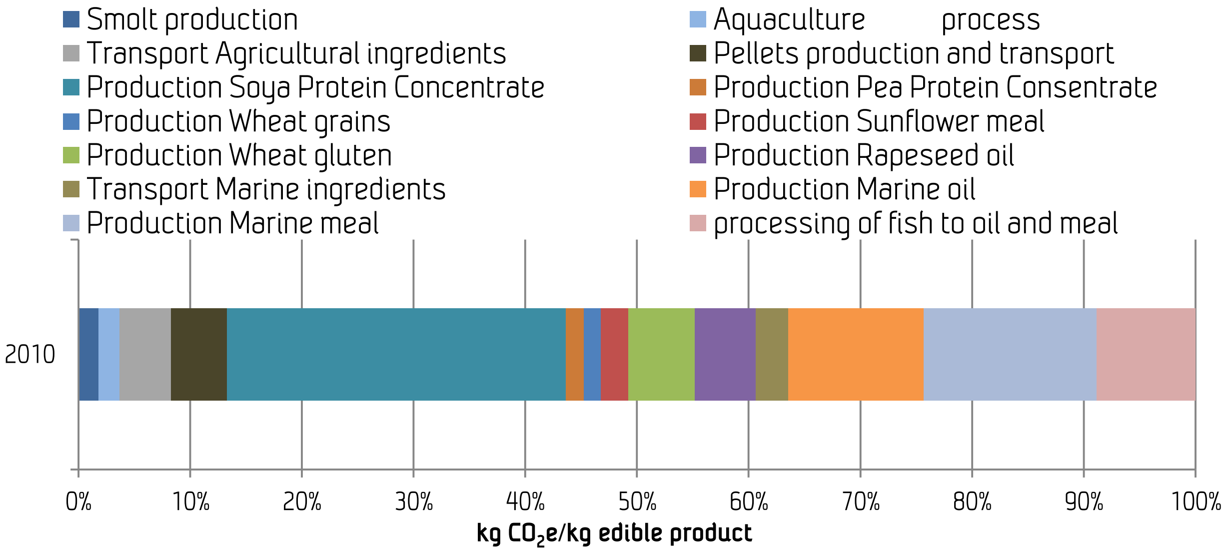

Figure 4-2 Contribution (in %) from different processes to the carbon footprint of the 2010 salmon

Comparison 2010, 2010 HMI, 2010 NAMI, 2020 LAP and 2020 VEG diet

Figure 4-3 presents the different diets and their carbon footprint (per kilo edible product) divided into contribution from fisheries, growing of crops, processing of the ingredients, smolt production, the aquaculture process and transports.

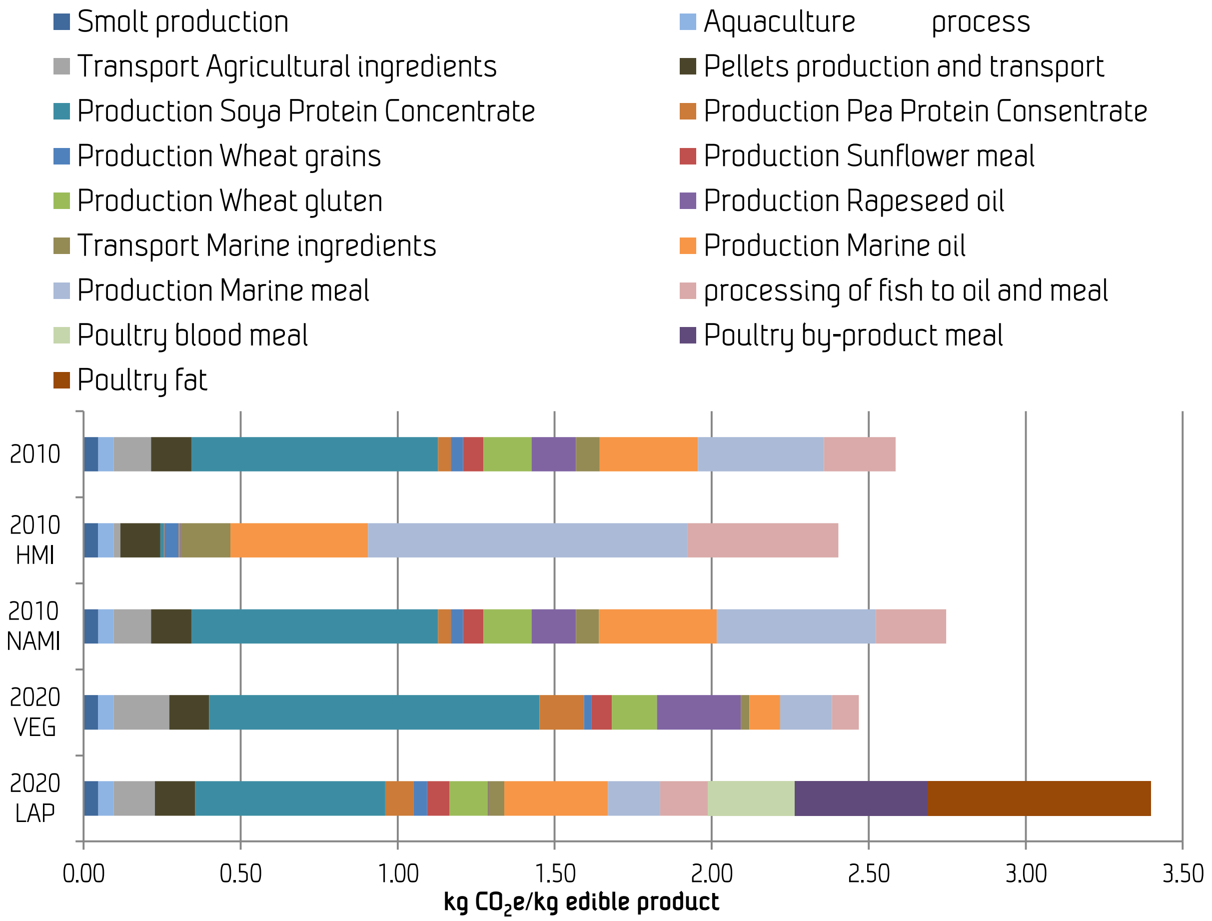

Figure 4-3 Total carbon footprint per kilo edible product for each diet

Increasing the share of marine ingredients (from 2010 to 2010 HMI).

These considerable changes; from 41 to 88 % marine ingredients, reduce the carbon footprint per kilo edible salmon with 7 %, from 2.59 to 2.40 kg CO_2e/kg.

Excluding American marine ingredients (from 2010 to 2010 NAMI).

Excluding all inputs of American marine species (Anchoveta, Menhaden and Chilean Jack Mackerel) increases the carbon footprint with 7 %. Inter-continental transports do not contribute in any large extent to the total results and the reduction of South American ingredients does not lower the carbon footprint. The American fisheries are energy efficient and the yield from fish to oil and meal is quite high for these species compared to the European species that replace them and these aspects are more important than the extra transport involved.

Reducing the content of marine oil and meal (from 2010 to 2020 VEG diet).

This change, content of fish meal is reduced to 10 % and fish oil to 5 % by replacing them with agricultural products, reduces the carbon footprint with 4.5 % (from 2.59 to 2.47 kg CO_2e/kg edible). This is a considerable change in the diet, but much of the marine ingredients are replaced with crops ingredients that actually have a higher carbon footprint than some of the more important marine ingredients. Table 4-1 presents the carbon footprint, area use an energy use per kilo of the different feed ingredients as they enter Norway (at pellets factory gate). Soy Protein Concentrate has a higher carbon footprint per kilo than most of the marine ingredients. On average the crop ingredients has a carbon footprint of 1.50 kg CO_2e/kg and the marine ingredients 2.24 kg CO_2e/kg, but important ingredients such as Anchoveta (20% of the marine inputs) have a carbon footprint that is 0.99 kg CO_2e/kg while SPC has 3.20 kg CO_2e/kg. The "vegetarian" salmon diet actually ends up with almost the exact same carbon footprint as the salmon from the diet with the most marine ingredients (2010 HMI) meaning that the increase in soy is outbalanced by the decrease in marine feed inputs.

Reducing the amount of marine inputs with poultry by-products (from 2010 to 2020 LAP diet).
This change increases the carbon footprint with 31 %. The choice of allocation strategy plays an important role in the final result here, i.e. whether by-products should be viewed as free of environmental burden occurring upstream or not. The carbon footprint for the poultry by-products is calculated with allocation based on the energy content in the main- and by-products of the chicken and pig, this gives similar results as if mass allocation is used. In practise mass allocation gives that using poultry by-products adds the same carbon footprint as if pure pig and chicken meat was put into the feed except an additional processing from by-product to fat and meal actually makes it even higher than for pure meat.

Table 4-1 Carbon footprint and area- and energy use for feed ingredient at pellets factory gate in Norway. Values are equal for oils and meals since mass allocation is used.

	Carbon footprint	**Field area**	**Area of Primary Production Required (PPR)**	**Energy use**
	kg CO_2e/kg	**m^2 land/kg**	**m^2 sea/kg**	**MJe/kg**
Anchoveta oil/meal	0.99	0.00	62.0	14.1
Blue whiting oil/meal	2.20	0.01	1 294	32.9
Boar fish oil/meal	1.85	0.00	176	27.5
Capelin, trimmings oil/meal	2.39	0.06	324	54.6
Capelin, Icelandic oil/meal	1.98	0.01	322	29.4
Herring, NVG oil/meal	1.54	0.00	330	23.1
Herring, silage	2.78	0.06	184	63.4
Herring, trimmings oil/meal	2.56	0.06	193	57.1
Mackerel, Atlantic oil/meal	1.31	0.00	321	19.5
Mackerel, Chilean Jack oil/meal	0.77	0.00	222	11.1
Mackerel, Horse oil/meal	2.71	0.00	314	40.8
Menhaden oil/meal	0.85	0.00	22.0	12.3
Norway pout oil/meal	1.55	0.00	149	23.3
Pearlside oil/meal	1.55	0.00	177	23.3
Pilchard oil/meal	1.60	0.00	70.0	24.0
Sand eel oil/meal	1.37	0.00	58.0	20.2
Sprat oil/meal	1.77	0.00	102	26.3
Whitefish, trimmings oil/meal	10.63	0.08	784	153.6
Pea protein concentrate (PPC)	0.92	9.54	0	14.8
Rapeseed oil	1.02	3.60	0	9.25
Soy protein concentrate (SPC)	3.20	4.06	0	5.87
Sunflower meal	1.24	12.10	0	12.75
Wheat gluten	2.08	1.83	0	36.57
Wheat grains	0.51	1.65	0	4.91
Poultry blood meal	5.79	NA	0	64.49
Poultry by-product meal	3.14	NA	0	35.59
Poultry fat	5.37	NA	0	60.59
NA = Not Available				

4.2 Area use

Area use for salmon diets

Figure 4-4 shows the agricultural area occupation and sea-primary-production-area required for salmon from the different diets. Occupied agricultural area per kilo edible salmon ranges from 0.3 to 5.6 m^2/kg. Note that only the field area directly used for farming is included. The 2020 LAP diet is not included here since data on the occupation of agricultural area for the poultry by-products was not found. Torrisen et. al. argue that the use of by products reduce the agricultural land occupied by the salmon, but these numbers show that these numbers are already fairly low (Torrissen et al., 2011).

Not using American marine ingredients increased the carbon footprint and it also increases the area of sea primary-production required. Even though the two types of area assessed are compiled in this graph it is emphasised that these are very different types of area: The possible output from 1 m^2 agricultural land is not comparable to the output of 1m^2 of sea surface with respect to e.g. possibility of food production. The land area is modified for food production whereas the sea area is not; the productivity in agriculture is naturally higher. Both types of area are limited, but today agricultural land is more limited than sea surface.

It has been mentioned that benthic impact from fishing gears is not included, but could potentially be important. In the 2010 diet 0.0774 kg of whitefish trimmings were used per kilo edible salmon. In Ellingsen and Aanondesen (2006) a seafloor area impacted of 1075 m^2/kg fillet from demersal trawl fisheries is concluded. This value was calculated based on economic allocation, this means that the fillet is attributed most of the benthic impact and the value would be lower if mass allocation was used. Assuming that around one third of these whitefish trimmings come from bottom trawls (according to the distribution of the total Norwegian cod quota to different gear groups) this give that the benthic impact per kilo edible salmon from the 2010 diet could be as high as 28 m^2/kg edible products. This number is close to ten times as much as the area of agricultural land occupied to grow crops for salmon. Although the uses of these different types of areas (field, marine primary production and benthic swept area) are highly different, the numbers are interesting to relate to. The actual environmental consequences from benthic impacts are difficult to quantify, as they depend on the local conditions and when the impact occurs. Ellingsen and Aanondsen (2006) discuss this in their article.

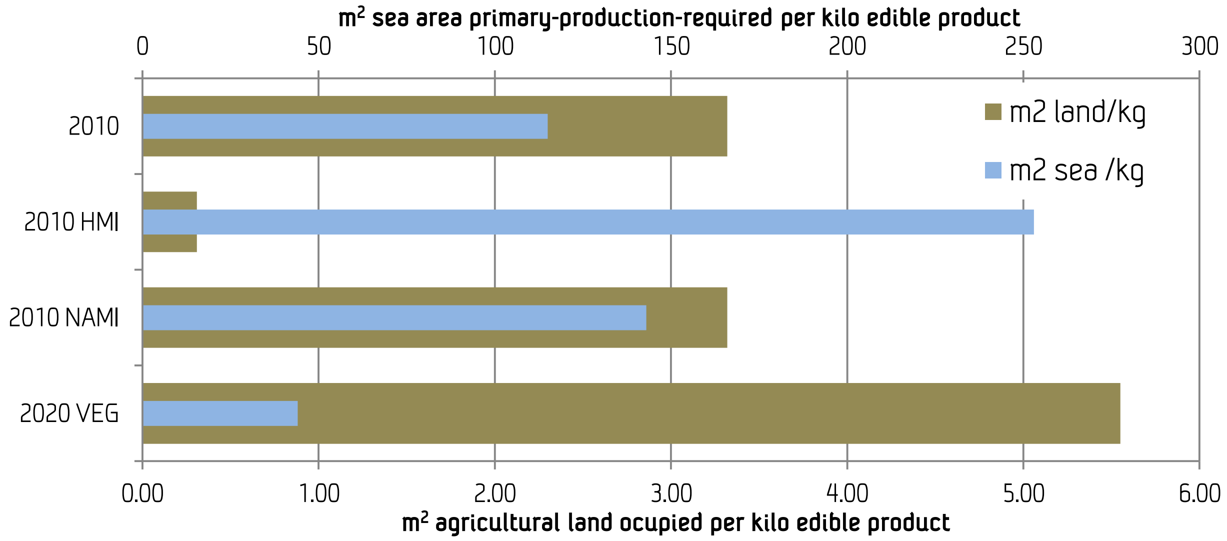

Figure 4-4 Agricultural area occupation and sea-primary-production-area required

Sea primary-production-area required

Figure 4-5 presents the relative contribution from the different marine ingredients to the sea-primary-production-area required for 1 kg edible salmon fed the 2010 salmon diet. The total is 115 m^2/kg edible products. Note that the aquaculture process is also included here; this is area that is directly occupied by the fish farm. Important contributors are Blue Whiting, NVG herring and whitefish- and herring trimmings. Blue Whiting contributes a lot due to the high trophic level it is attributed with: 4, the same is also the case for whitefish trimmings (see Table 3-3).

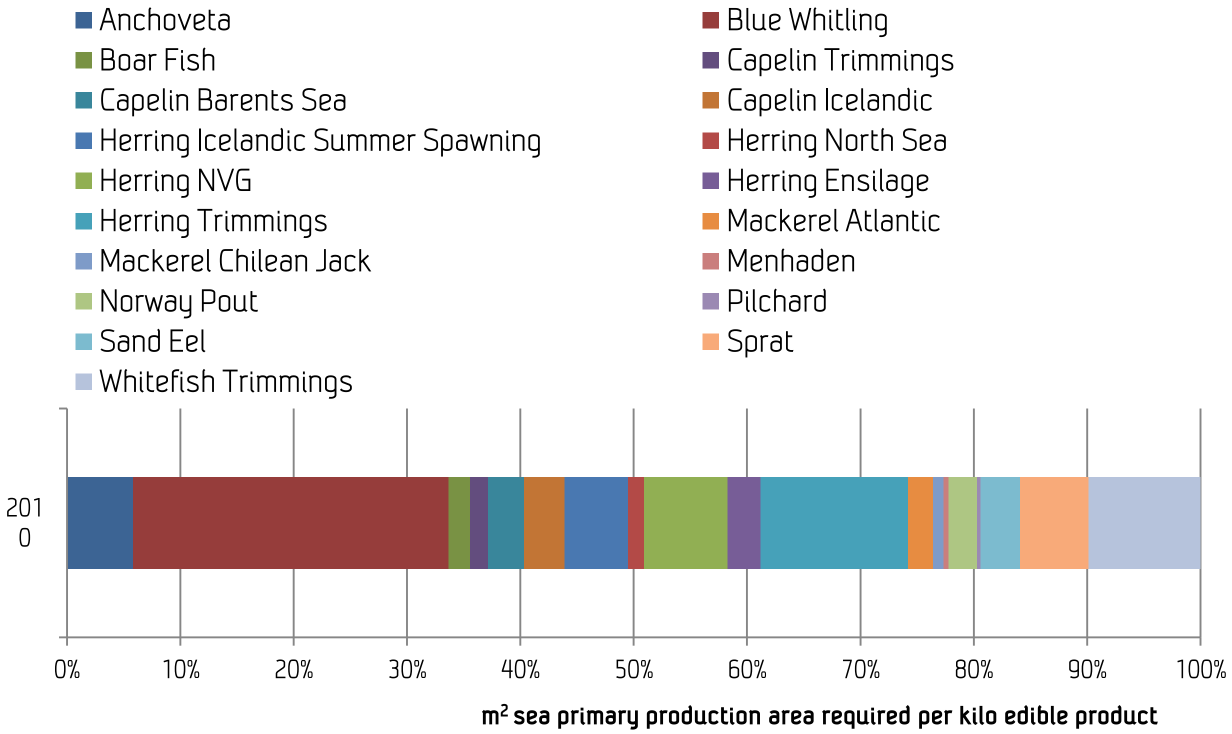

Figure 4-5 Contribution to sea primary-production-required per kilo edible salmon from 2010 diet

Figure 4-6 presents the sea primary-production-area required and the carbon footprint per kilo of the marine ingredients as they enter the pellets factory in Norway. Note that the two properties are on separate axis in the figure. The PPR is strongly dependent on the trophic level occupied by the particular species used in the feed. It is evident that species on a higher level in the food chain require a larger area of primary production. Hence, to reduce required primary production area species from lower trophic levels should be used. Blue Whiting point out as a species that has a relatively low carbon footprint, but that requires a lot of marine primary production to grow. This shows that there are evident trade offs between resource efficiency and climate efficiency.

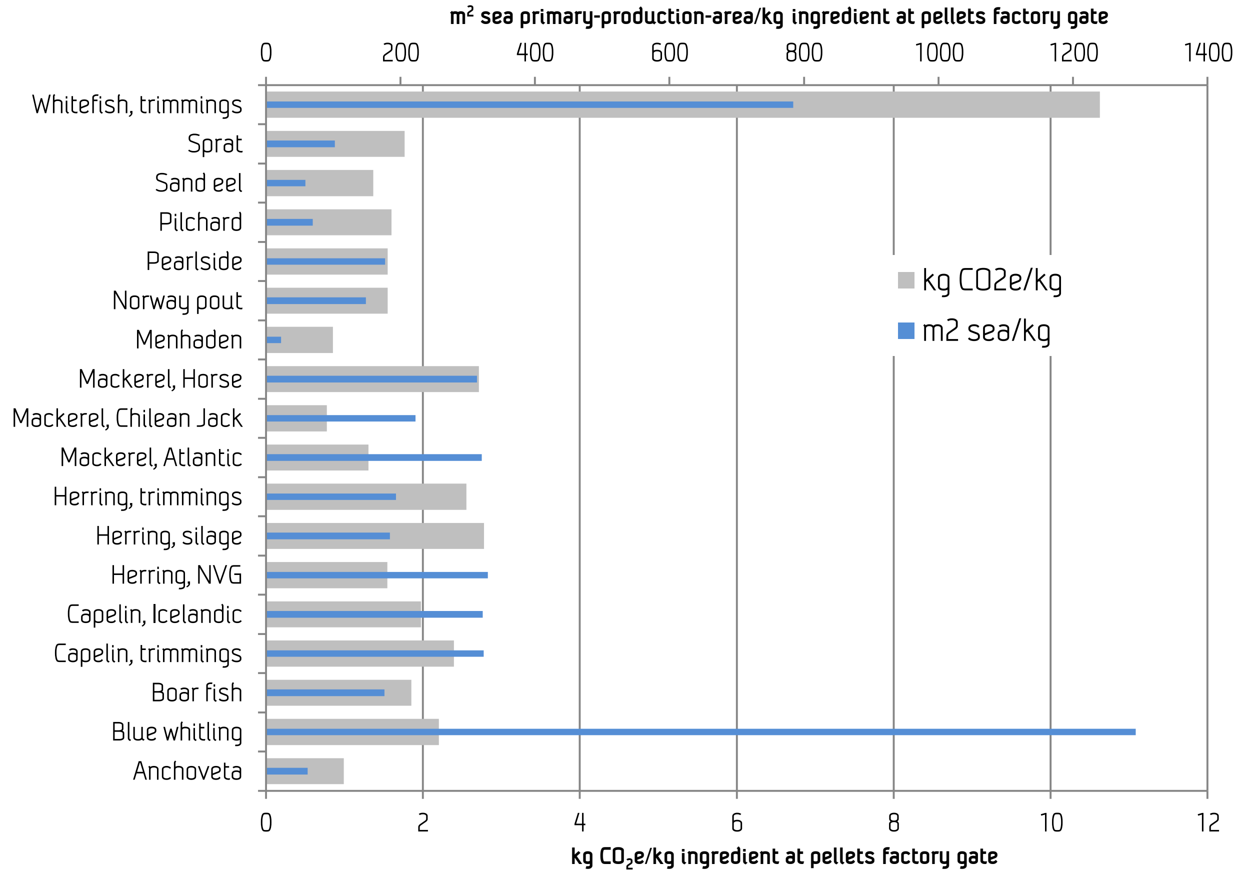

Figure 4-6 Contribution to carbon footprint and sea primary-production-area required per kilo edible salmon from 2010 diet.

4.3 Comparison Norwegian salmon and Swedish pig and chicken

Figure 4-7 presents the carbon footprint and the area of agricultural land occupied per kilo edible product of Norwegian farmed salmon and Swedish pig and chicken. Norwegian salmon fed the 2010 diet had the lowest carbon footprint of the three alternatives (2.59 kg CO_2e/kg edible) while Swedish chicken and pig have a carbon footprint of 3.40 and 3.90 kg CO_2e/kg edible product. Salmon also occupies the least agricultural land, 3.32 m^2/kg. Swedish chicken and pig occupies 6.95 and 8.35 m^2/kg edible product.

Actually the salmon from the 2020 VEG diet would also occupy less agricultural land than the chicken (5.55 m^2/kg). In this figure the sea primary production required is not included, and it is important to remember that even though the salmon occupies less agricultural land it has a high sea primary-production-requirement (115 m^2/kg edible 2010 salmon).

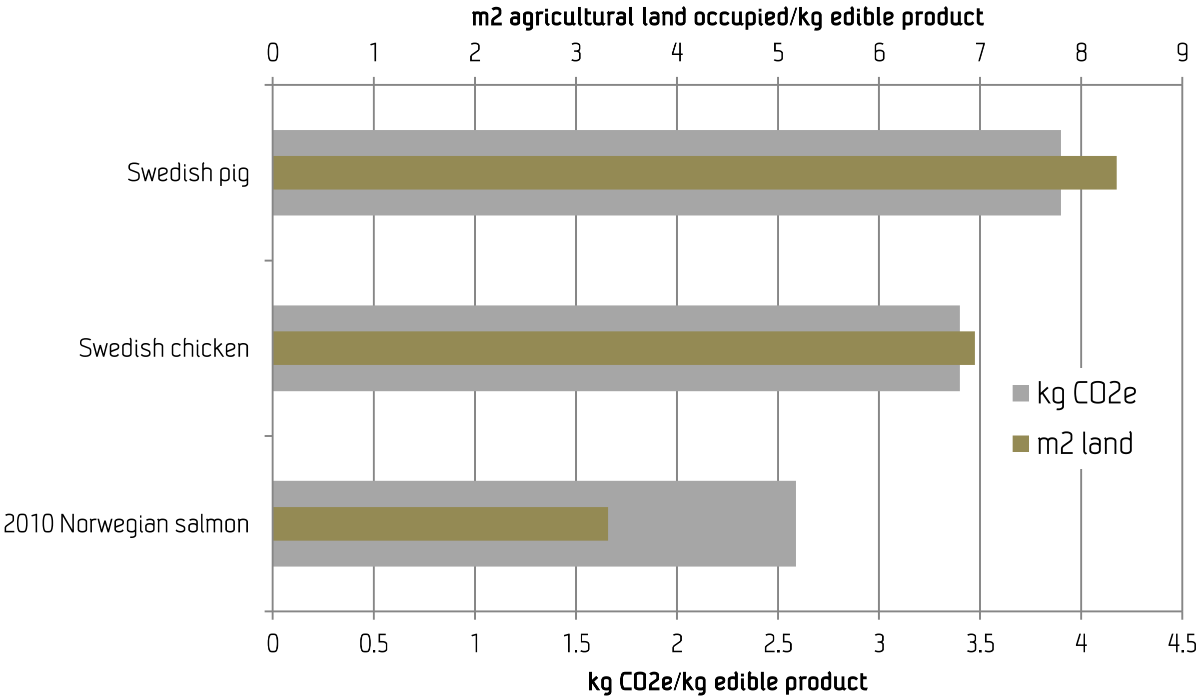

Figure 4-7 Carbon footprint and land occupation by Norwegian farmed salmon and Swedish pig and chicken

4.4 Energy use

Cumulative energy demand and carbon footprint

Figure 4-8 presents the cumulative energy demand (CED) and the carbon footprint of the salmon fed the different diets. Figure 4-9 presents the contribution to the CED from different processes in the production system of the 2010 salmon. These results reflect that the cumulative energy demand is closely connected to the energy use in fisheries; the salmon from the diet with the largest portion of marine ingredients also end up with the highest CED. Energy used as diesel in fisheries and transport and natural gas and electricity in processing of fish to meal/oil and pellets are important contributors to the cumulative energy demand of each diet.

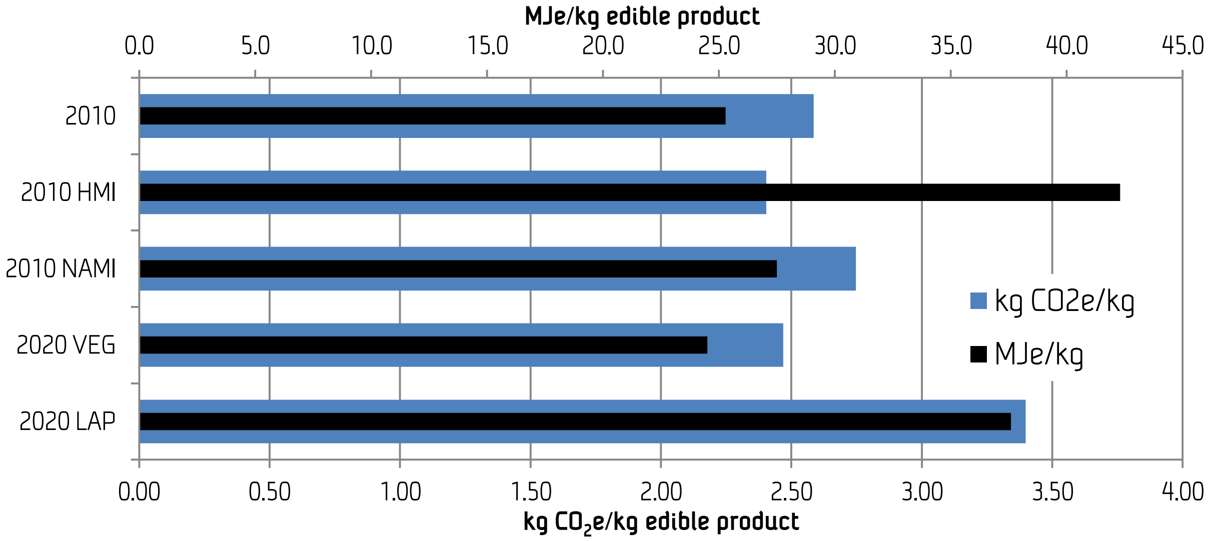

Figure 4-8 Cumulative energy demand and carbon footprint from the different diets

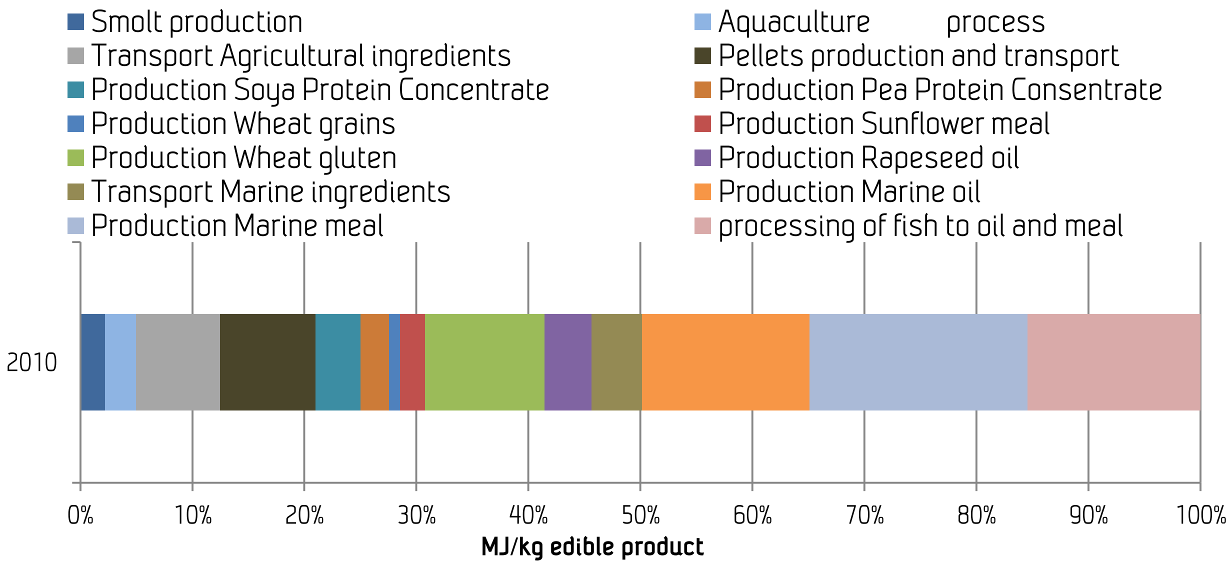

Figure 4-9 Contribution (in %) to total cumulative energy demand for 1 kilo edible salmon from the 2010 diet

Table 4-2 Results

	Occupied agricultural land	Required sea-primary-production-area	Cumulative energy demand (CED)	Climate impact																	
	Total	Total	Total	Total	Per process [kg CO_2e/kg]																
Diet	m^2 land/kg	m^2 sea /kg	MJe/kg	kg CO2e/kg	Smolt production	Aquaculture process	Transport Agricultural ingredients	Pellets production and transport	Production Soy Protein Concentrate	Production Pea Protein Concentrate	Production Wheat grains	Production Sunflower meal	Production Wheat gluten	Production Rapeseed oil	Transport Marine ingredients	Fishing og ingredients to Marine oil	Fishing of ingredients to Marine meal	processing of fish to oil and meal	Production and processing of Poultry blood meal	Production and processing of Poultry by-product meal	Poultry fat
2020 LAP	NA	110	37.6	3.40	0.05	0.05	0.13	0.13	0.61	0.09	0.04	0.07	0.12	0.00	0.05	0.33	0.17	0.15	0.28	0.42	0.71
2020 VEG	5.55	44.1	24.5	2.47	0.05	0.05	0.18	0.13	1.05	0.14	0.02	0.07	0.14	0.27	0.03	0.10	0.17	0.09	NA	NA	NA
2010 NAMI	3.32	143	27.5	2.75	0.05	0.05	0.12	0.13	0.79	0.04	0.04	0.06	0.15	0.14	0.07	0.38	0.51	0.22	NA	NA	NA
2010 HMI	0.31	253	42.3	2.40	0.05	0.05	0.02	0.13	0.01	0.00	0.05	0.00	0.00	0.00	0.16	0.44	1.02	0.48	NA	NA	NA
2010	3.32	115	25.3	2.59	0.05	0.05	0.12	0.13	0.79	0.04	0.04	0.06	0.15	0.14	0.08	0.31	0.40	0.23	NA	NA	NA
2010	CED per process [MJ/kg]				0.55	0.71	1.89	2.15	1.02	0.65	0.24	0.56	2.71	1.06	1.13	3.79	4.92	3.90	NA	NA	NA

NA = Not Available

5 Conclusions

The carbon footprint results for salmon correspond with previous analyses of Norwegian farmed salmon, but this study has provided more detailed data and results as well as an update on the feed used in salmon farming. In this way, the study has expanded the knowledge of where in the value chain of salmon GHG emissions occur and for the first time calculated the area use required.

If one tries to compose a diet lower in greenhouse gas emission, it is important to have good data on the actual carbon footprint of each specific ingredient. Major changes in the diet altered the carbon footprints with ± 7 %. To increase the share of marine ingredients or to exclude them can give almost the same final result. One important reason that reducing the share of marine ingredient doesn't lower the carbon footprint is that it is replaced with soy protein concentrate that is attributed with a high carbon footprint since soy produced in Brazil contributes to deforestation.

To exclude American marine ingredients does not lower, but rather increase, the carbon footprint even though inter continental ship transports are avoided. The required marine primary production was neither reduced; the American species are sourced through energy efficient fisheries and come from low trophic levels and give high meal and oil yields. It must be emphasised that the data that is used in this report present average values for different fisheries and within each fishery the span between those that perform with the least and the most energy use can be high.

As shown in previous studies production and processing of the feed ingredients are the most important climate aspects in the production system of farmed salmon, but transportation of feed ingredients and the processing from ingredients to feed pellets are also important climate aspects. Transports contribute with 8 % of the total carbon footprint of the 2010 salmon and pellets production with 5 %. The efficiency of the use of feed, the feed conversion ration, is a key parameter for the final carbon footprint and area use of the salmon. The FCR may differ from one feed formulation to another, but in this study the same feed conversion factor has been used for all feed formulations.

Using by-products from poultry to replace marine ingredients, from pelagic fisheries, increase the carbon footprint given the methodological choices taken, especially with regard to co-product allocation based on mass. Chapter 2 gave references to journal articles that study the details of economic vs. mass allocation. The use of by-products from pelagic and demersal fisheries is also attributed with high carbon footprint using the present methodology.

In the comparison of carbon footprint and occupation of agricultural land between Norwegian salmon and Swedish chicken and pig, the salmon has the lowest carbon footprint and occupies the least agricultural land. Even a salmon that is fed a diet with more than 85% agricultural ingredients would occupy less agricultural land than chicken. Pig had the highest values for both categories. Even though salmon has a relatively low occupation of agricultural land it requires a lot of marine primary production to sustain the fish that is used in the feed and if the area impacted by demersal gear to produce whitefish was included it would increase further. Considering the public debate about the area use of aquaculture, this debate is entirely concerned with the coastal area occupied by the farm itself, but as this study has shown, this area is very small (0.424 m^2/kg edible) compared to the area of primary production required to produce the marine inputs to the feed (115 m^2/kg edible), the crops used in the feed (3.3 m^2/kg edible) and the benthic area trawled (28 m^2/kg edible). On the other hand, agricultural land is a more limited resource than marine primary production. However, there is increasing recognition that biological production in the oceans is limited and that global capture fisheries extract a large portion of the primary production of the seas. When composing a salmon feed that is lower in greenhouse gas emissions, it is important to be aware that some species such as Blue Whiting that has a relatively low carbon footprint requires a very high marine primary production since Blue

Whiting occupy a high trophic level. It is also important to avoid replacing marine ingredients with resource-intensive agricultural inputs such as soy, sunflower meal and wheat and corn gluten or even poultry by-products. A couple of new fish species have been included in salmon diet compared to the 2007 diet reported in Winther et al (2009), e.g. Boarfish and Pearlside. Very little is known about these species in terms of stock size and status, fuel efficiency, processing yields etc and therefore they have been modelled using data for other types of pelagic fisheries, but this represents a source of uncertainty in the present study and if these species are to be used more, it is important that more knowledge about them is gained.

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