SENSE

'HarmoniSed Environmental Sustainability in the European food and drink chain'

Deliverable: D.1.1

Key environmental challenges for food groups and regions representing the variation within the EU

Chapter 3

Salmon Aquaculture Supply Chain

WP1: Harmonised environmental impact assessment methodology

Task 1.1: Establishment of key environmental challenges of food and drink production and supply chains

Final version

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PREFACE

This report is a review of key environmental challenges of aquaculture salmon supply chain including an overview of salmon feed and aquaculture production and processing into fresh and smoked products. It is a part of Deliverable 1.1 in the SENSE project, which also contains complementary reports on environmental challenges in supply chains of beef and dairy products and orange juice, which have been chosen as examples of food supply chains in Europe.

The report was compiled through collective literature searches in academic journals and professional reports; web-based information; and through pre-existing knowledge and prior research activity of the writing team of this report. The report is not an exhaustive account but is intended to give a ”helicopter view” of the main environmental challenges in the aquaculture salmon value chain based on a review of LCA studies as well as providing insight to monitoring programs and environmental certification schemes for salmon production.

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GLOSSARY AND ACRONYMS

SENSE	Harmonised Environmental Sustainability in the European food and drink chain
FCR	Feed Conversion Ratio
FIFO	Fish in – Fish out
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
LCI	Life cycle inventory analysis
LUC	Land use changes
GWP	Global warming potential
AP	Acidification potential
ODP	Ozone depletion potential
BRU	Biotic resource use
EUT	Eutrophication

Summary

An overview of the aquaculture salmon supply chain and the key environmental impacts has been achieved by reviewing of studies on environmental challenges and impacts involved in aquaculture and seafood supply chains. The aim is to establish a list of the key environmental impacts for aquaculture salmon based on a review of studies on Life Cycle Assessment (LCA). Aspects of emission and resource use of the salmon aquaculture sector will be evaluated to match the challenges with available impact assessment methods and need for methods adjustment or development (Task 1.2). The most important methodological areas have already been identified and the aim is to use LCA as a holistic approach for the SENSE tool. However, since LCA does not include assessment of all challenges, the report also addresses the characteristics of the salmon aquaculture chain and indicators for environmental performance that are applied in the industry. Furthermore, regionalisation of aquaculture production according to technologies and species and bio geographical regions is briefly addressed.

Aquaculture production systems

The first part of the report gives a historic overview of salmon aquaculture production systems in a global context. Since 1970 the salmon production industry has grown to become a major component of global aquaculture production. Its production is concentrated in Northern Europe, Canada, and Chile. The main producing countries of cultured salmonids (salmon and trout) are in relative order: Norway, Chile, Scotland, Canada, the Faroe Islands (Denmark) and the US. Established industries also exist in Ireland, Iceland and Australia.

The aquaculture salmon supply chain starts with the <u>feed production</u>, including fisheries for the feed (fish meal, fish oil, fish ensilage) and crop cultivation (e.g. soy protein, wheat, rapeseed oil), additionally vitamins, minerals and colour are added. The composition of the feed used in aquaculture has changed considerably during the last decade. The use of <u>soya and other crops</u> has increased, whereas <u>less of forage fish</u> is used, instead trimmings from fish and by products from feedstock are used. The development in feed has been in response to concerns because of limited resources of fish for human consumption and the high cost of fish as ingredient in feed. Recent technical developments in rearing techniques and compound aquafeed have improved the <u>FCR (feed conversion ratio)</u>in aquaculture. The replacement of fish by vegetable ingredients has been considered an environmental benefit although this may be controversial. Vegetable feed has a positive effect on the <u>FIFO (fish in – fish out) ratio,</u> but may have an effect on the nutrient content of the salmon. Nutrient balance accounting and resource budget (protein, fat, energy, phosphorous, <u>n-3 fatty acids (EPA, DHA)</u>) are methods that have been used to monitor the retention of nutrients in the farmed fish (Ytrestöyl *et al.,* 2011). It is foreseen that the development of feed will continue in the coming years with a focus on utilizing micro- or macroalgea and microbial cultures as a source for feed ingredients.

The salmon aquaculture production in Northern Europe is typically based on smolt production in freshwater in a land based hatchery and farming in a <u>net pen system</u>. Primary processing includes

slaughtering, gutting, filleting, chilling and packaging. The salmon is sold fresh or frozen, either whole or fillets and the most common secondary processing is smoking. In the report two cases are suggested for transport of either fresh chilled whole fish to secondary processor in Europe or fully processed smoked products transported from Norway to markets in Europe. The finished smoked salmon products are commonly vacuum packed (or modified atmosphere) in plastic packaging material and cardboard boxes while fresh fish is transported in EPS (Expanded Polystyrene) boxes sometimes with added cooling mats or ice. Transport and refrigeration during transport is of key importance when comparing different food supply chains and the impacts of local and global production. There are opportunities to minimize the environmental impact of transport by supply chain management and considering energy consumption and use both in primary production within the fisheries including fishing, meal/oil manufacture and transportation of meals/oils to fish farms, as well as transport of finished products to the market.

Key environmental challenges in salmon production

The environmental challenges of aquaculture are highlighted in part two. There have been specific environmental concerns related to the potential loss of biodiversity as a result from activities in the salmon aquaculture industry. These are related to the use of medicine for control of diseases and salmon lice, and the effect of escapees on the wild salmon. The efficiency of feed and farming systems can have an impact e.g. in the case of excess feed. This will cause eutrophication which may influence the benthic ecosystem because of nutrient enrichment of sediments and the water column. Exploitation of forage fish for feed has been a controversial issue, since this puts pressure on fish stocks and may have an impact on the seafloor. The use of soya and other crops for feed has also a considerable environmental impact because of land use changes caused by cultivation and the use of fertilizers, pesticides and water for irrigation. These issues have influenced public opinion and their perception towards aquaculture, which is sometimes a priori negative image. However, the aquaculture sector has made considerable efforts to mitigate the environmental effects for example by changing the composition of feed and development of aqua feed, as well as improved aquaculture technologies and good practices. Governmental monitoring and legal requirements in some countries i.e. Norway and Canada require that aquaculture farms report occurrences of sea lice, escapees, the use of medication and water quality and sediment monitoring in the areas close to the farms. This implies that data on these aspects may be readily available and currently there is an increasing awareness that monitoring data should be accessible in the public domain to enhance the transparency and help building an image of responsibility for the sector.

Environmental impacts assessed by LCA

Studies on LCA of aquaculture of salmon have focused on the effects of different composition of feed. Although this report is on salmon production and net-pen systems, we also consider other species farmed in Europe like trout, and arctic charr, as well as turbot and seabass. Additionally, since the main environmental challenges for aquaculture systems are dependent on the type of rearing system, other rearing technologies like closed system aquaculture are of interest. This is of relevance to prepare for more extended use of the SENSE tool for aquaculture products.

Feed production is most often the major contributor to environmental impacts in conventional aquaculture systems (Aubin *et al.,* 2006; Ellingsen and Aanondsen, 2006; Tyedmers and Pelletier,2007; Winther *et al*., 2009: Ziegler *et al.,* 2012)), while the impact of energy use is dominating in recirculation systems (Aubin *et al*., 2009; Ayer and Tyedmers, 2009). Feed producers source raw materials from diverse fish, crop, and livestock sources globally, each with characteristic resource dependencies and environmental impacts. Fuel use in fishing, and feed production in aquaculture are key contributors to greenhouse gas emission (Ziegler *et al*., 2012) and the impact of fuel use for global transport involved in sourcing feed is also of concern. Reports from LCA studies agree that the production of feed including the crop production and the fisheries accounts for the majority of salmon aquaculture's supply chain energy use, biotic resource use, greenhouse gas emissions and acidification. The fish farm stage of production is a significant contributor to the eutrophication impact which has been shown to be highly dependent on the type of rearing systems, the type of feed and the feed conversion ratio (Ayer & Tyedmers, 2009; Aubin *et al.,* 2009; Boissy et al., 2011; Pelletier et al., 2009). It should be mentioned that eutrophication may be a potential opportunity when considering the possibilities involved in polyculture systems.

The indicators and methods applied for chemical discharges and assessment of ecotoxicity are not well developed and their use for environmental impact assessment of aquaculture have been questioned (Ford *et al.,* 2012). Land use for crop production for feed and sea primary production-required to sustain the fish used for salmon feed and the benthic area influenced by fishing gear have been calculated to assess the impacts of feed for salmon (Ytrestöyl *et al.,* 2011). Water use is of importance especially in water scarce areas and land based systems and water use for irrigation in production of crop for feed.

Processing, packaging, transport, sale, consumption and waste management have not been commonly included in life cycle stages in seafood LCAs. This is particularly the case in aquaculture studies, while fisheries studies have often followed products through the transport stage (Ziegler *et al.*, 2012). Results from recent studies which have focused on environmental impacts of the processing and transport steps have shown that they are not significant in the overall impacts for the products when the transport is a short distance to the market within Europe. However, when considering the product type (whole fish or fillets), long distance transport and mode of transport (air or ship) the transport was found to have a large impact on the energy use and GWP and trucking is also an important contributor to GWP. LCAs that have focused on the transportation phase of chilled fish supply chains agree that sea freight is by far more environmentally friendly transportation mode than air freight and therefore it is very important to consider how food is produced and transported to the market and not only where it is produced in terms of environmental performance of products (Andersen, 2002; Freidberg, 2009; Tyedmers *et al.,* 2010; Ingólfsdóttir *et al*., 2010). The reported values for GWP for salmon aquaculture products varies. For fresh whole gutted salmon transported by air to Tokyo a very high value of 13.86 kg CO_2 equivalents per kg edible fish was reported (Winther *et al*., 2009; Ziegler *et al.,* 2012). Typically, values in the range of 2.2–3.0 kg CO_2 eq / kg edible fish have been reported for aquaculture salmon to the market (Ellingsen *et al*., 2009; Pelletier et al., 2009; Winther et al., 2009). The impacts of packaging material and chilling in transportation were the

main contributors to environmental impact potentials in a seafood supply chain systems (not including the fisheries) when comparison was made between chilled and superchilled fillets (Claussen *et al.,* 2011). The environmental impact of EPS packaging has been shown to be considerable, where the main contribution is energy use in the production of EPS granulates (Ingólfsdóttir *et al.*, 2010).
The GHG emission (CO_2 equivalents) of Atlantic salmon shows an emission comparable to wild caught Atlantic cod and chicken while substantially less than beef and pork when compared based on calculations of edible product. There are, however regional differences ranging from 1.78 kg CO_2 eq./kg (whole weight) for Norwegian-produced salmon to 3.27 CO_2 eq./kg (whole weight) for fish produced in the United Kingdom (Pelletier *et al.*, 2009), but this has been explained by difference in feed ingredients and higher use of marine by products for salmon produced in the United Kingdom

The impact category ozone depletion is related to the use of refrigerants. However, new refrigerants are being developed where replacement of the HCFC R22 with environmentally harmless refrigerants like ammonia is in progress. According to Ziegler *et al.,* (2012) this change would reduce the carbon footprint of fish products by up to 30% if the right substitutes were chosen.

Key impact categories and their classification to global or regional impacts
In part three of the report the key environmental impacts of relevance in each step of the aquaculture salmon supply chain have been identified as summarised below:

Production step	***Cause***	***Impact category***	***Global /Regional***
Feed – crop cultivation	Fertilizer use in crop production	Terrestrial eutrophication, Water eutrophication, Acidification	R
	Use of pesticides in crop production for feed	Biodiversity, Ecotoxicity, Human toxicity,	R
	Water use - Irrigation in crop production	Water depletion	R
Feed - fisheries	Bioresource use - Forage fish for feed	Biotic resource depletion	G
	Use of fossil fuels and energy use	Climate change Abiotic resource depletion Acidification	G G/R R
Aquaculture	Land use, sea floor use, sea surface and coastal area use (area altered by farm waste)	Land use	R
	Excess feed, faeces / Nutrient release - changes in nutrient N and P concentration in the water column and sediments	Eutrophication	R
	Sea lice and escapee Disease outbreak, parasite abundance Reduction in wild salmon survival	Biodiversity	R
	Chemical discharges /medicine use, antifoulants	Ecotoxicity (Tterrestrial / aquatic)	R
	Energy use rearing system /recirculation	Climate change	G

		Acidification	R
	Water use in aquaculture	Water resource depletion	R
Processing, storage, retail	Energy use Packaging (EPS boxes), cleaners Refrigerant use and leakage Water use for processing / cleaning	Climate change - GWP Acidification Abiotic resource depletion Ozone depletion Water resource depletion	G R G/R G R
Transport	Use of fossil fuels and energy use Refrigerants	Climate change - GWP Energy Acidification Abiotic resource depletion Ozone depletion	G R G/R G
Waste	CH_4 from waste handling	Climate change - GWP	G

Regional differences in aquaculture production affecting environmental impacts

Regionalisation is briefly addressed by looking into production technologies according to regions and species and the characteristics of the biogeographical areas of the aquaculture production in Europe.

The SENSE project will analyse the overall supply chains from "cradle to grave" including the raw material for feed, to the production site and processing and further to the retail.

Recommendations

- Many of the LCA studies on aquaculture have functional unit of tons live weight salmon and conversion factors can then be applied to make a comparison between studies if other functional units are applied. In SENSE it is recommended to use the functional units of kg edible product for all the products studied (rather than edible portions). It may be of interest for consumers to have information based on 100g product in line with nutritional labelling requirements.
- Climate change - GWP and energy use are important indicators for logistics in food supply chains and can be applied in the SENSE tool to assess the environmental impacts of the post processing activities and transport regardless of product type.
- Because of the concerns of limited natural resources in the salmon supply chain it is recommended that the SENSE tool should include assessment of use of fossil fuels, energy use, biotic resource use , land use (seafloor/coastal area) and water use
- Sustainable use of resources and minimizing of waste is of key importance in food supply chains and therefore mass balance, yield and material flow analysis should be considered for inclusion in the SENSE tool to communicate the performance of the food supply chains.
- The reliability of indicators for ecotoxicity to assess chemical discharges from aquaculture have been questioned and need to be further addressed in Task 1.3 to determine if these indicators can be recommended for impact assessment in the SENSE tool.
- The content of the various certification schemes and standards should be taken into consideration in the development of the SENSE tool to make sure that the tool is developed

according to the current trends and needs of the industry. It is recommended to perform gap analysis to compare requirements of different standards and schemes and identify data availability and synergies in data collection for the LCA.

- Eutrophication impacts, caused by nutrient releases on the benthos or freshwater, or loss of biodiversity caused by impacts of sea lice concentrations and escaped fish in the case of salmon farming are well understood and regularly monitored and thus the data may be readily available.

- The effect of efforts over time to improve performance should be identified when defining the indicators. The results from environmental assessments should have relevance for more than just documenting the present situation in the industry. It is recommended that the SENSE work in WP2 and WP4 should focus on sensitivity analysis to include different scenarios:
  - different feed composition and feed conversion rates
  - compare energy use in e.g. processing according to regions with different electricity grids
  - different production system (closed cage system, recirculating, flow through, net pens)
  - additional aquaculture species (Atlantic salmon, Arctic charr, trout)
  - processing type and packaging methods (fresh, frozen, chilled, superchilled, smoked)
  - transport modes (air, ship, water, trucks, automobiles)
- The transport to secondary processing and retail may be of special interest for the SENSE project where the energy use and GWP (carbon footprint) can be compared regardless of products. It is therefore of interest to include the transport to the retailer and the delivery of the finished smoked salmon products to consumers highlighting the use of energy, need for refrigeration and waste generation

- Frequent evaluations as are intended by the application of the SENSE tool should not necessarily imply full LCAs, but rather use of indicators that are monitored by the industry according to regulatory requirements or voluntary certification schemes.

- The advantage of indicators is that they facilitate a proactive approach to environmental and sustainability improvements. Trends in the industry are visualized so that problems can be dealt with or prevented before they become too serious or the good performance can be communicated for marketing purposes.

- Efforts to explain the significance of a local production of certified high-quality aquatic products in close proximity to European markets are considered of high importance.

- The SENSE tool could facilitate frequent evaluations of important aspects in order to assess the performance of the industry, to determine if improvements are needed, and to document the successes or failures of earlier measures to improve the environmental performance.

- The frequency of possible analysis for certain impacts of aquaculture should be considered i.e. LCA is usually based on annual data from companies, while the lifecycle of salmon is 2 years.

1. Part 1: Food chain process mapping and systems description Aquaculture production systems

Aquaculture has a long history back in time and has been an integrated part of producing animal protein to world population. Various fish species have been used and different farming methods have been developed.

Farming of fish in the temperate climate zones has been concentrated on a limited number of fish species and the closer to equator the more variety of fish species have been farmed. Traditionally, the production has taken place in ponds (intensive farming) or in wet land areas (extensive farming).

Figure 1 Traditional Danish rainbow trout freshwater production site. Earth ponds and paddy wheels for aeration

Figure 2 Net pens in saltwater, with a transport vessel (Picture E. Larsen)

Carp is the most prevalent cultured species world-wide, and is, especially popular in the eastern part of Europe. In the northern part of Europe new production methods for saltwater farming in the coastal areas for salmon and rainbow trout were introduced in the 1970'ies. After some turbulent years, this sector really became a success in the 1990'ies. There have been some drawbacks, but now the production is stately increasing and Chile is catching up after some troubled production years, caused by diseases. In 2011 the world production of Atlantic salmon totalled 1.61 million tonnes. Norway produced 61 % of this amount (NSC, 2012).

The world production of fish from aquaculture is dominated by the Asia-Pacific region, which produce approx. 90 % of the world production. This is due to China's enormous production which accounted for more than 2/3 of the world production in 2008 (Bostock *et al.,* 2010). China is by far the largest fish-producing country, with production of 47.5 million tonnes in 2008 (32.7 and 14.8 million tonnes from aquaculture and capture fisheries, respectively)(FAO, 2010).

Since 1970 the salmon production industry has grown to become a major component of global aquaculture production, being "the most widely" consumed aquaculture product in the developed world (Murray *et al*, 2011). Its production is concentrated in Northern Europe, Canada, and Chile. The top producing countries of cultured salmonids (salmon and trout) are in relative order: Norway, Chile, Scotland, Canada, the Faeroe Islands (Denmark) and the US. Established industries also exist in Ireland, Iceland and Australia (Cohen Commission, 2011). The leading producers of farmed salmon were Chile and Norway with 31% and 33% respectively of worldwide production based on figures from 2006 (FAO 2008). However, figures from 2010 reflect the decline in the production in Chile and Norway then accounted for 65% (944.600 tons) of the total salmon production, while UK, Chile and Canada had similar production levels accounting for 10%, 9% and 8%, respectively, of the annual production (FAO, 2010).

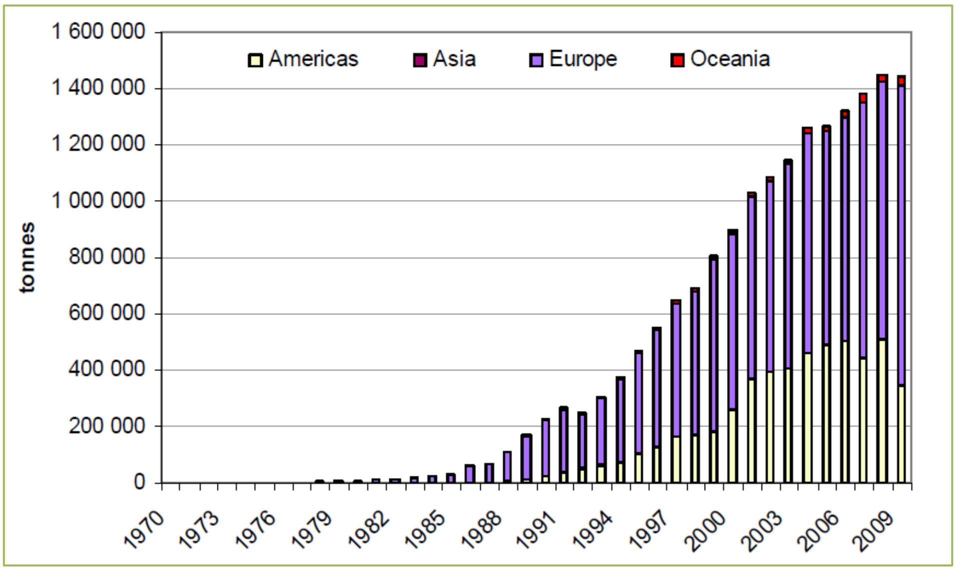

Figure 3 The world salmon aquaculture production per continent since 1970 (FAO data 2010)

The food sector has grown steadily in the past decades, aquaculture being one of the fastest growing animal food-producing sectors in the world. Aquaculture accounts for almost half of the total food fish supply and the percentage is increasing every year (FAO, 2010). The demand for aquaculture products will continue to grow over the next two decades as a key source of animal protein for growing urban populations (Hall *et al.*, 2011). For 2030 it is expected that 70% of all seafood products consumed will be farmed (Pelletier and Tyedmers, 2008). This increase in production brings potential environmental challenges regarding emissions of pollutants, water quality problems, production and processing practices, contribution to global warming, acidification and eutrophication, among others (Samuel-Fitwi *et al.* 2012). Environmental monitoring procedures and practices in salmon cage aquaculture and the regulatory process for pre-development of environmental impact assessment (EIA) in Canada, Chile, Ireland, New Zealand, Norway, the United Kingdom and the United States of America are well established. All the 7 countries have a regulatory system in place for a systematic study of the environmental costs and benefits of a proposed new salmon farm (EIA). The EIA system highlights potentially negative environmental impacts but socio-economic costs and benefits are generally not part of the EIA process (Wilson *et al.,* 2009).

Demand for sustainable aquatic products has been growing, in line with a similar trend in the food sector. Organically certified food products demand have increased at a rate of 20-25% per year and fair trade food items demand have increased by 221% in the period from 1997 to 2003 (Pelletier and Tyedmers, 2008). The different production systems have different impact on the environment. There is diversity in the species that are farmed as well as in the system type, size, intensity, technique or marine environment used for production (Pelletier and Tyedmers, 2008). Aquaculture encloses a wide range of species and production practices in Europe where salmon and trout account for 51.1% of total volume produced. Common carp is the main freshwater species while marine fish has increased during the last years and the two main species seabream and seabass account for approximately 7 % of the total European aquaculture production. (FAO, 2010) (Figure 4).

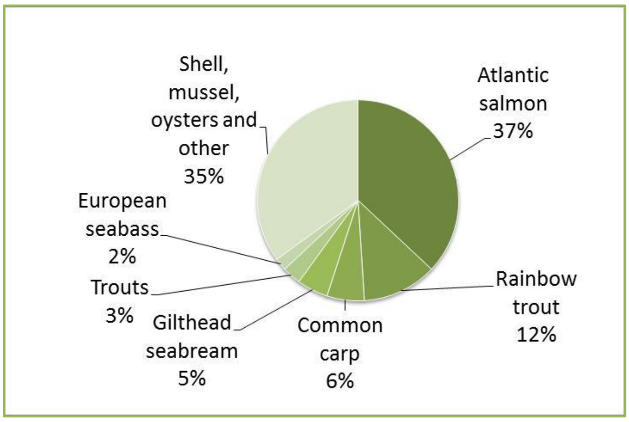

Figure 4 Relative contribution of the production volume of major species in aquaculture in Europe in 2008 (Source: FAO 2010)

Aquaculture production systems and technologies

Aquaculture production systems and technologies show a great diversity in Europe and a classification on the basis of the species produced has been suggested as follows (Váradi *et al.,* 2010):

a) Shellfish farming (oyster, mussels, clams, cockles and other shellfish species).
b) Freshwater farming in lakes, ponds or basins:
    - intensive production demanding high-quality water (trout);
    - extensive and semi-intensive aquaculture (common carp and associated species);
    - intensive aquaculture in closed system (eels and other species).
c) Marine finfish farming (Atlantic salmon, seabream and seabass, tuna and other marine fish farming)

More details on aquaculture technologies and developments in Europe can be found in Váradi *et al.* (2010). LCA studies have been performed to assess environmental impacts of different production system i.e. for hatcheries by Colt *et al*., (2008), and different farming production methods by Ayer and Tyedmers (2008).

Developments in rearing systems and feeding technologies have focused on reducing the environmental effects of aquaculture to maintain the sustainable development of this industry (ICES, 2012). While ecological environmental impacts of marine net-pen production systems for salmon have been of concern, other production systems based on closed system aquaculture (CSA) are of increasing interest, in particular because they offer controlled interface between the culture (fish) and the natural environment and the potential for control of inputs and outputs (EcoPlan Int. 2008). CSA systems include those using a onetime flow-through of water with varying degrees of input and output water treatment methods, to fully 'recirculating' systems where water is largely reused (also known as Recirculating Aquaculture Systems (RAS)).

Polyculture is an approach to minimise the environmental impacts of organic waste in aquaculture and has mitigation benefits. The most common integrated multi-trophic aquaculture (IMTA) approach combines fed aquaculture (fish) with extractive dissolved inorganic aquaculture (seaweed) and extractive particulate organic aquaculture (shellfish). This is based on the principle that the by-products (wastes) from one resource become inputs for another. There is considerable potential for the bioremediation of nutrient-rich waters, and efficacy of different combinations of species may vary to mitigate the impact of aquaculture. Most studies evaluate the integration of two species (e.g., fish and shellfish; fish and macro algae), although studies in Canada are currently testing the combination of three (fish, macro algae and shellfish) and more (same groups with the inclusion of sea cucumbers, sea urchins and others) species (ICEC, 2012).

1.1 Process flow chart of salmon supply chain and main environmental impacts

The most common marine finfish species in aquaculture is the Atlantic salmon (*Salmo salar*), which is bred in freshwater land based hatcheries and farmed in net pen systems. Process mapping on Norwegian net-pen salmon production was reported by Frederiksen *et al.,* (2007) and Karlsen et al., (2007). After hatching salmon is grown in freshwater (tanks or nets in lakes) until they reach a desired weight, size, and age. Afterwards they are moved to nets in saltwater until they reach approx. 4-4.5 kg. The main steps in aquaculture salmon supply chain are feed production, aquaculture production, primary and secondary processing and distribution to retail and consumer are shown in Figure 5. Transport and distribution channels vary depending on companies and markets. Two examples are given on logistics from studies performed earlier by SENSE partners; A) the fresh salmon (whole gutted with head on) is transported in ice in EPS boxes (T4 A) to secondary processor for smoking in France. The other example B) shows where the salmon is processed in Norway into smoked salmon products (T4B) and distributed to retail via primary and secondary distributors (T5). In the processing stage, the fish is gutted, de-headed, filleted, brined and smoked and finally, the salmon is packed, refrigerated transported and distributed to supermarkets across Switzerland (Buchspies *et al.,* 2011).

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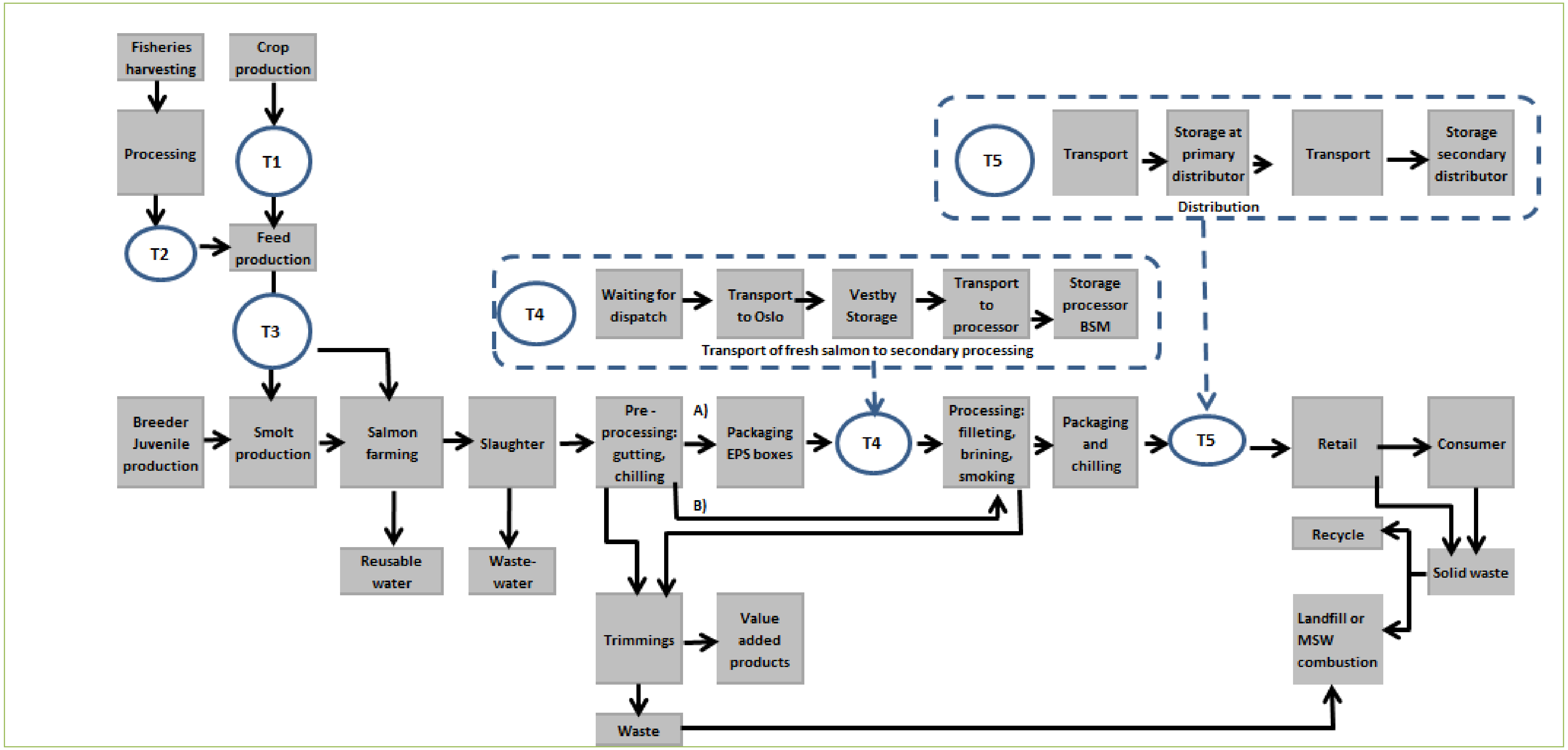

Figure 5 Flow chart of the main steps in aquaculture salmon supply chain including feed production, aquaculture production, primary and secondary processing and distribution to retail and consumer. Transport and distribution varies depending on companies and markets. Two examples are given: A) the fresh salmon (whole gutted with head on) is transported in ice in EPS boxes (T4) to secondary processor for smoking in France; B) the salmon is processed in Norway into smoked salmon products and distributed to retail via primary and secondary distributors in Europe.

1.2 Feed - Primary production

Feed is the main input in aquaculture production systems. Norwegian salmon producers, in 2010, used 1236 000 tons of feed to produce 612 097 tons of salmon fillet (Ytrestøyl *et al,* 2011).

Feed composition

The feed used in aquaculture is composed of industrial fish and agricultural products. Salmon feeds and feeding represent between 60 to 70% of total farm production costs and therefore any price increases in fish meal and oil will have a significant effect on farm profitability. In general, the price of fishmeal and fish oil is determined by market forces depending upon the quality and quantities/availability of the products in question in the market and the cost and availability of other protein sources for feed like soybean meal (Tacon, 2005). The changes in the use of fish meal and fish oil since 1970 are reflected by the increase in aquaculture and the sourcing of these materials for feed rather than industrial use as hardened oilIn 2005, 27% of the global fish meal production and 68% of the fish oil production was used in feed for salmonids worldwide. In 2009 aquaculture used about 81% of the total fish oil production while human consumption accounted for 13%, the remaining 6% was used for other purposes. Regarding fish meal production for the same year (2009) aquaculture used 63%, while chicken and pork production used 8 and 25% respectively, 4% was used for other purposes (Ytrestøyl *et al*, 2011).

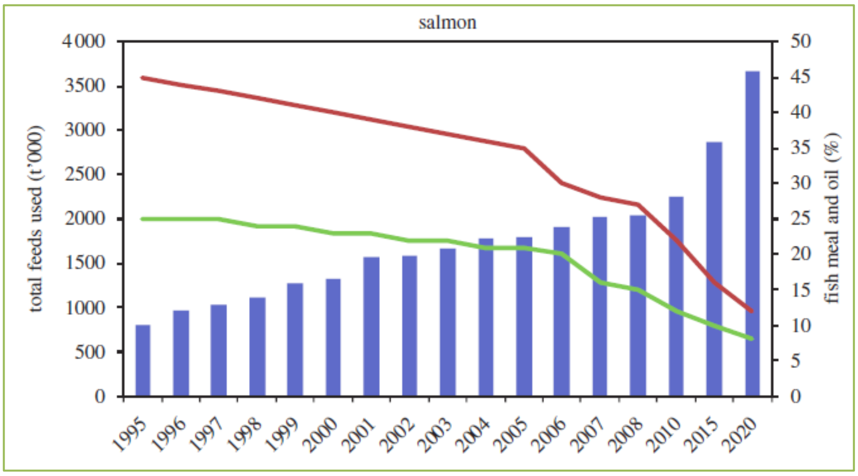

Figure 6 Estimated global use of fish meal and oil by the salmon farming industry projected to 2020. Blue, total feeds used; red, mean% fish meal; green, mean% fish oil. Source: Tacon & Metian; From Bostock *et al*. 2010.

The composition of feed for carnivorous fish like salmon has changed considerably in the last years. Fishmeal and fish oil inclusion in major fish diets has declined considerably since 1995. The reduction of fishmeal in compound aquafeed for salmon declined from: 45% in 1995, to 25% in 2008 and is predicted to be only 12% in 2020 (FAO, 2012). Similarly the fish-oil inclusion level in feed for salmon has decreased. However, the global use of fish meal and fish oil by the salmon industry are projected to increase until 2020 along with the expected growth of aquaculture industry (Figure 6).

In 2005, over two thirds of salmon feeds by weight were composed of fishmeal and fish oil (Tacon, 2005; Ellingsen and Aanondsen, 2006). Ellingsen and Aanondsen (2006) presented an example of feed ingredients in a salmon diet as follows:

- 68% of fish products (35% of fish meal, 5% of fish ensilage, and 28% of fish oil),

- 28% of plant products (7% of maize-wheat gluten, 6% of soy products, 3% of soil oil, and 12% of wheat),
- 4% of vitamins, minerals, and colour

In comparison, the composition of the control diet (average Norwegian diet 2010) used in a study to evaluate resource utilisation and eco- efficiency of Norwegian salmon farming in 2010 had lower levels of fish products and much higher level of plant based resources (Ytrestöyl *et al.,* 2011; Appendix Hognes *et al*., 2011) :

- 41,4 % of fish products (24,8% of fish meal and 16,6% of fish oil),
- 56,4 % of plant products (12,5% of rapeseed oil, 19,6% soy protein concentrate, 4,5% pea protein concentrate, 6,4% wheat gluten, 8,5% of wheat grain, 4,9% of sunflower meal), plus
- 2,2 % of vitamins, minerals, and micro ingredients

Continued research on fish-oil substitutes is a priority and emphasis on maintaining the quality of the farmed species with respect to n-3 PUFAs in the final products. Additionally, in feed development it is important to carefully consider different nutritional, environmental, and social related issues.

Feed processing

The main international feed companies are Skretting (Nutreco, Netherlands), Ewos (Cermaq, Norway), Alitec (Provimi Group, Netherlands) and Biomar (Denmark), and the salmon companies Marine Harvest-Stolt (Nutreco) and Mainstream (Cermaq). Currently, over two-thirds of the total global salmon aquafeed production is produced by two companies, namely Skretting (Nutreco) and Ewos (Cermaq).

The fish feed is composed mainly of proteins, fats, cereals, vitamins and minerals that are grounded, and mixed to later on be extruded, dried, and coated to become pellets. An overview of feed manufacturing can be found in the FAO guidelines on good aquaculture feed manufacturing practice (FAO, 2001) and good practices for the feed industry (FAO and IFIF, 2010).

Alternative feed ingredients

Compared to other terrestrial animal and plant protein sources fishmeal is unique in that it is not only an excellent source of high quality animal protein and essential amino acids, but is also a good source of digestible energy, essential minerals, vitamins and lipids. The fish oil is the source of the essential polyunsaturated fatty acids (PUFA). There have been questions regarding if the fish meal and fish oil production as ingredients in feed will be able to sustain the growing aquaculture industry (Huntingon & Hasan, 2009; Frid and Paramor, 2012; Nasopoulou and Zabetakis, 2012). Additionally, the use of marine-based salmon feed has been debated due to the possibility of using the raw material directly for human consumption instead of for feed. With increased production volume, the aquaculture industry will have to find new sources for the marine-based feed in the future (Ellingsen *et al*., 2009).

Alternatives and the role of "feed" fisheries in fish and animal farming were synthesized based on four regional analyses and a number of country case studies (Huntington, 2009). Recommendations were made with regard to the sustainable sourcing of raw materials for aqua feeds in particular improved management of feed production and product development to meet the increased global demand for fishmeal and fish oils. Partial replacement of fish based feeds with vegetable based feed like soya is an opportunity to secure feed availability (Nasopoulou and Zabetakis 2012; Boissy *et al.* 2011), however the use of soy based feed has drawbacks since it contributes to LUC (land use changes) and loss of biodiversity. The possibilities to use algae and microbes as alternative sources for feed are being explored. Seaweed as an ingredient for feed has gained interest and commercial feed ingredients based on seaweed are already available in Ireland[1].

Table 1 A summary of the different fish species used in Norwegian salmon feed and their meal and oil share in tonnes for 2010 (From Ytrestøl *et al* (2011))

Species	**Fish meal (tonnes)**	**Fish oil (tonnes)**
Anchoveta,	81 832	24 **655**
Blue whiting	22 007	2 223
Sprat (brisling)	21 492	45 735
Norway pout	14 753	4 508
Atlantic herring- Norwegian spring-spawning	10 828	8 581
Atlantic herring- North Sea	11 243	12 699
Atlantic herring- Icelandic summer-spawning	7 166	7 479
Capelin	20 777	2 466
Sandeel	41 882	24 913
Atlantic mackerel	3 420	4 129
Chilean jack mackerel	4 805	0
Boar fish	11 886	0
Gulf menhaden	0	20922
Other/unknown	5 077	6 970
SUM FORAGE FISHERIES	**257 167**	**165 277**
Trimmings/silage	**68 292**	**53 396**

The amount of worldwide fish that can be used for feed has quotas to prevent overexploitation, since the fish supply is limited. Fish meal and fish oil production have been fairly constant at about 6 and 1 million tonnes/year respectively.[2] It has been estimated that around 68% of fish millage (FM) and 89% of fish oil (FO) are used for feed. Salmonid production (salmon, trout, charr and white fish) consumes 21% of FM and 56% of FO (Boissy *et al.* 2011). Table 1 is a summary of the different fish species used in Norwegian salmon feed and their meal and oil share in tonnes for 2010. The percentage of fish meal that is derived from trimmings represents more than 20% of the total fish meal. In the fish oil case the trimmings and silage are the source of almost 25% of the total fish oil.

The trend has been that more consumable fish is used for human food and an increased part of marine by-products are now also utilized as raw material in the feed production. In addition the salmon is also changing from a diet dominated by marine raw material to an increased share of soy, wheat, and rape. Usually the oil that has been used as a replacement of fish oil in fish feed is soybean, linseed, rapeseed, sunflower, palm and olive oil. Also, other products such as olive pomace are currently being explored (Nasopoulou and Zabetakis, 2012).

[1] http://www.aquafeed.com/newsletter_pdfs/nl_000461.pdf

[2] http://www.euraquaculture.info/

Organic feed

Certification for organic salmon aquaculture requires the use of organic crop ingredients and fisheries by-product meals and oils. The use of organically certified feeds represents a 50% extra feed cost for producers (Mente *et al*, 2011). Correspondingly, it has been estimated that the average premium price in the EU for organic goods is around 15%. Moreover, price premiums for organic salmon between 26 and 99% were reported in a survey undertaken in 2002-2003 (Georgakopoulos and Thomson, 2005).

In organic aquaculture, in addition to satisfying nutritional requirements feed has to be in accordance with sustainability principles. Acceptable ingredients in organic feeds include:

ANIMAL ORIGINATED FEEDS: Marine animal products and by-products including processed aquaculture originated ingredients (e.g. fish meal, shrimp shell) and aquatic feed animals (e.g. worm, zooplankton). For this category ingredients should come from sustainable exploitation of fisheries resources and cannot be used for herbivore species or the same species (avoiding cannibalism). Trimmings from non-organic production are acceptable until December 2014 and should not exceed 30% of the animal daily intake.

PLANT ORIGINATED FEEDS: Includes organically produced/authorized materials from aquatic origin (e.g. seaweed, algae) and from land origin (e.g. cereals, oil seeds, legume seeds, roots, forages, etc).
MATERIALS OF MINERAL ORIGIN AND FEED ADDITIVES: Includes organically produced/authorized mineral materials as sodium, potassium, calcium, phosphorus, magnesium and nutritional additives as vitamins, trace elements, preservatives, antioxidants, among others. More detailed information on the ingredients allowed and forbidden in organic feeds can be found in Mente *et al*. (2011).

1.3 Aquaculture farming production

In general the following steps describe the aquaculture production of net-pen systems:

- The breeder produces salmon roe and delivers juvenile salmon to producer
- Juvenile salmon producer uses feed, water and oxygen under controlled temperature and light conditions)
- Smolt producer uses feed and water, controlled temperature and light conditions.
- Fish is vaccinated,
- Fish farms use feed and water, controlled temperature and light conditions (4-6 kg 10-18 months)
- The cages in net-pen systems are made of a steel or plastic structure and a net.
- During the operation electricity/diesel is used and a transport boat is required

Smolt production

Production of smolts is the first step of salmon aquaculture. This step takes place at on-shore freshwater hatcheries. In 2008, there were 224 concessions for smolt production facilities in Norway (FHL 2008).

- Smolt production - on shore hatchery in freshwater / weight of 60- 90 -125g
- Several different technologies are applied for water reuse system
- A share of water that leaves the rearing unit is first treated and then reused. This reduces freshwater and energy needed.

The development of fertilized eggs is often accelerated by heated water.

The young hatchlings feed on plankton and insects and eventually other fish. Liquid oxygen is often injected into the water until the hatchlings reaches smolt size (60-125 g or larger).The transition from a freshwater smolt to a salmon to be transferred to salt water takes in the wild approximately two years but in aquaculture one year or less. In general, smaller producers buy salmon fingerlings when it is time to stock their net cages. Large companies tend to maintain adult brood stock and sell eggs or recently hatched animals as well as grow them out to market size. The sales from hatcheries are more profitable than producing mature salmon. Moreover, well-run hatchery operations offset the cost of stock through profits from the sale of excess production (www.worldwildlife.org).

Salmon farming

After smoltification when the salmon has been adapted to seawater, it is transferred to floating marine net-pens. At that stage, the salmon weights approx. 60-90g (Colt *et al.,* 2008). The pen holds salmon but is open to the marine environment. Growth period in the net- pen ranges from 14 to 25 months before harvesting when the salmon has gained a weight of 2-5.5 kg. The net-pen structure usually consists of several cages located around 100 m off-shore or in fjords for sheltering from storms (Tyedmers, 2000).

Transport from farm to slaughter / processing

Well boats transport live salmon to primary processor/slaughter

Energy use is mainly for operation of the well boat.

1.4 Processing (Slaughterhouse and packaging)

In the processing stage, the salmon is slaughtered, gutted, filleted, brined and cold smoked. Depending on the company and supply chain the fish may be processed in Norway into final cold smoked products and then transported to the markets in Europe (Example B).

Alternatively, the fish is transported whole with head on and iced in EPS boxes to secondary processing, a smokehouse in Europe (France) (Example A)

Salmon slaughtering

The salmon is kept alive in sea water at shore in cages before it is slaughtered. Then the fish are pumped into the factory where they are put into a chilled tub to be rendered unconscious (CO_2 is not allowed in Norway). Different methods are applied for slaughtering, it is either done by hand or in machines applying electric stunning and then cutting the main artery. The fish is kept in a bleeding tub for approximately 45 minutes after slaughtering and then it is cooled down in a cooling tub (at 0°C).

Primary Processing

From the cooling tub, the salmon is transferred to gutting (automatic gutting machine). After gutting, it is cleaned, first by hand cleaning (special vacuum pumps) and then by using an air bubble bath. After cleaning, it is graded and packed according to size (4-5 kg). After it has been packaged in EPS boxes (approx. 20kg) with ice (~5 fish in the box, and ice / fish ratio = 3/1), the package is weighted and labelled. Finally, the boxes are loaded on pallets (27 boxes) according to requirements made by the buyer of the product.

Figure 7 Fresh salmon packed in EPS box covered with flake ice (left) and typical packages for vacuum packed smoked salmon in cardboard boxes.

Packaging

A. The whole gutted fresh fish packed in EPS (Expanded PolyStyrene) boxes. EPS boxes loaded on pallets and transported by truck to Boulogne sur Mer where it is received by a processing company for further processing into cold smoked salmon products and distribution in France (Chill-on project)

B. In secondary processing in Norway the salmon is first filleted and then brined /salted and cold smoked. The smoked salmon is sliced, put on aluminium coated card-board and vacuum packed in plastic packages. After processing, the salmon is transported by lorry to supermarkets across Switzerland (Buchspiess *et al*., 2011).

Energy

The energy use is for refrigeration including the ventilated air cooling condition system and operation of the manufacturing equipment

The main contributor to GHG emissions at the processing stage is different types of energy. The hotspots for processing are difficult to estimate if the energy is reported as a total for the whole processing plant/slaughterhouse and not for unit processes.

Waste in primary and secondary processing

Research suggests that aquaculture production systems can have big amounts of waste; that there is a percentage of the catch that is not used due to legal (quota) or market (low value) reasons. A study presents discard global estimates of around 8%, representing 410 thousand tonnes in Europe, 1.5 million tonnes in North America, and 2.5 million tonnes in Asia. The amount of wasted product can vary a lot depending on the country, for instance in Denmark 80% of fish trimmings are re-processed into fish meals and oil while in France, Germany or the UK that number is between 50 and 33% and drops down to 10% in Spain (Frid and Paramor 2012).

1.5 Secondary Processing - Smoking

The processing in the smokehouse includes the following processing steps: receiving raw material and filleting, salting/brining, draining, cold smoking, cooling, slicing and packaging. The raw material used for smoking in different smokehouses is processed 2-3 days up to one week after slaughtering, depending on the manufacturing procedures and the length of transport to the smokehouse. The salmon is first filleted and it is important to consider that while transforming the fish to fillet there will be losses and the fillet factor can vary depending on the handling and practices as well as the condition of the raw material. Ellingsen and Aanondsen (2006) present conversion factors between Kg of live animal to Kg of fillet of 2.3. Salting and smoking procedures can vary regarding temperature during smoking, type of wood used and time. Traditional cold smoking and dry salting is common, some producers use brining and salt injection techniques. The cold-smoked salmon products are sliced and vacuum packaged or vacuum packed as whole fillets.

Waste

Waste management in smokehouses and emissions from the smoking needs to be considered

Energy use

Type of energy used in the processing step depends on the region and the common electrical grid. The energy use is mainly for the smoking oven and ventilated cooling chambers as well as operation of manufacturing equipment for slicing and packaging. The finished products are vacuum packed (or modified atmosphere) in plastic packaging material and cardboard boxes or EPS (Expanded Polystyrene) boxes sometimes with added cooling mats.

1.6 Transport to secondary processing and retail

The main market for smoked salmon products in Europe is France followed by Germany, UK, Italy, Be/Ne/Lux, Spain and Scandinavia (Marine Harvest, 2012). The transport from the aquaculture production in Norway to Boulogne sur Mer (A) is used as an example for the transport to secondary processing and retailer in the SENSE project.

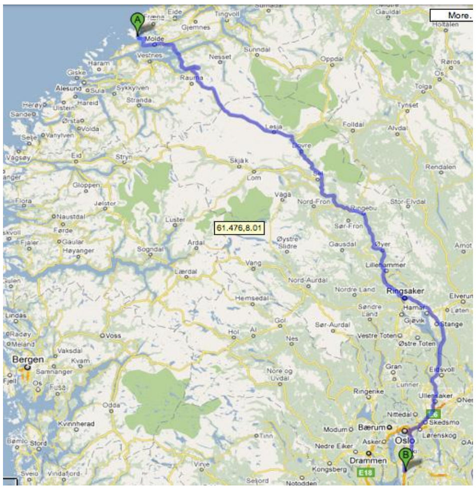

Figure 8 The route between Aukra (Norway) and Vestby (Norway) (left) and the route between Vestby (Norway) and Boulogne sur Mer (France) (right).

Refrigerated transport

The current cold chain distribution system in Europe is complex and involves numerous stakeholders, who sometimes have limited understanding of the importance of chilling and the significance of energy transfer. Fresh fish products are often chilled in refrigerated seawater and ice (liquid ice) and after packaging in boxes extra ice is added. As a result large quantity of ice is transported with the fish, and consequently higher GHG emission from the transport. However, the ice ensures longer shelflife of products and prevents spillage, which may thus actually contribute to a lower carbon footprint for the products.

Table 2 Main transportation steps in salmon production and estimated distances for A) fresh salmon (whole gutted with head on) transported in ice in EPS boxes (T4 A) to secondary processor for smoking in France (Chill-on project- UoI)

Transport	Step description	Estimated distance	Type of transport
T1	Transport of crop to feed producer		
T2	Transport of fish to feed producer		
T3	Transport of feed to salmon farming		
T4 A	Transport from farm to Transport hub (i.e. Aukra (Norway) – Vestby (Norway)) Transport from hub to producer (i.e.Vestby (Norway) – Boulogne sur Mer (France))	560 km 1730 km	Truck / Ferry
T4 B	Transport from farm to secondary processor	Short distance	Truck
T5a	Transport from producer -> Distributor, Boulogne sur Mer (France)	>5 km	Small truck
T5b	Transport: Primary distributor -> Secondary distributor Paris(France)	250 – 1000 km	Small truck
T5c	Transport: Secondary distributor -> End customer (Retail / Restaurant) (local) End customer retrieval (multiple stops) Paris(France	>50 km 250 – 1000 km	Small truck

Waste

The cold chain has many weak links and temperature fluctuation of the products are frequent in transport in particular at handover points. This results in reduced product quality and shortened shelf life of the fresh products, and potentially larger amount of waste and hence a larger environmental burden per kg consumed product (Magnussen, Haugland, Torstveithemmingsen, Johansen, & Nordtvedt, 2008).

1.7 Retail

The most common secondary processed product based on Atlantic salmon, is smoked salmon. The European market for this product was 150,000 tonnes product weight (PW) in 2011, where France and Germany were the largest markets

At the retail sector the fish is kept in a refrigerator until the last date of sale. The shelflife of smoked fish products is typically 2- 4 weeks depending on the level of salt used in the products.

Products not sold before the date of expiry will be destroyed (waste). Retail stores can throw away large quantities of food. Usually, this consists of items that have reached either their best before, sell-by or use-by dates. Food that passed the best before, and sell-by date, and even some food that passed the use-by date is still edible at the time of disposal, but stores have widely varying policies to handle the excess food. Some stores put effort into preventing access to poor or homeless people, while others work with charitable organizations to distribute food. Retailers also contribute to waste as a result of their contractual arrangements with suppliers. Failure to supply agreed quantities renders farmers or processors liable to have their contracts cancelled. As a consequence, they plan to produce more than actually required to meet the contract, to have a margin of error. Surplus production is often simply disposed (Tristram, 2009).

Energy

At retail the environmental impact is dependent on the energy used to refrigerate the fish products and the refrigerants used in the cooling equipment (Parfitt, *et al*.). The retail sector has been mentioned as one of the main contributors for waste. We have no specific data on the specific amount for fish/salmon products.

Refrigeration

Retail food stores have significant impacts on the environment. These are indirect emissions through the energy consumption but also direct emissions through refrigerant leakage. Around 70% of the energy consumed in supermarkets is electricity mainly used to drive the refrigeration equipment in the store (other processes are lighting, heating, ventilation). Smaller super- markets and convenience stores will not have many of the ancillary services and the proportion for refrigeration will be higher.

1.8 Consumer

At the consumers the salmon products are either fresh or smoked and consumed or stored (in a freezer or refrigerator). Calculations emphasize that food waste at the consumer level is considerable

Energy

At the consumer level the energy use is mainly to refrigerate fish products and the energy to cook/prepare the fish and the waste that originates from the preparation and use that contribute to the environmental impact. At this stage as for processing and retail the type of energy used refrigeration will determine the environmental impact. There can be considerable wastage of fish at the consumer stage (Gustavsson *et al.,* 2011) as is the case for food in general, that the majority of food waste is related to the consumer level (Parfit *et al.*, 2010).

Post-consumer waste

A considerable amount of food is wasted through the food chain. Gustavsson *et al* (2011) estimated that approximately about 100 kilograms per person per year is wasted at the consumption stage. In a EU report on waste it is estimated that around 90 million tonnes of food waste are generated in the EU each year (European Commission, 2010). An estimate of food waste using both EUROSTAT and available national data for the main sectors showed that household is contributing similar as manufacturing. Percentage breakdown of EU27 food waste arising in the main sectors were as follows: Manufacturing (39%), Household (42%) Retail /Wholesale (5%) and Food Service/Catering (14%). The study estimates annual food waste generation in the EU27 at approximately 89Mt, or 179kg per capita.

2 Part 2. Key environmental challenges in salmon production

2.1 Environmental challenges for aquaculture

The environmental challenges for aquaculture have been in the focus for years as outlined in a report by Nash (2001) (Table 3). These challenges are related to the local impacts caused by nutrient enrichment of the ecosystem, chemical discharges and occurrences of pathogens, parasites, and escapees.

Table 3 Main areas of environmental challenges for aquaculture (Nash, 2001)

1. The impact of bio-deposits (fish faeces and uneaten feed) from farm operations on the environment beneath the net-pens.
2. The impact on benthic communities by the accumulation of heavy metals in the sediments
3. The impact on non-target organisms by the use of therapeutic compounds (both pharmaceuticals and pesticides) at net-pen farms.
4. The physiological effect of low dissolved oxygen levels on other biota in the water column.
5. The toxic effect of hydrogen sulfide and ammonia from the bio-deposits below a net-pen farm on other biota in the water column.
6. The toxic effect of algal blooms enhanced by the dissolved inorganic wastes in the water column around net-pen farms.
7. Changes in the epifaunal community caused by the accumulation of organic wastes in sediments below net-pen farms.
8. The proliferation of human pathogens in the aquatic environment.
9. The proliferation of fish and shellfish pathogens in the aquatic environment.
10. The increased incidences of disease among wild fish.
11. The displacement of wild salmon in the marketplace by farmed salmonids.
12. The escape of Atlantic salmon - a non-native species.
13. The impact of antibiotic-resistant bacteria on native salmonids.
14. Impacts on human health and safety.

Aspects of environmental concern which are of importance for salmon aquaculture were summarised by Ellingsen *et al*. (2009) (Table 4). The main impacts are caused by: Use of fossil fuels for energy and diesel for fishing (raw material for feed) and transport; Exploitation of fish resources for feed production; Eutrophication caused by waste feed in aquaculture, faecal matter and excretory products which influence a) the organic enrichment of sediments and can have an effect of benthic assemblage; and b) nutrient enrichment of the water column; Additionally, eutrophication caused by excess nutrients in agriculture for production of vegetable part of feed must be included. Biodiversity loss because of interaction with the wild population a) Escapes causing genetic dilution of the wild stock b) disease and parasite transfer and potentially causing diseased wild stock and influencing health and increase in mortality; Spreading of salmon lice; Chemical discharge originating from a) use of anti-fouling agents and b) medicines, which can have potential influence on the loss of sensitive species (biodiversity loss); land use; and energy use in all parts of the value chain.

The use of medicine for control of diseases and salmon lice, and the effect of escapees on the wild salmon are specific issues of concern for salmon aquaculture. Exploitation of forage fish puts pressure on fish stocks and efficiency of the feed and farming systems have an impact on eutrophication and nutrient enrichment of sediments and the water column.

Table 4. Environmental impacts—aquaculture (Adapted from Ellingsen *et al.,* 2009)

Aspect/cause	Impact category (consequence)	Method
Use of fossil fuel	Greenhouse effect, acidification. Use of non-renewable resource	Indicator, LCA
Exploitation of fish	Pressure on fish stocks (biological diversity)	Indicator
Use of crops for feed	Greenhouse effect , Eutrophication caused by excess nutrients (phosphorous and nitrate), Acidification	LCA, indicator
Waste feed	Nutrient enrichment of the water column, Eutrophication (Organic matter in water and sediments), secondary greenhouse gas emissions (N_2O)	LCA, indicator
Escape	Threatens the wild salmon (biological diversity)	Indicator
Predator control measures	Biodiversity loss. Increase mortality in seabirds or marine mammals by predator control measures	Indicator, LCA
Use of delousing/ medication/ vaccines	Threatens the wild salmon (biological diversity) transmission of diseases into the wild	Indicator
Chemical discharges	Ecotoxicity, loss of sensitive species (biodiversity) i.e. cooper emissions from pens/boats paintings	Indicator, LCA
Vessel/facility design	Visual/smell problem	Indicator
Use of drinking water	Limited amount of available water	LCA, indicator
Land /seafloor use	Visual disturbance, limitations to coastal zone use, deterioration of the benthos,	LCA, indicator

Aquaculture technologies and preventive measures

Aquaculture technologies have been improved and preventive measures have been implemented regarding the responsible, safe, and effective use of feeds and feed additives, chemicals and chemotherapeutants (vaccines) to prevent diseases and medication used to control sea lice, as well as other aquaculture practices which might reduce health and safety risks to humans and wild life. Animal welfare issues are taken into consideraion and limits for stocking density are set as well as preventive measures and procedures to minimize escapes.

Animal welfare issues in aquaculture

Animal welfare issues in aquaculture are linked to good aquaculture practices, the effects of disease, handling, transport, food deprivation, and slaughter technique on fish welfare. The effects of stocking density, is an area of welfare concern and appears to comprise of numerous interacting and case specific factors. Stocking density/total biomass per site in Norway is limited and the procedures for licences are regulated. Surveillance of aquaculture production in various countries includes ensuring effective monitoring of sea lice for example in Canada (Fisheries and Oceans, Canada, 2011) and in Norway where the IMR (Institute of Marine Research) has particular focus on the effects of sea lice on farmed fish, the effects of escaped farm-raised fish on natural populations, and the effect of organic matter (fouling) from farming operations on the hard and deep bottom.

Water quality monitoring

Farm operation effects on water quality are usually measured using internationally standardized methods. To ensure the well-being of the fish most farms measure dissolved-oxygen levels on a regular basis. Determination of metabolites such as phosphates and ammonia is sometimes required for acquiring certification according to voluntary standards for a single farm, and this may also be required as a condition of the farm’s operating permits. There may be concern about the cumulative and far-field effects on water quality of several farms in one area, especially in nutrient-poor areas.

Coordinated nutrient monitoring is often included within the specifications of an Area Management Agreement. This implies that the requirement requires data on any sampling of phosphorus, nitrogen, total suspended solids (TSS) and biological oxygen demand (BOD). The seafood industry (capture and farmed) must monitor for an increasing number of harmful algal species in the water column and for an increasing number of algal toxins in seafood products.

2.2 Environmental impacts assessed by LCA

Life Cycle Impact Assessment according to ISO 14040 and 14044 (ISO 2006a, 2006b) and the ILCD handbook (JRC, 2010) will be applied in the SENSE project as a tool to assess the key environmental impacts of food supply chains. The standards describe the method and basic requirements for undertaking an LCA. LCA aims at providing a comprehensive view of environmental impacts. However, not all types of impacts are equally well covered in a typical LCA. The need for standardized methodology to assess the environmental impact of products has been emphasised by numerous authors and organization (Ziegler *et al*., 2012). Standards for carbon foot printing are being developed for example ISO 14067 expected to be finalized for publication in March 2014 and ISO 14065:2007 (Greenhouse gases - Requirements for greenhouse gas validation and verification bodies for use in accreditation or other forms of recognition). British standards (BSI) have developed a specific standard on life cycle greenhouse gas emissions for goods and services and guidelines (PAS2050/2011) and a seafood-specific GHG emission standard (PAS 2050-2:2012). The carbon footprint of a product has received a lot of attention but it is limited to studying only the environmental impact category “global warming potential.” Life cycle assessments of food, which cover more impact classes than just climate impacts, have been performed since the 1990s. Most of the studies include in addition to climate impacts also eutrophication, acidification, and energy use. Some studies include also land and water use, human toxic effects, ecotoxic effects, tropospheric ozone formation, and ozone depletion.
ILCD handbook gives guidelines for selection of characterisation methods to assess the following environmental impact classes

1. Climate change,
2. Ozone depletion,
3. Human toxicological effects,
4. Particulate matter/Respiratory Inorganic

5. Ionizing radiation
6. Photochemical ozone formation
7. Acidification
8. Eutrophication
9. Ecotoxicological effects
10. Land use
11. Resource depletion
12. Other impacts (noise, accidents, desiccation, erosion, and salination)

Environmental impacts of aquaculture production systems have been assessed by Life Cycle Assessment (LCA) in several studies where both regional impacts (e.g. eutrophication and acidification) and global impacts (e.g. climate change and ozone depletion) have been considered. A review of existing literature on the application of LCA for seafood was recently carried out to summarize the range of available reports and studies regarding GHG emissions from seafood supply chains (Parker, 2012). For tracing of nutrient flows and estimating the nutrient retention efficiency, mass balance models are more suited than LCA models. Nutrient balance accounting to estimate outputs of phosphorus, nitrogen and suspended solids was recently reported for Norwegian salmon farming by Ytrestøyl *et al.* (2011).

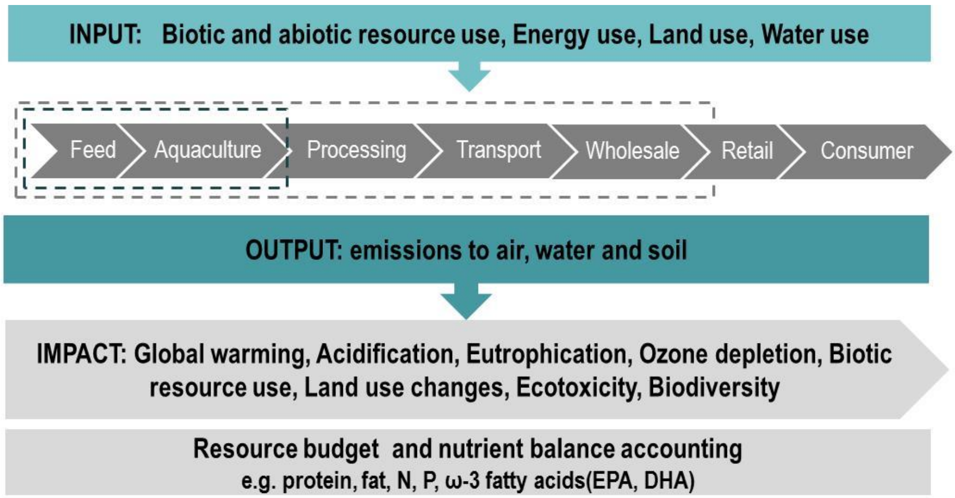

Figure 9 A generic aquaculture supply chain from feed to consumer showing different boundaries (dotted lines), the input resources and the output emissions influencing the environmental impacts as have been assessed in LCA studies on aquaculture systems and salmon supply chain. Resource budget accounting has also been performed for salmon.

Functional Unit

Most LCAs have reported the environmental impacts relative to a given mass of live weight fish or fillet. Very few have extended the life cycle to incorporating processing activities and additional ingredients for value-added products (Parker, 2012). In some cases, analysis of these additional processes have identified non-fishery ingredients as important drivers of GHG emissions; such is the case for canned mackerel with added oil (Buchspies *et al.,* 2006) and fish burgers (Svanes *et al.*, 2011). The following Table 5 gives examples of functional units, allocation and tools used for different studies on LCA on salmon. It is important to notice that 3 out of the 4 cases have as a system boundary “farm gate”. Not including processing facilities for instance implies that the impacts of extra processes and ingredients are not considered as stated before. However, some studies on seafood have also included processing and transport steps (Ellingsen *et al*., 2009; Ziegler *et al*., 2012)

Table 5 System boundaries, functional units and allocation for salmon LCAs (Henriksson et al, 2012)

Reference	System	Functional Unit	System boundary	Allocation	Software	Database
Pelletier and Tyedmers, (2007)	Salmon feeds	1 tonne of live weight	Farm gate	Gross nutritional energy	SimaPro v.7.0	Ecoinvent v.2, personal communication
Ayer and Tyedmers, (2009)	Various	1 tonne of live weight	Farm gate	Gross nutritional energy	SimaPro v.7.0	Ecoinvent 1.2, IDEMAT 2001, LCA Food 2005, personal communication
Pelletier *et al.* (2009)	Cage	1 tonne live weight	Farm gate	Gross nutritional energy	Simapro v.7.1.8	Ecoinvent v.2
Ellingsen and Aanondsen (2006)	Net cage	200 g fillet	Market	Mass/ Economic value	SimaPro v.6.0	ETH-ESU 96, Buwal 250

The functional unit in many studies focusing only on the production was ”tonne of live weight” (Ayers and Tyedmers (2009), whereas studies that covered the whole supply chain (taking into account the processing and transport to retail), had either a functional unit of ”1kg of fillet” (Buchspiess *et al.,* 2011; Ellingsen *et al*., 2009) or portion (i.e. 200g fillet). Calculations of live salmon to the functional unit of 1 kg edible part has been assumed as 1.74 kg of live salmon would yield 1 kg edible fillet (Winther *et al*., 2009; Hognes *et al*., 2011)

Allocation

LCA studies include several methodological choices which are uncertain and may potentially influence their results. Examples include allocation methods, time limits for the inventory analysis and choices of characterisation methods for the impact assessment. The choice of allocation procedure is one of the most controversial methodological issues in LCA. The need for allocation arises when the environmental loads must be divided between two or more different processes/co-products. According to the ISO 14044 standard for LCA, allocation shall be dealt with in agreement with the three following steps (ISO 14044: 2006):

1. Wherever possible, allocation should be avoided.
2. Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them.

3. Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them.

Furthermore, the ISO 14044 (ISO, 2006) states that when two or more allocation procedures seem to be relevant a sensitivity analysis needs to be carried out to show the impact of the different allocation procedures. The ISO standard also requires that a clear justification is made on the chosen allocation method/s. Currently, step three above, is the most frequently selected allocation procedure in published seafood studies, i.e. allocation based on other relationships between input and output (Svanes *et al*, 2011). Most of these published LCA studies have applied economic allocation, although mass allocation and system expansion have also been applied (Ayer *et al.,* 2007). Economic allocation is however not stable over time as economic allocation is sensitive to changes in market prices (Svanes *et al.*, 2011; Ytrestøyl *et al*., 2011). The same holds true for system expansion. Additionally, the economic value does not represent the biophysical flow of materials and energy in seafood product systems. On the other side it reflects the driving factors behind the production patterns and thus is useful in most cases where the attribution of environmental impacts to economic products is of interest. In any case the choice of allocation method has to be in line with the underlying questions of the study and the goal and scope definition.

It has been stressed that more research is needed for development of more relevant allocation procedures (Ayer *et al,* 2007; Tyedmers & Pelletier, 2007; Pelletier & Tyedmers, 2011). Many researchers agree that a standardised method to evaluate the environmental impacts is needed using harmonised allocation method. However, the choice of allocation procedures will depend on the intended goal of the study and the questions to be answered. Allocation according to gross chemical energy content has e.g. been suggested. Svanes *et al.* (2011) performed a case study to test the differences between mass, economic, novel hybrid and gross energy content allocations. The difference between allocation methods was found to be large, with the largest differences when using economic allocation while mass allocation gave the smallest variations. Moreover, the energy allocation results were very close to those of mass allocation.

2.3 LCA studies on seafood

LCA is becoming a widely used tool to create environmental profiles of different food products. Over the last years the number of LCAs has grown steadily. Table 6 is a compilation of different impact categories that have been studied while assessing seafood production systems. According to the overview (Table 6), LCA studies on seafood have included global warming potential, acidification potential, eutrophication potential and ozone layer depletion potential. Additionally, some studies have also focused on abiotic depletion potential, photochemical oxidant formation potential, cumulative energy demand/primary energy use ratio, and to a minor extent on human toxicity potential, energy consumption, or eco-toxicity potential.

Table 6 Impact categories reported in different LCA studies on seafood processing or supply chain (From Vázquez-Rowe et al., 2012)

Impact categories in seafood processing or supply chain studies	Eyjolfsdottir et al (2003)	Ziegler et al (2003)	Thrane (2004)	Ellingsen & Aanondsen (2006)	Hospido et al (2006)	Fikseaunet (2007)	Pelletier et al (2007)	Pelletier & Tyedmers (2010)	Ziegler & Valentinsson (2008)	Sund (2009)	Fet et al (2010)	Fulton (2010)	Parker (2011)	Svanes et al (2011a)	Svanes et al (2011b)	Vázquez-Rowe et al (2011a)	Ziegler et al (2011)	Vázquez-Rowe et al (2012)
Species, products*	C	C	P	CS	T	P	V	V	L	C	P	C Po S	K	C	C	H	Sh	O
Energy Consumption	✓		✓	✓														
Global warming Potential	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Abiotic depletion Potential				✓	✓	✓	✓	✓	✓			✓				✓	✓	✓
Acidification Potential	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓
Eutrophication Potential	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓
Ozone depletion Potential	✓		✓		✓	✓	✓	✓	✓				✓	✓	✓	✓	✓	✓
Photochem. oxidant formation Potential			✓		✓	✓	✓	✓	✓					✓	✓		✓	✓
Cum. energy demand/ primary energy use							✓	✓	✓	✓		✓	✓	✓	✓		✓	
Human toxicity Potential	✓			✓		✓	✓	✓									✓	
Freshwater aquatic eco-toxicity potential	Eco-toxicity Potential	✓	Eco-toxicity Potential	Eco-toxicity Potential		✓	✓	✓										
Marine aquatic eco-toxicity potential						✓	✓	✓	✓							✓	✓	✓
Terrestrial eco-toxicity potential						✓	✓	✓									✓	

*Species or products: C=cod, P= fish products; S=salmon; T=tuna; L=lobster; Po= pollock; K= krill; H=hake; Sh=shrimp O=octopus; V= seafood

An overview of the resource use in the processing steps of aquaculture salmon production, from cradle to grave are shown in Figure 10 and the main environmental impact categories of the salmon supply chain as estimated based on the reported LCA studies.

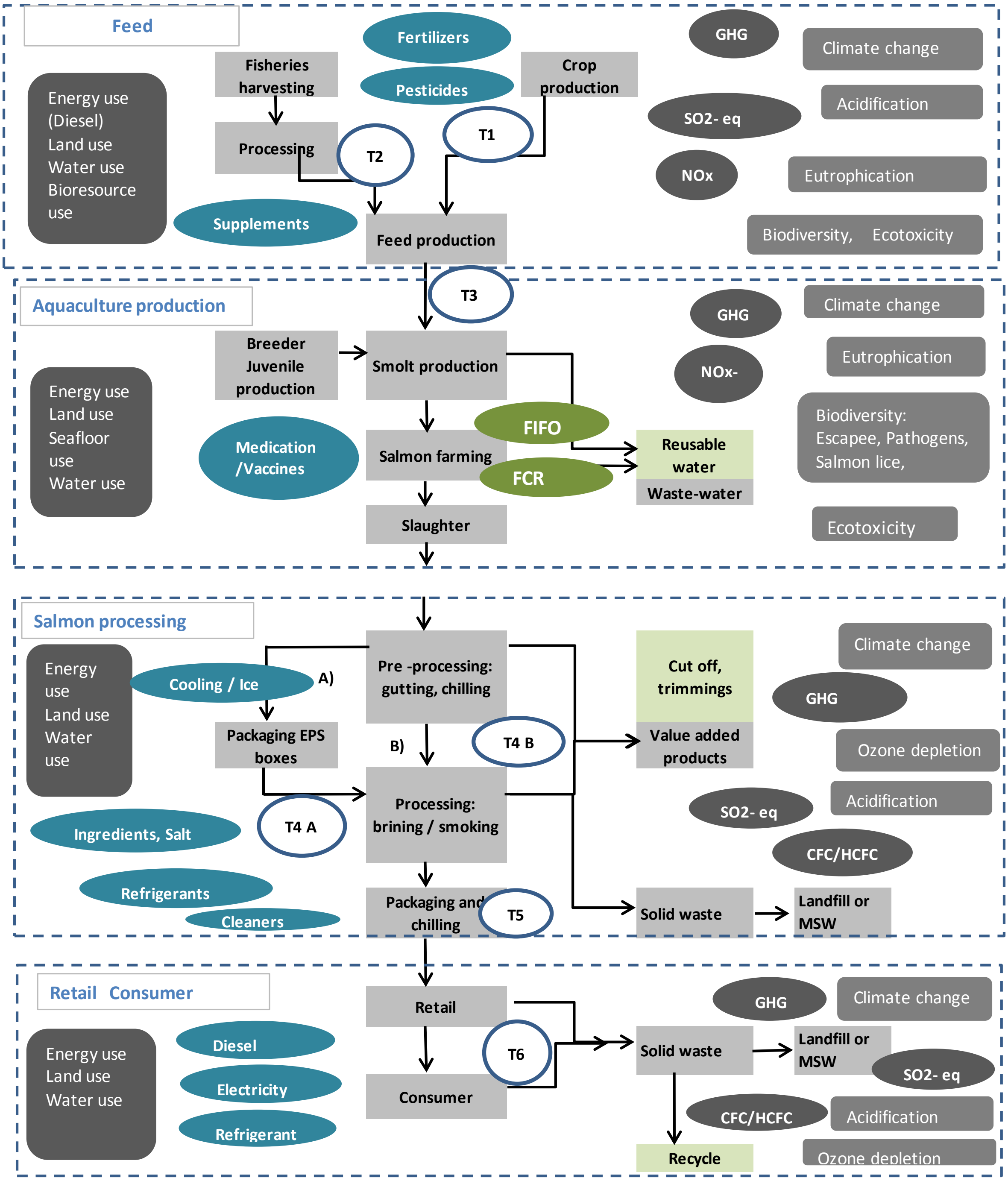

Figure 10 Flow diagram of aquaculture salmon production from cradle to grave showing input resources, output emissions and the most common environmental impacts assessed by LCA (climate change, ozone depletion, eutrophication, acidification, terrestrial and marine aquatic and sediment toxicity, and challenges that cause threats to biodiversity (chemical discharges (antifoulants and medicines), pathogens, escapees, and sea lice)

2.4 LCA studies on aquaculture supply chain

Studies on LCA on aquaculture species (Atlantic salmon, Rainbow trout, Arctic char, turbot, sea bass, tilapia and shellfish) have focused on the feed and production systems and the characteristics of different farming systems (Parker, 2012).

Studies on salmon and marine net-pen production systems have been carried out for Norway, Canada, UK and Chile, marine cages in Scotland, marine floating bag, saltwater flow through system and land based recirculating systems in Canada (lca.seafish.org). LCA studies on aquaculture production related to the salmon supply chain are further explored herein to gain an overview on the characteristics of different regions in Europe and in other countries where salmon aquaculture is common (Canada, US, UK and Chile) and how the environmental impacts from aquaculture may affect the regions differently. Feed production is most often the major contributor to environmental impacts in conventional aquaculture systems (Aubin *et al.,* 2006; Ellingsen and Aanondsen, 2006; Tyedmers and Pelletier,2007; Winther *et al*., 2009: Ziegler *et al.,* 2012), while the impact of energy use is dominating in recirculation systems (Aubin *et al*., 2009; Ayer and Tyedmers, 2009) More recent studies have included the impact of processing and transport (Ellingsen *et al.,*2009; Winther *et al.,* 2009; Ziegler *et al.,* 2012).

2.5 Feed - Bioresource Use

Exploitation of fish for feed – composition of feed

The comparative life cycle impacts of feed production within and among regions, is of interest in the overall environmental impact of salmon production. In general, fish- and livestock-derived inputs contribute disproportionately on a per-unit mass basis when compared with crop-derived inputs.

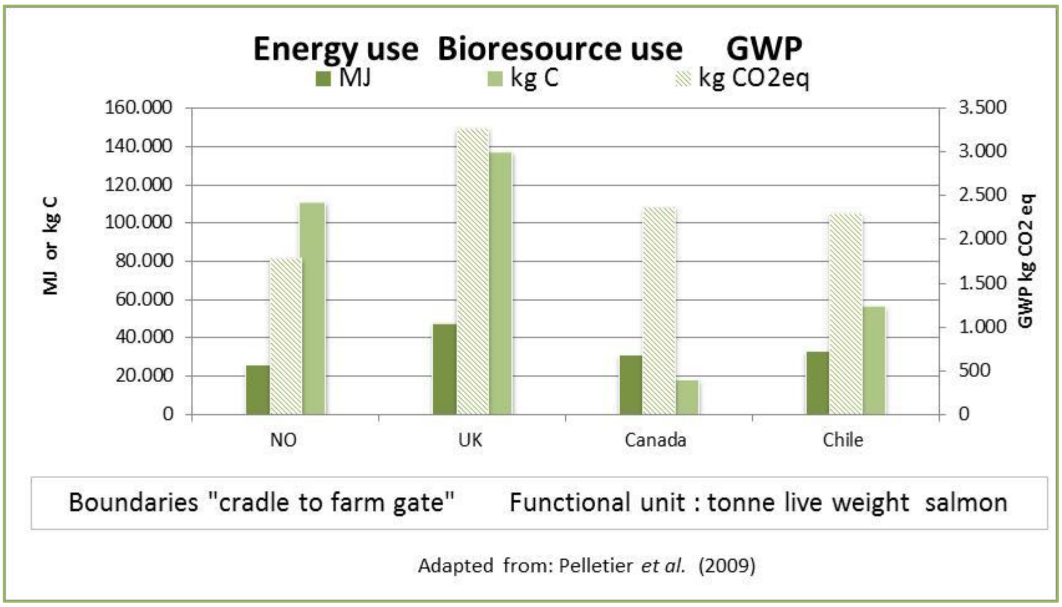

Figure 11 Energy use, bioresource use and GWP for aquaculture salmon ”cradle to gate” fed with traditional diet in the four countries Norway, UK, Canada and Chile (From: Pelletier et al. 2009)

Studies by Pelletier and Tyedmers (2007), Pelletier *et al.* (2009) and Boissy *et al.* (2011) highlight the environmental impact of bioresource use reflected by different feed composition (Table 7). When comparing by LCA farmed salmon in Canada, Chile, Norway and UK the environmental impacts reflected the different feed composition for the different regions (Pelletier *et al.,* 2009) (Figure 11).

Fish and poultry-derived ingredients generated substantially greater impacts than crop-derived ingredients in the study of Pelletier & Tyedmers (2007) (Table 7). Furthermore, replacing fish meals/oils from dedicated reduction fisheries with fisheries by-product meals/oils markedly increased the environmental impacts of feed production, largely due to the higher energy intensity of fisheries for human consumption, and low meal/oil yield rates of fisheries by-products. In this case an organic production failed to reduce the environmental impacts of feed production for the suite of impact categories considered (Pelletier & Tyedmers, 2007).

Table 7 GWP, acidification, eutrophication, and use of energy, water and bioresources reported in different LCA studies of the farm-gate production of salmon in Norway, UK, Canada, and Chile (Adapted from Pelletier and Tyedmers, 2007, Pelletier *et al.,* 2009 and Boissy *et al*., 2011)

References Functional unit	**Region / Species / System /Allocation**	**GWP**	**Acidification**	**Eutrophication**	**Energy**	**Water use**	**Bioresource use**
		kg CO_2eq	kg SO_2eq	kg PO_4-eq	MJ	m^3	kg C
Pelletier & Tyedmers (2007) **Canada / Salmon 1 tonne feed**	(C) Conventional feed Gross nutritional energy content	1,400	12.6	5.3	18,100		10,600
	(OA) Organic crop ingredients /conventional fish and poultry ingredient	1,250	11.8	4.9	17,100		10,600
	(OBP) Organic crop ingredients/fisheries by-products ingredients	1,810	24.6	6.7	26,900		45,100
	(ORF) Organic crop ingredients/reduced fisheries ingredients	690	2.3	2.3	9,860		6,300
Pelletier et al., (2009) 1 tonne live weight salmon	NO (40 % crops, 58,6 % fish)	1,790	17.1	41.0	26,200		111,100
	UK (30 % crops, 66,6 % fish (use of trimmings))	3,270	29.7	62.7	47,900		137,200
	Canada (50% crops, 31,6 % fish, 19,9 % livestock)	2,370	28.1	74.9	31,200		18,400
	Chile (40% crops, 42,2 % fish, 15% livestock)	2,300	20.4	51.3	33,200		56,600
Boissy, *et al*. (2011) 1 tonne live weight salmon	Atlantic salmon / standard diet	2,150	10.3	40.2	32,159	30	
	Atlantic salmon / low marine-fishery capture diet	2,480	13.4	43.7	31,688	34.1	
	Rainbow trout / standard diet	2,220	12.7	42.2	55,730	72.6	
	Rainbow trout / low marine-fishery capture diet	2,220	13.5	47.9	55,057	69.5	

Analysis including feed production and fish production (slaughtering, processing and sales NOT included)

Allocation: Gross nutritional/chemical energy content; Functional Unit: live weight tonne of salmon or salmon feed

Crop-derived inputs accounted for only one-third of UK diets but almost 50% of feed milled in Canada. In contrast, the proportion of fish-derived ingredients is the lowest in Canada (31.6%) and Chile (42.2%), and much higher in Norway (58.6%) and the UK (66.6%) (Pelletier *et al.,* 2009). Livestock co-products were small but noteworthy contributions to feeds milled in both Canada (19.9%) and Chile (15.1%). In Norway and the UK, fish-derived inputs contributed an average of 71% and 84%, respectively, across impact categories while only accounting for 58% and 66%, respectively, of the mass of the feeds milled. Similarly, in Canada and Chile, fish- plus livestock-derived inputs accounted for just over 50% of the mass of all feed inputs (Pelletier et al. 2009). This difference in fish derived input is clearly reflected in the high value of the biotic resource use (BRU) caused by the application of trimmings in the UK feed and fish oil and fish meal in Norway compared to lower ratios in Chile and Canada. However, Torrisen *et al. (*2011) questioned that the environmental impacts should be considerably lower when feeds contained reduced proportions of fish and poultry-derived ingredients, emphasizing the importance of co-product allocation procedures. Further, low-impact fishery ingredients like menhaden meal used in Chile outperformed high-impact crop ingredients like wheat gluten (Pelletier *et al.* 2009) (Figure 11). Additionally of interest is the hypothetical replacement of all fishery derived ingredients with menhaden in 2007 Norwegian salmon production, which could have reduced the industry's greenhouse gas emissions by 57%.

The environmental consequences of replacing fish meal and fish oil with plant-based sources in salmonid feeds were investigated using LCA by Boissy *et al*. (2011). Two scenarios of Atlantic salmon (*Salmo salar*) and rainbow trout (*Oncorhynchus mykiss*) farming were compared. The first scenario used a Standard Diet (STD) with high levels of fish meal and fish oil, and the second a Low Marine-Fishery-Capture Diet (LFD) in which fish meal and fish oil were replaced by plant protein and oil sources.

Table 8 adapted from Boissy et al (2011) shows the different feed composition in fish oil based feed versus a vegetable oil based feed and the origin of the ingredients. The assessment confirmed the substantial contribution of feed to the environmental burdens of fish production and the LFD scenario led to a significant decrease in biotic resource use compared to the STD scenario with the same total energy demand. However, the climate change potential was approximately 18% higher in the vegetable oil based feed for salmon 2,150 kg CO_2eq compared to 2,480 kg CO_2eq (Table 7)

Table 8 Example of feed composition in standard (STD) fish oil based feed versus a vegetable oil based feed (LFD low fish diet) and origin of ingredients (adapted From Boissy *et al*., (2011))

Ingredients	**3mm**		**Origin**
	STD	LFD	
Wheat	7	7.2	France
Wheat gluten	15		France
Fish meal	32		Peru
Soybean meal	12.5		Brazil
Soy protein concentrate	5		Brazil
Fish oil	22.8	-	Norway
Camelina oil	-	4.5	USA
Palm oil	-	7	Malaysia
Rapeseed oil	-	11.4	Germany
Corn gluten meal 60	4.3		USA

Environmental impacts of feeds depended highly on the geographic origins of feed ingredients from fishery (e.g., fish oil from Norway or Peru) and from terrestrial agricultural crop species (e.g., palm oil or rapeseed oil). This study demonstrated the importance of a multicriteria method to give stakeholders the most accurate information on the potential consequences of replacing fishery products with plant-based sources in aquafeeds (Boissy *et al.,* 2011).

When switching from animal based feed to plant based feed it is important to consider factors as eutrophication or terrestrial eco-toxicity (http://www.euraquaculture.info/) and LUC coupled to soy bean production, as well as nutritional differences e.g. amino acids (Nasopoulou and Zabetakis, 2012; Mente *et al,* 2011)

Generally, fish growth rates are similar in systems that use standard fish based feed versus systems with mix plant-fish based diets, nevertheless this fact is dependent on the species, level of replacement, and production system (Nasopoulou and Zabetakis 2012; Boissy *et al.* 2011).

Feed Conversion Ratio

Different fish species vary in their food consumption patterns and therefore in their feed needs and habits. Some fish species are carnivores and therefore their food conversion rate is not particularly efficient. Salmon for instance has, in nature, a prey-predator efficiency conversion of about 1 to 10, making necessary 10 kg of prey to produce 1kg of salmon (http://www.aquamaxip.eu/). The EU project "Consensus" (http://www.euraquaculture.info/) estimated that to produce 1kg of farmed salmon there is a need of about 3 kg of wild fish as feed (figure estimated without including recovering of meal and oil from aquaculture waste). It is important to note that due to better production systems and improvements on feed producing technologies the conversion ratio in general is improving rapidly. The feed composition differs for different regions and consequently the feed conversion ratio (FCR) as has been reported for salmon in the UK, Norway, Canada, and Chile (Table 9). These differences are due to for example changes in feed composition and feeding technologies, but also regional variations. While replacing fish based feed with vegetable based feed it is important to consider that some plants have as a component phytic acid, which reduce salmon's intestines ability to absorb phosphorus. FCRs for many aquaculture species dependent on industrially manufactured compound aquafeeds are projected to decline as a result of improved feed efficiency and management (FAO, 2012).

Table 9 Feed conversion factors for salmon (kg feed per kilo salmon to slaughter in live weight)

Reference	Norway	UK	Canada	Chile
Pelletier and Tyedmers (2007) (FCR - feed to flesh)			1.3	
Pelletier *et al.,* 2009	~1.1	~1.33	~1.31	(~1.5)
Ellingsen and Aanondsen (2009)	1.29			
Norwegian Fisheries and Aquaculture Association (FHL, 2010)	1.3			

FIFO (fish in – fish out)

Two decades ago, the main ingredients for Norwegian salmon feed were fish meal and fish oil. However, in 2010 only 52% of the ingredients were of marine origin, and the remaining 47% of plant origin (on dry matter basis) and added supplements (Ytrestøyl *et al.,* 2011). This change in diet has influenced changes in the fish-in-fish-out (FIFO) ratio (the amount of forage fish used to produce the amount of fish oil and meal required to produce 1 kg of salmon) in Norwegian diet during the last decades. FIFO is used as a measure of the amount of marine resources that is consumed in the production of farmed fish. The calculation of the FIFO ratio is based on two conversion ratios. The first is the conversion ratio of forage fish into fish meal (FM) and fish oil (FO). The second conversion ratio is the amount of feed (kg) consumed to produce one kg of salmon (economic feed conversion ratio, eFCR).The FIFO ratio for fish oil and fish meal in Norwegian fish farming has decreased from 7.2 and 4.4 in 1990 to 2.3 and 1.4, respectively, in 2010. When correcting for use of by-products from capture fisheries, the 2010 values were 1.8 and 1.1, respectively (Ytrestøyl *et al*., 2011).

Nutrient – balance accounting and resource budget (protein fat energy, phosphorous , n-3 fatty acids EPA, DHA).

Several indicators and methods for measuring sustainability and eco-efficiency of aquaculture productions have been developed, such as, marine nutrient dependency ratio and various nutrient retention ratios. Evaluation of sustainability of aquaculture is complicated, and different aspects have to be addressed. The outcome will depend on which impacts are included in the analysis and how the impacts are allocated between co-products in production processes that generate several products. “There is currently no single method that is robust enough to cover all environmental impacts related to food production and several methods must be used in combination to evaluate the eco efficiency of food production” (Ytrestøyl *et al*., 2011).

Nutrient – balance accounting to estimate outputs of phosphorus, nitrogen and suspended solids was reported for Norwegian salmon farming by Ytrestøyl *et al.* (2012). For tracing of nutrient flows and estimating the nutrient retention efficiency mass balance models are more suited than LCA models. Access to representative data on nutrient composition of the feed, final product and, particularly in the parts of the salmon that are not consumed by humans, was vital for tracking the nutrient flows when making a resource budget for the Norwegian salmon production in 2010.

The Norwegian aquaculture industry has an accurate system for reporting detailed aquaculture production data, and information of ingredients used for feed production in 2010 was provided by BioMar, Ewos and Skretting. Marine Harvest provided data on nutrient content in salmon. Data on fish composition was also obtained from official databases (Nifes sjømatdata, Matvaretabellen). With this information, the total nutrient flow in Norwegian salmon farming in 2010 could be estimated.

Phosphorus is a limiting element in vegetable (as fertilizer) and animal (as feed) systems and as such should be carefully managed. In Norway the 3 leading feed producing companies (BioMar, Ewos, and Skretting) used 12046 tons of phosphorus for Salmon feed. Of this amount 27% was retained in the salmon while the remaining 73% went to the sea (Ytrestøl *et al*, 2011).

2.6 Feed - Energy use and GWP

Feed plays a critical role in GHG performance of aquaculture. Reports from LCA studies agree that the production of feed from fisheries and crops accounts for the majority of salmon aquaculture's energy use and greenhouse gas emissions (Aubin *et al.,* 2006; Ellingsen and Aanondsen, 2006; Tyedmers and Pelletier (2007); Winther *et al*., 2009: Ziegler *et al.,* 2012). Fuel use in fishing, and feed production in aquaculture are key contributors to greenhouse gas emission (Ziegler et al., 2012). Life cycle assessment (LCA) carried out by Tyedmers and Pelletier (2007) showed that dependence on energy in aquaculture is correlated with production intensity mainly due to production and delivery of feed in agreement with studies on rainbow trout (Grönroos et al. 2006). Another factor to consider is the local availability of crops and fish feed ingredients, since sourcing of raw material for feed processing can involve energy demanding transportation. Feed producers source raw materials from diverse fish, crop, and livestock sources globally, each with characteristic resource dependencies and environmental impacts. The main hotspots in the feed primary production are the emissions from crop production (mainly fertilizer (N) and GHG emissions from burning diesel in operation of vessels in fisheries and manufacturing of fish meal (different energy sources). It has been estimated that in aquaculture systems feed production is often accountable for up to 80-90% of the total energy needs and environmental impacts (Ytrestøyl *et al.*, 2011). In a study by Winther *et al*. (2010) the feed production accounted for 75% (2,72 kg CO_2eq /kg fish) of the total GWP of all process steps of salmon produced in Norway and transported by truck to Paris (Figure 12).

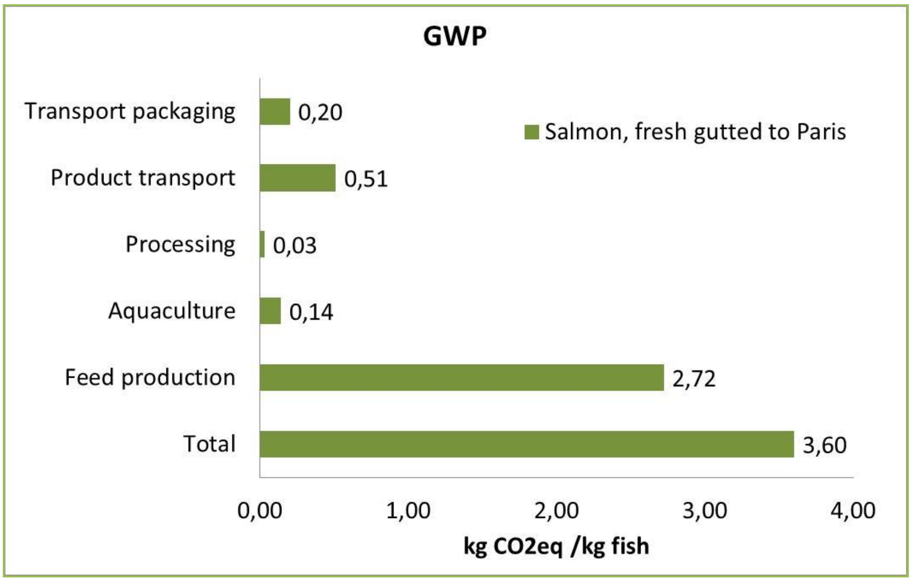

Figure 12 GWP in process steps of a salmon supply chain (Adapted from Winther *et al.,* 2010)

Comparison of the contribution of feed ingredients and different processes to CO_2 footprint showed large contribution of the soya protein concentrate, which was similar to the contribution of the combined effect of production of marine meal and oil. If LUC coupled to soy bean production would be included the contribution from soy would be even higher (Hognes *et al.,* 2011; Ytrestøyl *et al.*, 2011). Transport from crop grower to feed production manufacturers and further to salmon production need to be taken into account. Environmental cost consideration of shipping and transporting fishmeal by container from South

America to Europe including fossil fuels burnt and GHG emissions is of interest in this context Huntington (2004).

2.7 Feed - Land use

Natural resources availability is limited. There is a need to measure and control the impacts of different activities and how they will influence future access to resources. This is especially relevant for aquaculture production considering use of forage fish in feed and the trend to switch from a seafood based feed to a mixed plant-seafood feed. In a recent study by Hognes *et al.* (2011) the area used for farmed Norwegian salmon was estimated as follows:

Occupational agricultural land was calculated for the crops in the feed as the land area occupied by the growing crops (land use/kg crop /year) and other land use at the farm was not included. The results show that the total agricultural area required for the Norwegian salmon 2010 was 3.3 m^2 per kg edible products while Swedish chicken and pig occupied 7.0 and 8.4 m^2 per kg edible products, respectively. The high marine feed occupied only 0.3 m^2 agricultural land per kg edible products

Sea area primary-production-required (PPR) to sustain the fish used in the salmon feed and benthic area that is influenced by fishing gear is considered for the fishery ingredients in the feed. In this case the benthic effect of fishing gear on the bottom was not relevant since pelagic gears are not in contact with the bottom. The PPR was calculated using trophic levels for the species together with levels of primary-production-per-area in the Large Marine Ecosystem (LME) where they are caught (Hognes et al., 2011 / Ytrestöyl *et al.,* 2011). The total sea area required to sustain the primary production for production of marine ingredients in the 2010 diet was 115m^2/kg edible product. If only marine ingredients form the North Atlantic would be used the area required was 153m^2 sea area/kg edible products, since the respective species used for fish meal and oils occupy higher trophic levels in the marine food web compared to South-American forage species (Figure 13).

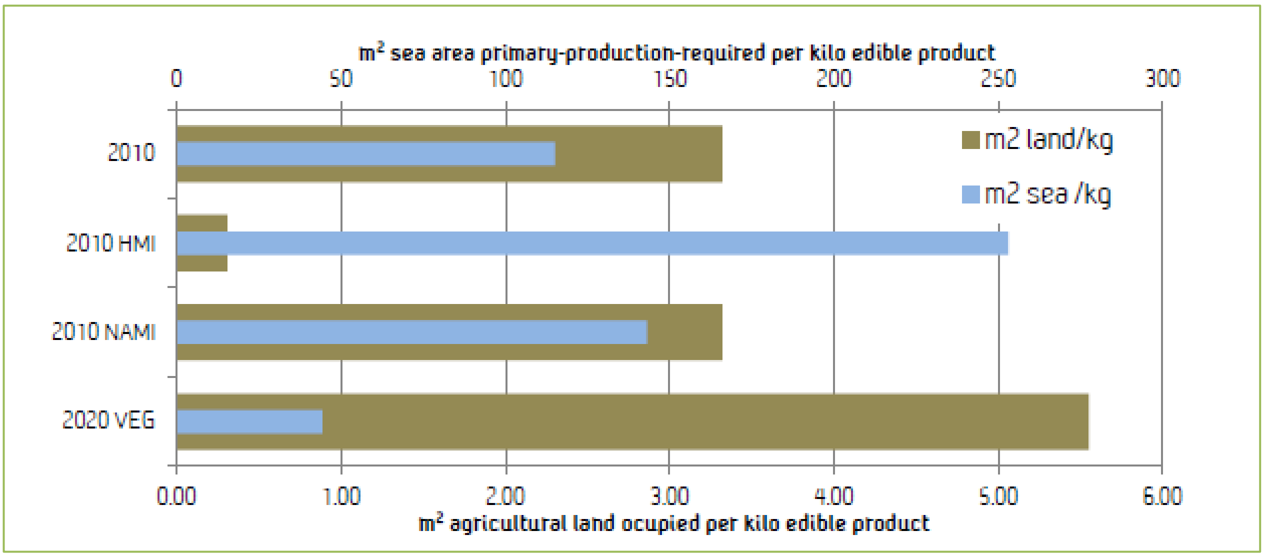

Figure 13. Agricultural area occupation and sea-primary-production area required (Source: Ytrestöyl *et al*., 2011)

Seafloor impact of fisheries and discards

Regarding the use of fish for feed the assessment of seafloor impacts are of interest. Recent studies on the application of LCA methodology in fisheries management involve assessment of fishing efforts on seafloor impact and energy use and proposed new indicators in relation to assessing the impact of fishing gear. This implies that total discarded mass could increasingly be distinguished from potential impact by applying two new concepts: primary production requirements and threatened species affected (Hornborg *et al.,* 2012; Nilsson and Ziegler, 2007).

Land use change (LUC) is measured as the percentage of global land cover that is converted to crop land, to further on distribute deforestation emissions over time. Until now there is no well accepted methodology on how to calculate LUC. Schmidt *et al.* (2012) proposed a model in which through the use of IPCC´s GWP, amortisation is avoided. Advantages of the model are that it can be used with attributional and consequential LCA and that it considers land occupation upstream effects.

2.8 Aquaculture - Eutrophication

Assessment of different rearing techniques

For traditional fish cage aquaculture, increased amounts of organic matter, dissolved and particulate nutrients loads, particularly organic phosphorus and nitrogen (in the form of ammonia) may encourage eutrophication with negative consequences for pelagic and benthic communities.

Accumulation of organic wastes (fish faeces and waste food) under aquaculture farms may also induce local organic enrichment. Sediment organic enrichment may lead to increased oxygen uptake, ammonium release and sulphate reduction and a decrease in the abundance, biomass and diversity of benthic invertebrates at farm sites as compared to reference sites (Hargrave, 2005). The overview in Table 10 from the different studies mentioned before, further emphasizes that the eutrophication potential is highly depended on the type of rearing system and the feed conversion factor in the different studies.

Further, the LCA study of Jerbi *et al*. (2012) on different rearing systems (traditional raceway TR and cascade raceway CR) of Mediterranean sea bass (*Dicentrarchus labrax*) demonstrated the different environmental load of the two systems. The impact categories considered on a global level were global warming potential (GWP), net primary production use (NPPU) and energy use (EU). At the regional scale eutrophication potential (EP), acidification potential (AP), water dependence (WD) and surface use (SU) were estimated. The diet process contributed to the majority of the impacts in both systems. The sea bass rearing stage was the main contributor of eutrophication. Feed efficiency appeared to have a dominant influence on the level of impacts involving diet process. The difference in the environmental load is the direct result of the relative ability of fish reared in TR to better convert their diet into biomass with a feed conversion ratio of 1.7, compared to 2.1 in CR.

Table 10 Eutrophication reported in LCA studies of different rearing systems and feed composition for salmonids

References Functional unit	Region / Species / System	Eutrophication
		kg PO_4-eq
Pelletier and Tyedmers (2007) **Canada / Salmon** **1 tonne feed**	(C) Conventional feed	5.3
	(OA) Organic crop ingredients /conventional fish and poultry ingredient	4.9
	(OBP) Organic crop ingredients/fisheries by-products ingredients	6.7
	(ORF) Organic crop ingredients/reduced fisheries ingredients	2.3
Pelletier *et al.* (2009) **1 tonne live weight salmon**	NO (40 % crops, 58,6 % fish ingredients)	41.0
	UK (30 % crops, 66,6 % fish ingredients (use of trimmings))	62.7
	Canada (50% crops, 31,6 % fish, 19,9 % livestock)	74.9
	Chile (40% crops, 42,2 % fish, 15% livestock)	51.3
Boissy, *et al.* (2011) **1 tonne live weight fish**	Atlantic salmon / standard diet	40.2
	Atlantic salmon / low marine-fishery capture diet	43.7
	Rainbow trout / standard diet	42.2
	Rainbow trout / low marine-fishery capture diet	47.9
Aubin, *et al.* (2009) **1 tonne live weight fish**	Rainbow trout in fresh water	65.91
	Sea-bass in sea cages	108.85
	Turbot in an inland re-circulating system	76.97
Ayer & Tyedmers (2009) **Atlantic salmon** **Atlantic char** **1 tonne live weight fish**	Conventional marine net-pen system - Salmon - British Columbia	35.3
	Marine floating bag system – Salmon - British Columbia	31.8
	Land-based saltwater flow-through system - Salmon - British Columbia	29.9
	Land-based freshwater recirculating system - Arctic Char - Nova Scotia)	8.4

2.9 Aquaculture – GWP and energy use

Different rearing systems - GWP, acidification and energy use

Feed production is most often the major contributor to environmental impacts in conventional aquaculture systems while the impact of energy use is often dominating in recirculation systems. The variety in energy use in the production on the farm depends on a lot of factors, such as water flow and the power supply (from the common grid or by diesel engines on the facilities). Concerns have been raised because of unanticipated impacts in assessments of the sustainability of closed-containment systems. Although these systems may have less impact on biodiversity loss and eutrophication, they may have more global impacts since they are often more energy and material demanding. Table 11 is an overview of LCA studies for different rearing systems from cradle to gate for salmonids showing results of environmental impacts.

Table 11 LCA for different rearing systems from cradle to gate for showing results of environmental impacts for the functional unit 1 tonne of live fish weight

References	Type of system	GWP	Acidification	Eutrophication	Energy	Water
		Kg CO_2eq	Kg SO_2eq	Kg PO_4eq	MJ	m^3
Aubin, *et al*., (2009)	Rainbow trout in fresh water	2753	19.17	65.91	78,229	52.6
	Sea-bass in sea cages	3601	25.30	**108.85**	54,656	48,785
	Turbot in an inland re-circulating system	6017	**48.28**	76.97	**290,986**	4.8
Ayer & Tyedmers (2009)	Conventional marine net-pen system	2073	18	35.3	26,9000	
	Marine floating bag system	1900	15.8	31.8	21,1000	
Atlantic salmon and Atlantic char	Land-based saltwater flow-through system	2770	16.6	29.9	97,9000	
	Land-based freshwater recirculating system	**28,000**	22.6	8.4	34,7000	

The impact of different production system used in the Mediterranean area, were studied by Aubin *et al*. (2009). They used LCA to compare three fish farms that represented contrasting intensive production systems: rainbow trout in freshwater raceways in France, sea-bass in sea cages in Greece, and turbot in an inland re-circulating system in France. Emission of nitrogen and phosphorus accounted for more than 90% of each farm's potential eutrophication impact. In the trout and sea-bass systems, feed production was the major contributor to potential climate change and acidification impacts and net primary production use (NPPU). In these systems, the main source of variation for environmental impacts was the feed conversion ratio. On the contrary potential climate change and acidification impacts were largely influenced by energy consumption on-site in the turbot re-circulating system. Similarly, according to a LCA study on two rearing techniques (traditional raceway TR and cascade raceway CR) of Mediterranean sea bass (*Dicentrarchus labrax*) (Jerbi *et al*., 2012), the major part of the energy consumption was due to the rearing phase through water pumping and oxygen injection and production. The main difference between the two systems was the water recirculation flow through system and tanks disposition. For all the studied impacts, the assessment revealed that CR presented more environmental burden than TR. The major differences between the two farming systems lay in Global Warming Potential GWP and energy use.

Ayers and Tydemers (2008) performed life cycle assessment (LCA) to quantify and compare the potential environmental impacts of culturing salmonids in a conventional marine net-pen system with those of three reportedly environmentally-friendly alternatives; a marine floating bag system; a land-based saltwater flow through system; and a land-based freshwater recirculating system. Results indicated that while the use of closed-containment systems may reduce the local ecological impacts typically associated with net-pen salmon farming, the increase in material and energy demands associated with their use may result in significantly increased contributions to several environmental impacts of global concern, including global warming, non-renewable resource depletion, and acidification

2.10 Aquaculture - Ecotoxicity

Chemical discharge from aquaculture farms including remains of chemotheropeutants can be a threat to biodiversity. The impacts measured as marine, terrestrial or human ecotoxicity has been included in a few studies (Table 12) while others have chosen to leave this out because methodologies are still under development and there may be uncertainty in the assessment.

Table 12 Ecotoxicity assessment in different rearing systems of salmonids

References / Functional unit	Type of system	Terresterial ecotoxicity	Marine ecotoxicity	Human toxcity
		kg 1,4-DB eq		
Ayer & Tyedmers (2009) **Atlantic salmon Atlantic char**	Conventional marine net-pen system		822,000	639
	Marine floating bag system		96,000	624
	Land-based saltwater flow-through system		235,000	939
	Land-based freshwater recirculating system		91,200	3340
Boissy, *et al.* (2011) **1 tonne live weight salmon**	Atlantic salmon / standard diet	6.3		
	Atlantic salmon / low marine-fishery capture diet	8.7		
	Rainbow trout / standard diet	16.7		
	Rainbow trout / low marine-fishery capture diet	19.4		
Pelletier & Tyedmers (2007) **Canada / Salmon** **1 tonne feed**	(C) Conventional feed Gross nutritional energy content		60,700	
	(OA) Organic crop ingredients /conventional fish and poultry ingredient Gross nutritional energy content		61,100	
	(OBP) Organic crop ingredients/fisheries by-products ingredients Gross nutritional energy content		63,300	
	(ORF) Organic crop ingredients/reduced fisheries ingredients Gross nutritional energy content		47,600	

2.11 Aquaculture - Biodiversity threats

There are many impact classes, which life cycle assessment does not usually cover, like biodiversity, effects on fish stocks and animal welfare.

Sea lice

Sea lice are a threat to wild populations so compulsory delousing should be implemented in all jurisdictions (following Norway). A robust framework of basin-scale cooperation between farmers and wild fish interests regarding synchronous stocking and treatment has been encouraged to minimize medicine use. Sea lice, of which there are several species, are natural occurring seawater parasites, which infect the salmon skin and if not controlled they can cause lesions, secondary infection and mortality. Salmon lice can be a threat to wild salmon stocks, particularly the seaward-migrating wild smolts (Skilbrei and Wennevik, 2006). Sea lice are controlled through good manufacturing practices and the use of pharmaceutical products, cleaner fish (different wrasse species, eating parasites off the salmon skin), and hydrogen peroxide baths (well boats or enclosed cages). Sea lice may also be controlled by low temperature, where tests with pumping deep bottom water into farms have proven successful. In the event of occurrence of salmon lice, natural methods are preferred and the use of cleaner fish is recommended since they do an important job by grazing surviving female lice after medical treatment, or keep control over lice during the time the fish are stored in waiting/harvesting pens. During bath treatment against salmon lice preventive measures shall be implemented to minimize environmental impacts.

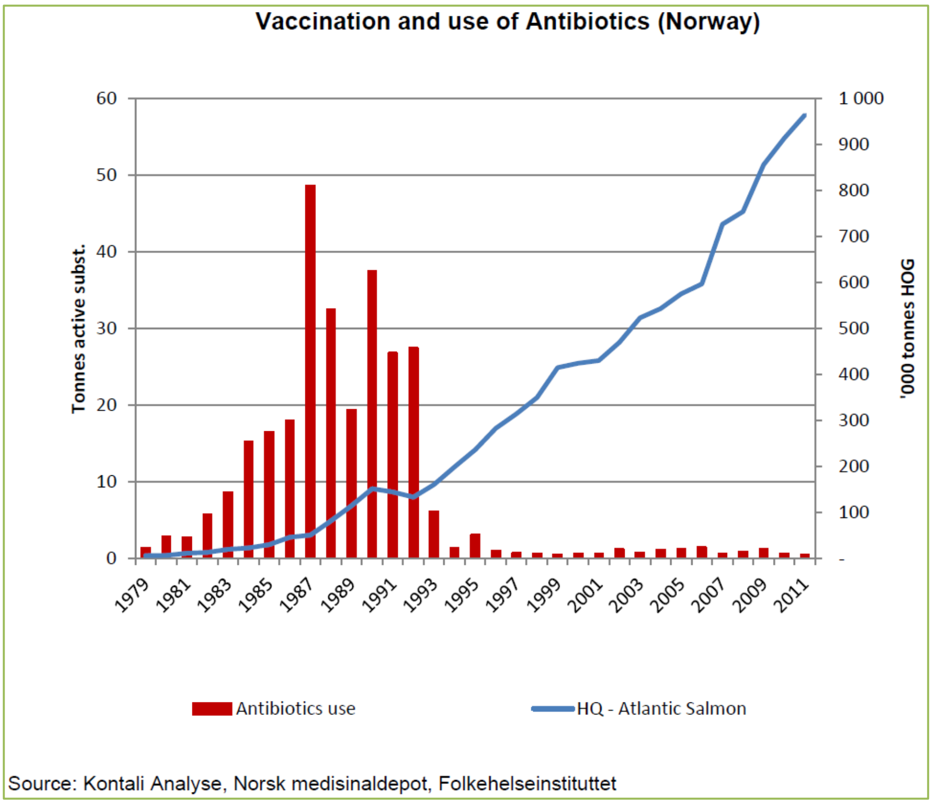

Figure 14 Vaccination and use of Antibiotics in Norway (Source: Marine Harvest Handbook)

Chemical discharges - Antifoulants

Chemical discharges like copper emissions from painting of pens/boats are of concern in aquaculture. Loucks *et al.* (2012) present a study of open-net salmon farms in Canada in which is shown that there is a close relation between this production system type and high levels of copper in the sediments and in the sea surface, surpassing local guidelines for marine life protection. However, copper is usually not allowed for pens and it is not allowed in organic production

Use of medication

In Norway, use of medicines was a considerable problem in the 1980s. Today, it is greatly reduced due to more effective vaccines, along with better localities and improved hygiene (Figure 14). Still, some consumers assume that the Norwegian farmed salmon is heavily medicated, which demonstrates the longterm consequences of negative environmental information and highlights the demand for objective and truthful information, including information about improvements (Ellingsen *et al.,* 2009).

According to Debio standard in Norway vaccination is permitted if it is established that there is or have been a disease in the area and that it cannot be controlled using prophylactic production methods. Organic certification is not affected by vaccination that is recommended by the fish health service or the veterinarian authorities.

Escapees

Escapees are considered especially important because of their potential to spread diseases to the wild and to threaten their biological diversity. The average amount of escaped salmon varies from country to country. Ford *et al.* (2012) presented figures on salmon escapes per country per year showing that the UK (Scotland) have more than double the average of the other countries considered (Norway, Canada and Chile) (Table 13).

Table 13 Average number of escaped salmon per tonne of Atlantic Salmon produced (From Ford et al, 2012)

	Norway (1999-2007)	**UK-Scotland (2002-2007)**	**Canada (1999-2007)**	**Chile (2003-2005)**
Average	0.92	2.12	0.59	0.36

Improvements in technologies for preventing escapes have been recommended. In Norway for example the escapes of farmed fish must be reported on a statutory basis, particularly in Atlantic areas and emphasis is on the need for environmental data collected at farms to be placed in the public domain to increase confidence in the regulatory process

2.12 Transport - Use of fossil fuels - GWP

Processing (fresh and frozen) and transport - Energy use and GHG emission

Processing, packaging, transport, sale, consumption and waste management have not been commonly included in life cycle stages in seafood LCAs. This is particularly the case in aquaculture studies, while fisheries studies have often followed products through the transport stage (Ziegler *et al.*, 2012). Transport and processing were not significant contribution factors to environmental impacts in a study on LCA of salmon supply chain including the transport of finished products from Norway to Paris (Ellingsen *et al*., 2009). However, transport and refrigeration during transport are of key importance when comparing different food supply chains and the impacts of local and global production. There are opportunities to minimize the environmental impact of transport by supply chain management and considering energy consumption and use both in primary production within the fisheries including fishing, meal/oil manufacture and transportation of meals/oils to fish farms, as well as transport of finished products to the market.

LCAs that have focused on the transportation phase of cold fish supply chains all verify that sea freight is by far more environmentally friendly transportation mode than air freight (Andersen, 2002; Freidberg, 2009; Tyedmers *et al.,* 2010; Ingólfsdóttir *et al*., 2010; Winther *et al*.,2009; Ziegler *et al*., 2012). It is thus very important to consider how food is produced and transported and not only where it is produced in terms of environmental performance of products. Processing before export can be favourable because of the greater potential to use by-products and the reduced need for transportation. When analysing by LCA the post landing activities of cold fish supply chains and comparing two different transportation modes from Iceland to Europe, the air freight had 18 times larger carbon footprint than the sea freighted supply chain (Ingólfsdóttir *et al.*, 2010). The carbon footprint of 1 kg of air freighted fresh demersal fish fillet was 4.7 kg CO_2-equivalents and in comparision 0.3 kg CO_2-equivalents for the sea freighted fish (excluding the fisheries stage).

It has been emphasised that the product form (fresh or frozen) matters and freezing makes slower transportation possible because of much longer shelf life of frozen products. When considering consumer choices of seafood with low environmental impact, buying frozen seafood products instead of fresh can be thus be very relevant as reported. Several studies have demonstrated this, for example a LCA study on a salmon supply chain where salmon was caught in Alaska and transported to Seattle (Freidberg, 2009). The shift of the Seattle based company from air freighted fresh salmon to frozen fish transported by sea revealed that there is a dramatic difference in the environmental impacts between the two modes. The Seattle based company therefore significantly reduced the environmental impact of their product, as well as saved money, by shifting from air to sea based transportation and from fresh to frozen (Freidberg, 2009).

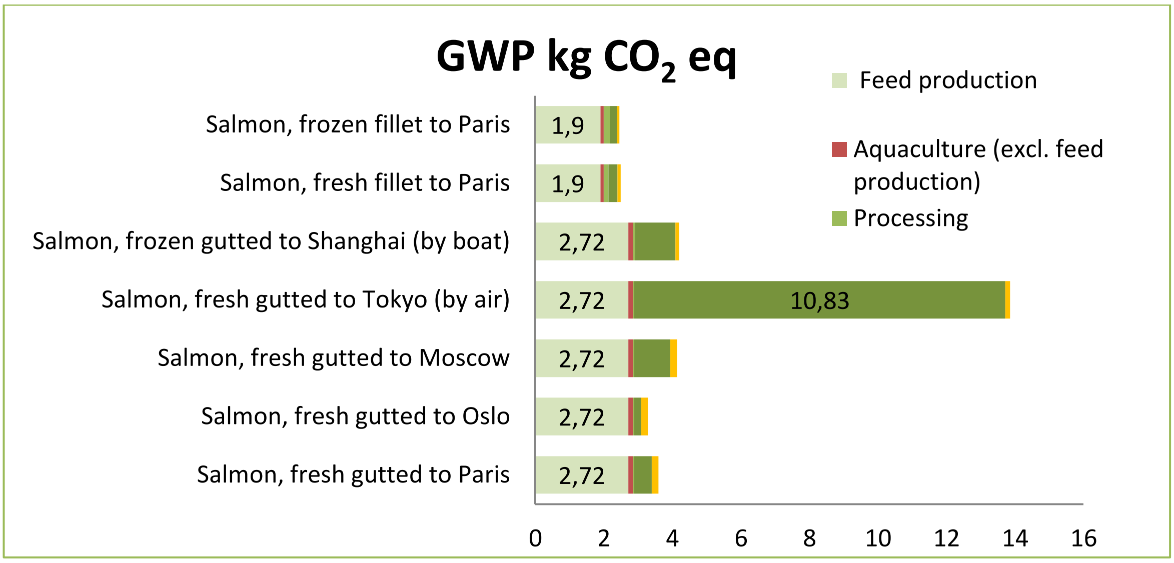

Figure 15 GWP and energy use for production steps of salmon products and transport to different markets (Functional unit:1 kg edible product at wholesaler) (Adapted from Winther *et al*. 2009)

Similarly, the importance of the transport mode was demonstrated in studies where carbon footprint of more than 20 Norwegian seafood products were quantified, including fresh and frozen, processed and unprocessed cod, haddock, saithe, herring, mackerel, farmed salmon, and farmed blue mussels (Winther *et al*.,2009; Ziegler *et al*., 2012). The most efficient seafood product was herring shipped frozen in bulk to Moscow at 0.7 kilograms CO_2 equivalents per kilogram (kg CO_2-eq/kg) edible product. At the other end was fresh gutted salmon air freighted to Tokyo at about 14 kg CO_2-eq/kg edible product (Figure 15). This wide range points to major differences between seafood products and room for considerable improvement within supply chains and in product choices (Ziegler *et al*., 2012).

Refrigerated transport – impact of chilling and packages

Product-specific studies may not necessarily be needed to estimate the impact of the emissions intensity of packaging materials or transportation modes, since this can be assumed to be similar across most seafood products (Parker, 2012). The finished smoked salmon products are commonly vacuum packed (or modified atmosphere) in plastic packaging material and cardboard boxes while fresh fish is transported in EPS (Expanded Polystyrene) boxes sometimes with added cooling mats or ice. The environmental impact of EPS packaging has been shown to be considerable, where the main contribution is energy use in the production of EPS granulates (Ingólfsdóttir et al., 2010).

Transportation by truck and packaging material were by far the two biggest contributors to impact potentials in seafood supply chain systems where comparison was made between chilled and superchilled fillets (Claussen *et al*., 2011). The current cold chain distribution system in Europe is complex and involves numerous stakeholders, who sometimes have limited understanding of the importance of chilling and the significance of energy transfer. Fresh fish products are often chilled in refrigerated seawater and ice (liquid ice) and after packaging in boxes extra ice is added. As a result large quantity of ice is transported with the fish, with higher greenhouse gas emissions from the transport operation as a consequence. The results of the study of Claussen *et al.* (2011) showed that the reduced need for packaging and transport of ice in a system applying superchilling, would compensate for the environmental impacts of a significant higher energy demand in superchilled production. Chilled fillets had approximately 30% higher impact potentials than the superchilled fillets for all environmental impact categories. This was explained as a direct reflection of the ice content in the boxes with chilled fillets, and was considered the most important parameter in this assessment. The sensitive analysis showed that the electricity input for the superchilled system had to increase considerably in order for the traditional chilled system to be the most environmentally friendly option. Total impact potentials were not affected by the electricity mix category (Norwegian or European) based on the sensitivity study. Thus, the additional energy required to achieve superchilled properties is minimal when considering the total energy used in transportation (Claussen *et al*., 2011).

2.13 Refrigerants and Ozone depletion

The ozone depletion is caused by free chlorine radicals that act as catalysts and remove ozone from the atmosphere and convert the ozone (O_3) to oxygen (O_2). Excess chlorine is present in the stratosphere as a result of releases of manmade chlorine containing chemicals. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are an example of these chemicals which have become widespread because of their chemical properties, especially as refrigerants, in air conditioning and refrigerating systems. According to Ziegler *et al*. (2012) an improvement is the replacement of the HCFC R22 with environmentally harmless refrigerants like ammonia (Svanes *et al.,* 2011b; Ziegler *et al.*, 2010).

2.14 Local ecological impact categories

Ford *et al., (*2012) proposed local ecological impact categories and indicators for Life Cycle Assessment of aquaculture. "Relatively well understood impacts, like those from nutrient releases on the benthos or freshwater, or the impacts of sea lice concentrations and escaped fish in the case of salmon farming, could be used in LCAs of aquaculture. These impacts are of interest to regulators and the public, and allow for the exploration of impacts at different spatial scales” (Ford et al., 2012).

Table 14 Proposed Local Ecological Impact Categories and Indicators for Life Cycle Assessment of Aquaculture (Ford *et al.,* 2012)

Impact - Indicator	**Comment on suitability of indicator**
Nutrient release	
area altered by farm waste,	well-developed indicators, should be possible to estimate with information frequently collected at aquaculture sites
changes in nutrient concentration in the water column,	These indicators may be of interest depending on the system in question, data availability, and types of comparisons investigators wish to undertake
percent of carrying capacity reached,	
percent of total anthropogenic nutrient release,	
release of wastes into freshwater	
Biodiversity	
number of escaped salmon,	well-studied impacts of salmon farming
number of reported disease outbreaks,	indicator could be applied to any aquaculture system.
parasite abundance on farms,	well-studied impacts of salmon farming
per cent reduction in wild salmon survival	the overall impact on the survival of wild populations of the species or closely related species being farmed, is of particular interest, but the data on wild conspecifics that would be needed to estimate it are rarely available.
toxic chemical releases	poorly understood
disease outbreaks on farms	poorly understood

Part 3: List of key impact categories and their classification to global or regional impacts

Through parts 1 - 2 of this report the environmental challenges that may arise in aquaculture supply chains have been reviewed and process steps explained for salmon aquaculture and processing of smoked salmon products. The main impact categories that have been addressed in LCA studies on salmon aquaculture are listed in Table 15 and their main influence on human health, natural environment or natural resources.

Table 15 The key environmental impacts of the salmon aquaculture supply chain

Impact category	**Influence**
Climate change - GWP	Human health
Ozone depletion – ODP	
Terrestrial acidification – AP	
Eutrophication – EP	Natural environment
Biodiversity loss	
Ecotoxicity (terrestrial / aquatic)	
Energy use	Natural resources
Bioresource use (biotic and abiotic)	
Land use (including seafloor – sea surface)	
Water use	

- Feed production is most often the major contributor to environmental impacts in conventional aquaculture systems where energy use, greenhouse gas emissions, acidifying emissions and biotic resource use in the case of fisheries derived ingredients in feed, are the main impact categories (Aubin *et al.,* 2006; Ellingsen and Aanondsen, 2006; Tyedmers and Pelletier,2007; Winther *et al*., 2009: Ziegler *et al.,* 2012).
- Comparison of the contribution of feed ingredients and different processes to CO_2 footprint showed large contribution of the soya protein concentrate, which was similar to the contribution of the combined effect of production of marine meal and oil. If LUC coupled to soy bean production would be included the contribution from soy would be even higher (Hognes *et al.,* 2011; Ytrestøyl *et al.*, 2011).
- Fuel use in fishing, and feed production in aquaculture are key contributors to climate change (greenhouse gas emission) (Ziegler *et al*., 2012)
- The fish farm stage of production is a significant contributor to the eutrophication, which has been shown to be highly dependent on the type of rearing systems, the type of feed and the feed conversion ratio (Ayer and Tyedmers, 2009; Aubin *et al*., 2009; Boissy *et al*., 2011; Pelletier *et al.,* 2009).
- The indicators and methods applied for chemical discharges (i.e. medicine, vaccines and antifoulants)and assessment of ecotoxicity are not well developed and their use for environmental impact assessment of aquaculture have been questioned (Ford *et al.,* 2012).

- Land use for crop production for feed and sea primary production- required to sustain the fish used for salmon feed and the benthic area influenced by fishing gear have been calculated to assess the impacts of feed for salmon (Ytrestöyl, 2011).
- Water use is of importance especially in water scarce areas and land based systems and water use for irrigation in production of crop for feed.
- The FIFO ratio (fish-in-fish-out-ratio), forage fish dependency ratio is widely applied as an assessment method for biotic resource use in the aquaculture industry.
- Feed efficiency appears to have a dominant influence on the level of environmental impacts. The difference in the environmental load has been shown to be directly related to relative ability of fish to convert their diet into biomass and lower impacts have been reported for systems with low FCR (feed conversion ratio). FCRs for many aquaculture species dependent on industrially manufactured compound aquafeeds are projected to decline as a result of improved feed efficiency and management (FAO, 2012).
- Climate change impact caused by fuel use for global transport involved in sourcing of feed ingredients, as well as transport and distribution of products to market can have a large impact depending on the distance and mode of tranport (Ellingsen *et al*., 2009; Pelletier *et al*., 2009; Winther *et al*., 2009).
- The environmental impact of EPS packaging has been shown to be considerable, where the main contribution is energy use in the production of EPS granulates (Ingólfsdóttir *et al*., 2010).
- Aquaculture challenges that cause threats to biodiversity e.g. pathogens, escapees, and sea lice are currently monitored in many countries and data may be available.

Key environmental impacts of the salmon aquaculture supply chain - Global and regional impacts

The overview gained in this report will be used as background to justify the selection of impact categories for aquaculture products for the SENSE tool. The selected impacts are similar to agricultural products identified for the milk and dairy, and orange juice supply chain in the SENSE project. The emission sources and output emissions are further explained in each step of the aquaculture supply chain in Table 16 and classified as global or local impacts.

Many of the aquaculture-related environmental impacts are not incorporated in appropriate impact categories in LCA. Therefore, it can be concluded in agreement with Samuel-Fitwi *et al*. (2012), that LCA will not to be sufficient to address all of the key global challenges generated from aquaculture i.e. nutrient and organic matter releases, impacts associated with provision of feed, introduction of diseases, introduction of exotic species, escapes, changed usage of coastal areas, and climate change. Thus, application of assessment tools like the SENSE tool based on LCA needs to be specifically adapted and the foreseen limitation clearly addressed, since existing LCA methodology will not adequately cover the assessment of environmental impacts of aquaculture.
Further evaluation of the applicability of indicators and selection of methodology to be applied to assess the main environmental impacts in the SENSE tool will be carried out to ensure that they will be reliable to

assess the different food products (salmon, orange juice and dairy/beef) and their supply chains. Methodology assessment and evaluation of the suitability of the indicators will be explored in Task 1.2, Task 1.3 and the availability and accessibility of data in questionnaires in WP 2.

Table 16 Summary of emissions in each production stage of salmon and key impact categories and their classification into global or regional impacts

Impact category	Production stage	Emission source	Emissions	Global /Regional
Climate change	Crops - cultivation	Fertiliser production	GHGs (e.g. CO_2)	G
	Crops - cultivation	Application of mineral and organic fertilizer	N_2O	
	Fisheries for feed	Energy use /diesel, refrigerant leakage	GHGs (e.g. CO2, CH4) CFC /HCFs	
	Feed production	Energy use	GHGs (e.g. CO_2, CH_4)	
	Aquaculture	Energy use		
	Processing	Energy use, refrigerant leakage	GHGs (e.g. CO2, CH4) CFC /HCFs (kg CO_2-eq)	
	Transport to consumers	Energy use, refrigerant leakage		
	Waste	Organic waste landfilled / Plastic package incinerated	GHGs (e.g. CO_2, CH_4)	
Acidification	Crops - cultivation	Fertilizer application, fuel consumption	(SO_2, NH_3, NOx)	R
	Transport to consumers	Energy consumption	SO_2, NO_{xs} (kg SO_2-eq)	
Eutrophication	Crop cultivation	Fertilizer application	PO_4, NO_3, NH_3, N_2O	R
	Aquaculture (juveniles, smolt, farming)	Excess feed, Nutrient enrichment	PO_4, NO_3, (kg PO_4-eq)	
	Processing	Waste water		
Biotic resource depletion	Fisheries / Feed	Forage fish for feed FIFO		R /G
Abiotic resource depletion	Processing to consumers	Other resource use	(kg Sb-eq)	R /G
Ecotoxity	Crop cultivation	Pesticides	Ecotoxic substances (kg DCB-eq)	R
	Aquaculture	Antifoulants, cleaners, medicine use		
Land Use	Crops - Primary production /veg. feed)	Crop production	(m^2)	R
	Juveniles, smolt production	Land based hatcheries	(m^2)	
Surface of water	Salmon farming	Net pens	(m^2)	R
Ozone	Fisheries / Feed prod	Refrigerants	Ozone depleting	G

depletion	Chilling, Processing, transport to consumers	Refrigerants	substances (e.g. CFCs, HCFCs) (kg R11-eq)	
Biodiversity	Salmon farming	Escapee, salmon lice,	no species	G /R
	Fisheries / Feed prod	Burden on stock		
	Crop cultivation	Deforestation /land use		
Water use	Crop cultivation	Irrigation /water use		R
	Juvenile and smolt	water use in hatheries or land based production		
	Processing	Cleaning		

Part 4: Regional differences in aquaculture production affecting environmental impacts

As detailed in Part 1, all salmon aquaculture production and processing areas fall into the North Atlantic region where main producers are Norway, UK, Faroe Islands and Iceland. Although the emphasis in the SENSE project is salmon other species and different aquaculture systems are also considered for a more complete overview and understanding of environmental impacts of aquaculture. Regionalisation of characterization factors in LCA for aquaculture may contribute to more accurate studies and provide better understanding of environmental impacts of the aquaculture supply chain in specific regions.

The methods for the impact assessment of land use, including impacts on biodiversity, and resource aspects such as freshwater resources, need to be assessed in relation to regions and characteristics of respective supply chains and this is not done in LCA's today. For example fish farming can cause locally important environmental impacts and water use may have tremendous environmental impact in water-scarce countries. Therefore, relevant impact assessment methods are needed to take into account impact categories and regionalization that is not adequately covered by the recommended standard methods. The method choice has to be made taking into account different strengths and weakness of the methodologies as well as research objectives.

Biogeographical regions and seas in Europe

Regarding geographic differences and environmental sensitivity related to aqua farming, information on biogeographical regions in Europe are available in a report on Europe's biodiversity - biogeographical regions and seas (European Environment Agency (2002). It is stated that eutrophication has been a major problem in many European coastal areas, but to a lesser degree in the Atlantic region.

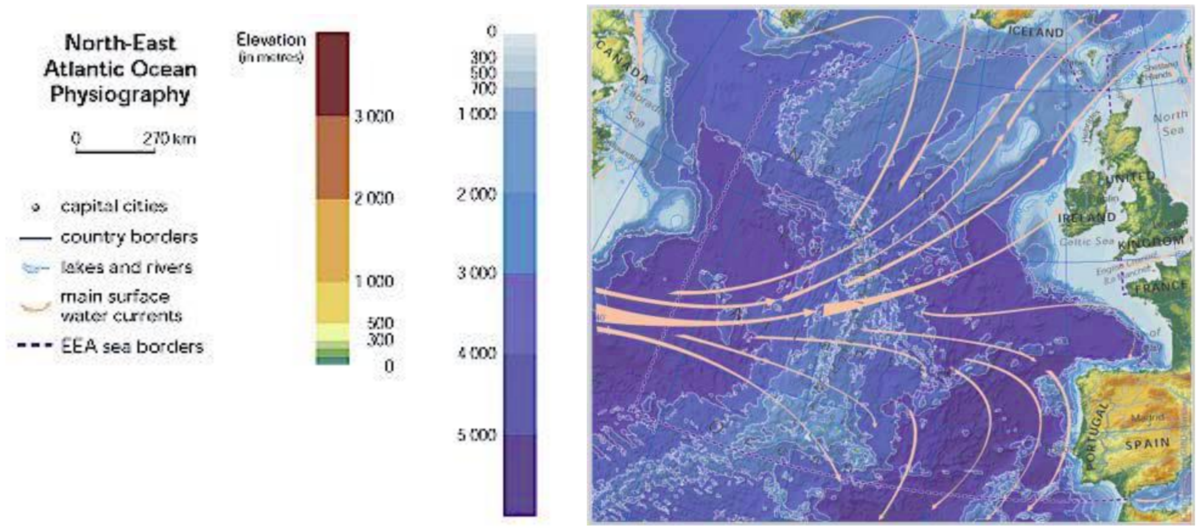

Figure 16 North-east Atlantic Ocean physiography (depth distribution and main currents) (Source EEA) (Note that the map does not cover all of NorthEast Atlantic Ocean, as specified by FAO zone 27, and the Mediterranean area is only partly shown)

In the North-east Atlantic Ocean (see Figure 16) the concentrations of nitrogen and phosphorus have been anthropogenically enhanced for some estuaries within the Celtic Sea and from restricted areas of estuaries and coastal lagoons in the Bay of Biscay, and the Iberian Coast. Available data on nutrients, dissolved oxygen and abundance of benthic fauna gives some evidence of eutrophication of the coastal zones in this region. In the greater North Sea eutrophication resulting from nutrient enrichment; primarily nitrogen and phosphorus affects mainly the coastal zone, particularly estuaries and fjords. Nutrient-related problems are widespread in the Wadden Sea, the German Bight, the Kattegat and the eastern Skagerrak.

The occurrence of low oxygen levels in seawater is highly dependent on hydrographical conditions, and is a problem only in some areas of the North Sea. Fishing, bottom trawling and fish farming put pressure on the ecological systems in the Baltic Sea. Eutrophication is one of the major environmental problems in the Baltic. There are indications that the frequency and the spatial coverage of harmful blooms in the Baltic Sea have increased. The Mediterranean region is one of the most vulnerable to suffer from water scarcity, aquatic eutrophication, soil and biodiversity loss etc. mainly due to high urbanization areas and the climate of this particular territory.

Regionalisation based on production technologies and geographical characteristics

Within Europe, ponds and lakes in Eastern Europe have traditionally been exploited for carp production while various species have been farmed in the Atlantic coastal areas of mid and south Europe. Rainbow trout is produced in Denmark and other Nordic countries as well as in the Baltic area. In the Mediterranean area, aquaculture (oysters, mussels and fish farms) is more recent and has been expanding rapidly in the last few years focusing on species like sea bass and gilthead sea bream.

The environmental impact of aquaculture farming production with regard to geographic location and regional differences were stated by Braaten (1992) as follows: "Eutrophication from fish farming is estimated to be a small problem on the west coast of Norway, Iceland, and the Faroe Islands, although local problems may arise in narrow fjords and enclosed areas. Overloading of nutrients is considered to be a major problem in the Baltic, the Belts and parts of Skagerrak and Kattegat."

The impact of number of pens in small fjords and determination of loading capacity as well as different production technologies, feeding technologies, water and energy use and waste management, has been the topic of various research initiatives, which have formed the basis for environmental assessment programs, monitoring and development of guidelines and regulations for the aquaculture industry.

European aquaculture can be divided into the following 5 segments (Table 17), which are based on the combination of driving technical forces and controlling environmental conditions, as suggested by the CONSENSUS platform for sustainable aquaculture in Europe (Váradi *et al.,* 2010).

Table 17 Main aquaculture species, production systems and technologies in Europe (Adapted from Váradi et al., 2010)

Production systems	**Species**	**Region / Characteristics**
Semi-static water systems	*Natural-food-based* pond culture of carps *High-market-value* indigenous fish species, such as European catfish, pike and zander, eels, as well as tench and other small cyprinids	*Central and Eastern European* countries Ponds, lakes, basins
	Freshwater species in extensive systems Commercially valuable species like striped mullet, golden-grey mullet, leaping mullet, European eel, European seabass, gilthead seabream.	*Mediterranean countries* Extensive lagoon farming - Italy has the largest areas of brackishwater ("valli"), Contributing to wetland resource management and water use in coastal lagoon systems (valliculture)
Flow-through systems	Exclusively land-based fish farming facilities Some freshwater systems utilize industrial cooling water or geothermal water. Freshwater systems allow the rearing of fresh water species (especially eel, catfish, zander, perch, tilapia) with low environmental impact	*Seawater and brackishwater farms are generally located at the seaside* - farms use the water of a river pumped through the production unit - other water sources i.e springwater, drilled and pumped groundwater, cooling waters or coastal waters
Recirculation aquaculture systems (RAS)	Freshwater and marine hatcheries for land-based culture of freshwater species (catfish, eel) and the culture of marine species such as turbot or sole The current European RAS industry can be divided into two groups from a technical point of view: hatcheries and ongrowing systems	*Land-based water-saving systems,* with a strict control over water quality, low environmental impacts and high biosecurity levels. On the other hand, they have high capital and operational costs and present difficulties in treating diseases
Coastal shellfish systems	Produce mussels in bottom, stake or suspended culture or oysters in suspended culture and coastal lagoons, as well as clams	Farming methods for the various species rely completely on naturally occurring plankton as a food source
Coastal and offshore finfish systems	Used for salmonids (salmon and trout) and marine species, including seabass, seabream, cod and tuna.	*Coastal and off-shore cages* have a broad range of shapes and sizes, and are made of different materials (steel, plastic or rubber).

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Annex 1

Standards and certification relevant for the aquaculture supply chain

In the context of the SENSE project the overview on international initiatives and stakeholder consultation on aquaculture certification programmes is important. For the development of the SENSE tool it is essential to evaluate how the tool can be applied in the food supply chain to facilitate the assessment of environmental indicators in line with current practices and future trends in the supply chain.

The FAO Code of Conduct for responsible aquaculture (1995) is the background for the development of environmental impact assessment procedures, monitoring programmes and certification schemes for aquaculture. The application of certification in aquaculture is now viewed as a potential market-based tool for minimising potential negative impacts and increasing societal and consumer benefits and confidence in the process of aquaculture production and marketing FAO (2010).

FAO Technical Guidelines on Aquaculture Certification

FAO Technical Guidelines[3] provide guidance for the development, organization and implementation of credible aquaculture certification schemes. They consider a range of issues which should be considered relevant for the certification in aquaculture, including: a) animal health and welfare, b) food safety, c) environmental integrity and d) socio-economic aspects associated with aquaculture.

Various standards and certification programmes for aquaculture species are available worldwide covering different aspects like quality, organic production, animal welfare, human health and environmental issues. However, concerns about their relevance and their credibility have been addressed in particular by the Salmon Aquaculture Dialogue and WWF[4] as well as various research initiatives. A benchmarking study on certification programmes for aquaculture products destined to European markets was performed by this initiative in 2007[5]. Four main areas of concern were identified in the study: Environmental issues, social issues, animal welfare and health and standard development and verification procedures. None of the standards analysed was in full compliance with the criteria stated and defined by WWF, showing that there was a need for improvement and further adaptation of regulatory frameworks of aquaculture certification programmes.

In recent years standards and certification schemes have been further developed and implemented to address the shortcomings mentioned in the benchmarking study in 2007.

[3] FAO Technical Guidelines on Aquaculture Certification 2011. ftp://ftp.fao.org/Fi/DOCUMENT/aquaculture/TGAC/guidelines/Aquaculture%20Certification%20GuidelinesAfterCOFI4-03-11_E.pdf

[4] Aquaculture salmon: WWF website http://www.worldwildlife.org/what/globalmarkets/aquaculture/dialogues-salmon.html

[5] Benchmarking Study on International Aquaculture Certification Programmes. World Wildlife Fund (WWF) Switzerland and Norway Zurich and Oslo 2007

List of standards for aquaculture (examples)

Aquaculture

- Global Aquaculture Alliance - Best Aquaculture Practices (BAP) standard[6]
- AquaGAP Standard for Good Aquaculture Practices Version 3, 13.10.2010[7].
- Aquaculture Stewardship Council - ASC Salmon Standard[8]
- GLOBALG.A.P. Aquaculture Standard
- Friend of the Sea

Organic Standards and certification in Aquaculture

- Soil Association[9]
- International Federation of Organic Agriculture Movements[10]
- Naturland [11]
- Debio Organic Aquaculture Standards [12],
- KRAV [13]

Standards for food supply chains

Global Food Safety Initiative (GFSI) recognizes the voluntary industry driven standards:

- SQF, BRC,IFS, ISO 9001, ISO 22000,

Global Aquaculture Performance Index (GAPI)

The Global Aquaculture Performance Index (GAPI) was developed by SERG (Seafood Ecology Research Group) at the University of Virgina as a tool to distill the best available data on the impacts of fish farming into a simple score of environmental performance by weighing ten impact categories (Volpe et al., 2010) [14]. The environmental benefits of 20 marine finfish aquaculture standards were compared by applying the GAPI as a tool for the quantitative assessment of the ecological impacts and to highlight the weakness and strengths of the different standards. The ultimate goal of such benchmarking is to demonstrate how standards can contribute to a more sustainable aquaculture industry (Volpe et al, 2011)[15].

The main outcome on the performance of the standards showed that some organic standards scored high because of their strong restriction on waste management and use and discharge of chemicals. Others that did not perform well either did not set standards in key impact areas or did not set measurable limits for

[6] http://www.gaalliance.org/

[7] AquaGAP Standard For Good Aquaculture Practices Version 3, 13.10.2010
http://www.aquagap.net/Docs/AquaGAP%20Standard%20V3.pdf

[8] ASC standards (2012). Final Salmon Aquaculture Dialogue Standards for the Aquaculture Stewardship Council, June 13, 2012: http://www.worldwildlife.org/what/globalmarkets/aquaculture/WWFBinaryitem28132.pdf
ASC Audit Manual for Salmon (2012). Retrieved from: http://www.asc-aqua.org/upload/ASC Audit Manual Salmon_draft.pdf

[9] http://www.soilassociation.org/LinkClick.aspx?fileticket=pM14JxQtcs4%3d&tabid=353

[10] http://www.ifoam.org/about_ifoam/around_world/eu_group-new/positions/publications/aquaculture/index.php

[11] http://www.naturland.de/fileadmin/MDB/documents/Richtlinien_englisch/Naturland-Standards_Aquaculture.pdf

[12] Debio – Organic Aquaculture Standards – June 2009,http://www.debio.no/_upl/standards_organic_aquaculture.pdf

[13] http://www.krav.se/KravsRegler/7/

[14] Volpe, J.P., M. Beck, V. Ethier, J. Gee, A. Wilson. 2010. Global Aquaculture Performance Index. University of Victoria, Victoria,British Columbia, Canada, 116p.

[15] Volpe, J.P., J. Gee, M. Beck, V. Ethier, 2011. How Green Is Your Eco-label? Comparing the Environmental Benefits of Marine Aquaculture Standards. University of Victoria, Victoria, British Columbia, Canada. 104p

these impacts The GAPI website (www.gapi.ca) provides a log of all data and respective sources that are publically available and traceable.

Table 18 Global Aquaculture Performance Index (GAPI) (Volpe *et al.*, 2010)

Global Aquaculture Performance Index (GAPI)	Impact Categories / Indicators	Indicator Description	Impact category weighing
Inputs	CAP: Capture-Based Aquaculture	The extent to which a system relies on the capture of wild fish for stocking farms, taking into account the sustainability of these wild fish inputs	5%
	ECOE: Ecological Energy	Amount of energy, or net primary productivity (NPP), that farmed fish divert from the ecosystem through consumption of feed ingredients	15%
	INDE: Industrial Energy	Energy consumed in production and in the acquisition and processing of feed ingredients	8%
	FEED: Sustainability of Feed	Amount, efficiency, and sustainability of wild fish ingredients of feed	15%
Discharges	ANTI: Antibiotics	Amount of antibiotics used, weighted by a measure of human and animal health risk	15%
	COP: Copper-Based Antifoulants	Estimated proportion of production using copper-based antifoulants	5%
	BOD: Biochemical Oxygen Demand	Relative oxygen-depletion effect of waste contaminants (uneaten feed and faeces)	5%
	PARA: Parasiticides	Amount of parasiticides used, weighted by measures of environmental toxicity and persistence	8%
Biological	ESC: Escapes	Biological Escapes (ESC) Number of escaped fish, weighted by an estimate of the per capita risk associated	8%
	PATH: Pathogens	Number of on-farm mortalities, weighted by an estimate of wild species in the ecosystem that are susceptible to farm-derived pathogens	15%

Eco-Benchmark

Of interest is a Finnish study where LCA was applied to assess five important impact categories: climate change, acidification, tropospheric ozone formation, terrestrial eutrophication, and aquatic eutrophication, which were then weighted in relation to each other to develop the so-called "Eco-Benchmark". The project was a consumer-oriented LCA-study, and resulted in a tool, which enables consumers, manufacturers, and experts in administrations and research organisations to assess the role of various products and consumption patterns in relation to total environmental impacts[16].

More extensive methods for weighing of environmental impacts on the same scale like the **ecological footprint** assessment have been used based on LCA (Monfred *et al.,* 2004)[17].

[16] Nissinen, A. & al. 2006. *"Eco-Benchmark for consumer-oriented LCA-based environmental information on products, services and consumption patterns."* In: Jørgensen, A., Molin, C. & Hauschild, M. (eds.). First symposium of the Nordic Life Cycle Association, October 9-10, 2006, Lund, Sweden. 14 p.

[17] Monfred, C. Wackernagel, M. And Deumling D. (2004) Establishing national natural capital accounts based on detailed Ecological Footprint and biological capacity assessments Land Use Policy 21, 3, 231–246.