Report 53/2011 • Published December 2011

Resource utilisation and eco-efficiency of Norwegian salmon farming in 2010

Trine Ytrestøyl, Turid Synnøve Aas, Gerd Marit Berge, Bjarne Hatlen, Mette Sørensen, Bente Ruyter, Magny Thomassen, Erik Skontorp Hognes, Friederike Ziegler, Veronica Sund and Torbjørn Åsgård

Nofima is a business oriented research institute working in research and development for the aquaculture, fisheries and food industry in Norway.

Nofima has about 470 employees. The main office is located in Tromsø, and the research divisions are located in Averøy, Bergen, Sunndalsøra, Stavanger, Tromsø and Ås.

Main office in Tromsø
Muninbakken 9–13
P.O. box 6122
NO-9291 Tromsø
Norway
Tel.: +47 77 62 90 00
Fax: +47 77 62 91 00
E-mail: nofima@nofima.no

Internet: www.nofima.no

Nofima AS
P.O. box 6122
NO-9291 Tromsø, Norway
Visiting address:
Muninbakken 9–13,
Tel.: +47 77 62 90 00
Fax: +47 77 62 91 00
nofima@nofima.no
www.nofima.no

Business reg. no.:
NO 989 278 835 VAT

Report

ISBN: 978-82-7251-945-1 (printed)
ISBN: 978-82-7251-946-8 (pdf)

Report no:
53/2011

Accessibility:
Open

Title:
Resource utilisation and eco-efficiency of Norwegian salmon farming in 2010

Date:
December 2011

Number of pages and appendixes:
65 + 1 appendix (30 pages)

Author(s):
Trine Ytrestøyl, Turid Synnøve Aas, Gerd Marit Berge, Bjarne Hatlen, Mette Sørensen, Bente Ruyter, Magny Thomassen, Erik Skontorp Hognes, Friederike Ziegler, Veronica Sund and Torbjørn Åsgård

Project no.:
21111

By agreement with:
Fiskeri- og havbruksnæringens forskningsfond

Contractors ref.:
FHF #900568

Three keywords:
Norwegian salmon farming; Sustainability; Efficiency

Summary:

This report consists of four parts:

Part 1 is an evaluation of some of the methods used for evaluating food productions in a sustainability perspective.

Part 2 is a description of some sustainability indicators often used to evaluate aquaculture productions (Fish in-Fish out ratio, marine protein dependency ratio, forage fish dependency ratio).

Part 3 is a resource budget for the Norwegian salmon production in 2010 showing the flow of major nutrients from feed to the different parts of the salmon product. The retention of protein, fat, energy, phosphorus and the essential ω 3 fatty acids EPA and DHA, is calculated both for the edible part and for the whole body of salmon. Alternative usage of the marine feed ingredients is also discussed.

Part 4 is an LCA of the 2010 salmon production for the impact factors agricultural land occupation, cumulative energy use, global warming potential and marine primary productivity. The salmon production in 2010 is compared to Swedish pig and chicken production. Possible future dietary scenarios in salmon farming are also evaluated; diets were fish meal and oil is replaced with plant ingredients and animal by-products are compared with the 2010 diet and with a diet with a high level of marine ingredients.

Executive summary

Atlantic salmon (Salmo salar) is the dominating species in Norwegian aquaculture, and in 2010, 927 876 tons were slaughtered. The sustainability of the salmon industry has been questioned, and the salmon industry has been criticized for the use of fish meal and oil in the production of salmon feed. At present, 27% of the global fish meal production and 68% of the fish oil production is used in feed for salmonids worldwide. 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). The fish-in-fish-out (FIFO) ratio is the amount of forage fish used to produce the amount of fish oil and meal required to produce 1 kg of salmon. 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. The limited supply of fish meal and fish oil makes this shift from marine towards plant ingredients necessary, but introduces other challenges from a sustainability perspective.

The Food and Agricultural Organization (FAO) projects that 70% more food need to be produced globally within 2050 to feed a population of 9 billion people and calls for urgent action in developing food systems that uses less energy and emits less greenhouse gases (FAO 2011a). The global food sector is responsible for around 30% of the world's energy consumption and contributes to more than 20% of the global greenhouse gas (GHG) emissions (FAO 2011b). In addition, land use changes (mainly through deforestation) contribute to another 15% of GHG emissions. This increase in food production will have to come through improvements in efficiency of livestock systems because most of the land area suitable for agriculture is already utilised. 30% of the worlds cereal production is currently used to feed livestock, and livestock productions also consume large amounts of freshwater, both for irrigation of feed crops and for drinking. Freshwater is becoming increasingly scarce and the livestock sector is probably the largest source of water pollution (FAO 2011b). The expansion and intensification of the livestock production sector the last decades has led to degradation of 20% of the world's pastures due to overgrazing. Deforestation to grow animal feed crops has led to extinction of many plants and animals and released large amounts of carbon dioxide into the atmosphere. The global food production is also heavily dependent on the use of phosphorus fertilizer. However, the current use of phosphorus is not sustainable due to losses at all stages from mining to crop field to human consumption. Phosphorus is not cycled at present, but moves through an open one way system where the final losses end up in the ocean.

Several indicators and methods for measuring sustainability and eco-efficiency of aquaculture productions have been developed, such as the simple fish-in-fish-out-ratio, forage fish dependency ratio, marine nutrient dependency ratio and various nutrient retention ratios. More extensive methods such as the ecological footprint model and life cycle analysis (LCA) are also applied for assessing the sustainability of aquaculture and other food production system. These methods have their strengths and weaknesses, and the outcome of an analysis 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. Evaluation of sustainability of aquaculture is complicated, and different aspects have to be

addressed in order to evaluate the sustainability of Norwegian salmon production. 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.

A Life cycle analysis (LCA) was performed for production of salmon with the impact factors i) occupation of agricultural land, ii) energy use, iii) carbon footprint and iv) ocean primary production using five differently formulated feeds: Diet 1: The average commercial feed in 2010, Diet 2: High content of marine ingredients (88% of the diet), Diet 3: 2010 diet with marine ingredients only from the North Atlantic, Diet 4: Containing poultry by-products, and Diet 5: High content of plant ingredients (85% of the diet). In conclusion, considerable changes in the salmon diet formulation did only cause minor changes in the carbon footprint except for the diet containing a high amount of poultry by-products (2020 LAP) which had a higher carbon footprint (3.4 CO_2e/kg, similar to Swedish chicken). This is a consequence of allocating the carbon footprint from poultry production to the poultry by-products according to their mass. Changing the diet composition from 85% plant ingredients to 88% marine ingredients resulted in almost the same carbon footprint (2.47 and 2.40 CO_2e/kg respectively). Excluding marine ingredients from South America and the Mexican Gulf from the 2010 diet increased the carbon footprint with 7% to 2.75 CO_2e/kg.

The Norwegian farmed salmon has a lower climate impact than the Swedish pig and chicken. The CO_2 footprint for the farmed salmon was 2.6 kg CO_2 equivalents/kg edible product in 2010, whereas the CO_2 footprint for chicken and pig production was 3.4 and 3.9 kg CO_2 equivalents/kg edible product respectively. The land occupation per kg edible product of Norwegian salmon was 3.32 m^2/kg which is lower than that of both Swedish pig (8.35 m^2/kg) and chicken (6.95 m^2/kg). Increasing the content of plant ingredients to 85% of the salmon diet will require 5.55 m^2 agricultural land to produce one kg of edible product. Production of 1 kg of edible chicken and pig require 2-3 times more phosphorus fertilizer compared to salmon production. In addition, salmon retain roughly twice as much of the phosphorus in the diet compared to chicken and pig.

The total agricultural area used for production of Atlantic salmon in 2010 was 5440 km^2 which is equivalent to half of the total cropland area in Norway. The total industrial energy input for the 2010 production of salmon in Norway was 41 400 TJ. 95% of the industrial energy input was used for harvest, production and transport of feed ingredients and feed. The ratio industrial energy input/energy output in the salmon product was 3.6 per kg live weight and 6.2 per kg edible product respectively.

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. In 2010, Norwegian salmon farming consumed 1 236 000 tons of feed, with an energy content close to 31 000 MJ, and 460 853 tons of protein. In total, 612 097 tons of salmon fillet, containing 6 646 390 GJ, and 121 807 tons of protein was produced. Salmon is an important source of the nutritionally important fatty acids EPA and DHA, and of the 49 373 tons of EPA+DHA in the feed, 12 909 tons were retained in the edible part of salmon. The retention of EPA and DHA was 58% in the whole body and 26% in the fillet. The retention of protein and energy was 26 and 21% in the edible part, respectively. These retention data can however not be compared to single productions or controlled studies, since all losses during the production of feed and salmon are included in the data used in the present study.

The conclusion from this study is that salmon farming is a more efficient way of producing nutrients for human consumption compared to chicken and pork production. Salmon farming occupies less agricultural land, uses less of the non-renewable phosphorus resources and has lower climate impact per kg product produced for human consumption. Salmon also retain the nutrients in the feed more efficiently than chicken and pig and is thus a more efficient converter of feed nutrients to nutrients for human consumption compared to land animal productions such as chicken and pig. Theoretical calculations indicate that using fish meal and oil from capture fisheries for salmon production may in fact provide more marine protein, energy and EPA and DHA for human consumption compared to utilising the marine fishery resources directly as a human food source.

Table of contents

Appendix: Carbon footprint and area use of farmed Norwegian salmon

1 Part 1

1.1 Assessing environmental costs of food production

1.1.1 The worlds fishery and aquaculture production

Aquaculture is the fastest growing animal food producing sector with an annual growth rate of 6.6% between 1970 and 2008. Aquaculture now accounts for almost half of the total food fish supply and the percentage is increasing every year (FAO, 2010). Capture fisheries and aquaculture supplied the world with 145 million tons of fish in 2009 of which 118 million tons were used as human food (Figure 1), resulting in a per capita food fish supply of 17 kg in 2009, and fish accounted for 15.7% of the global intake of protein. In 2008 the world aquaculture production was 52.5 million tons and was dominated by China (62% of the global production by volume) (FAO, 2010).

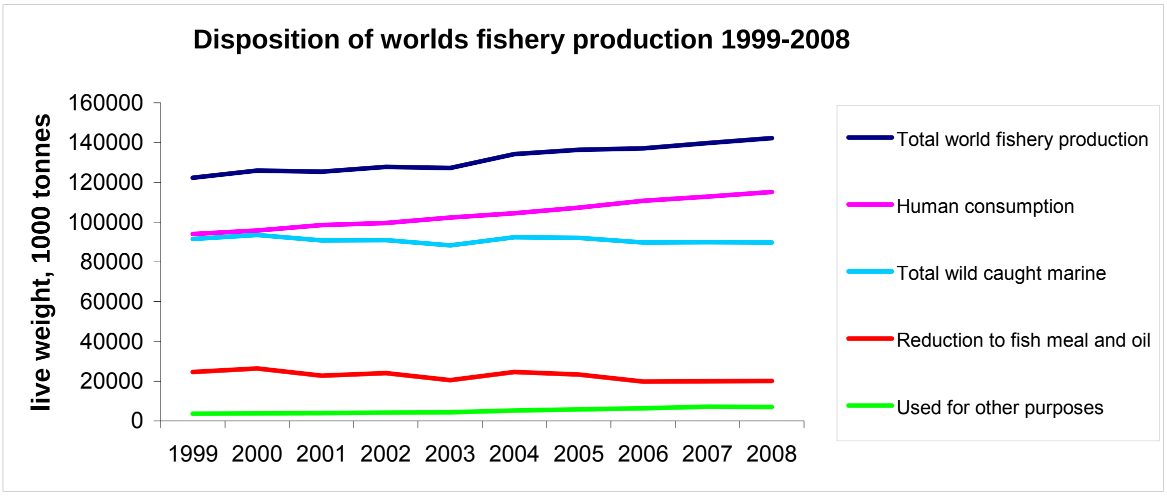


Figure 1 Disposition of the total world fishery production (freshwater and marine, including aquaculture production (data from FAO).

The production of fish oil has been fairly stable at around 1 million tons per year for the last 50 years while the production of fish meal has been declining in the last decade after reaching a peak of 7.5 million tons in 1995. The current production is around 4.5 million tons of which 25% originates from trimmings and by-products (IFFO). Between 1999 and 2008, the amount of the marine catch that was reduced to fish meal and fish oil decreased from 27 to 22%. Of the worlds total fishery production in 2008, 81% was used for human consumption, 14% was reduced to fish meal and oil and 5% was used for other purposes (FAO, 2010). The global capture fisheries production has been relatively stable at around 90 million tons in the last decade and around 20 million tons is reduced to fish meal and oil. In addition, unreported by-catch and discards are estimated to be around 38 million tons (Davies et al., 2009) which is considerably more than what is used for fish meal and oil production. Of the total production of fish meal and oil in 2006, between 56-68% of the fish meal and 83-89% of the fish oil produced were consumed by the aquaculture industry

(Jackson, 2006, 2007, Tacon and Metian 2008, FAO, 2010. During the last decade, the production of Atlantic salmon has increased by almost 70% from around 900 000 tonnes worldwide in 2000 to around 1.5 million tonnes at present (Figure 2), with Europe and the Americas as the major salmon producing regions (74 and 24% of the total production respectively) and farmed salmon is the most widely consumed sea product in the industrialised world (Naylor and Burke, 2005).

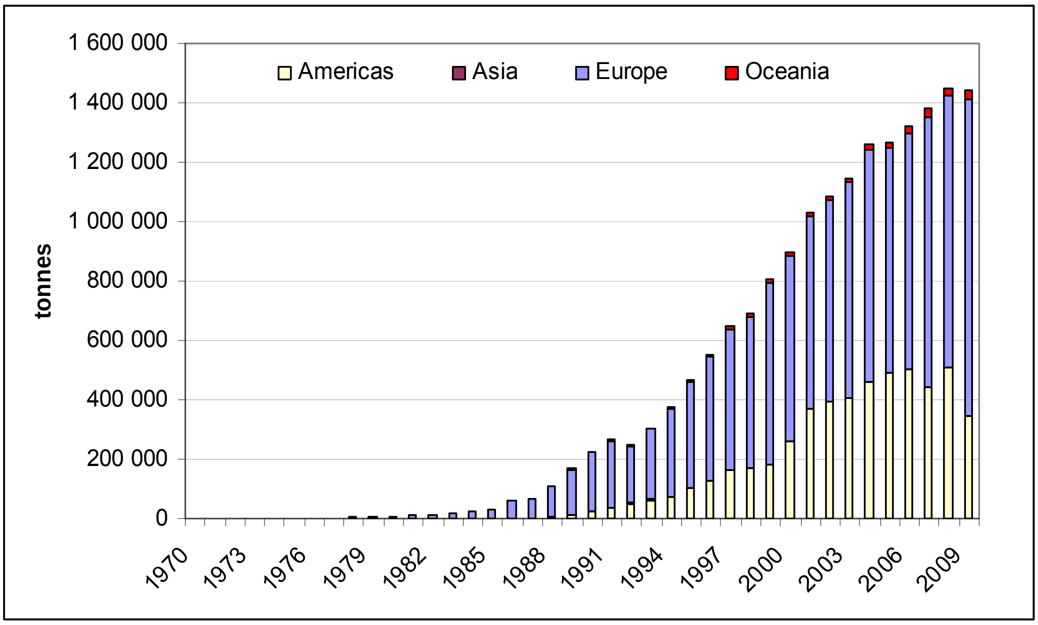


Figure 2 The worlds salmon production per continent from 1970 – 2009 (data from FAO).

In 2009, 68% of the fish oil used in aquaculture was consumed by the salmon industry (Figure 3). Some fish oil was also used for human consumption (13%) and 6% was used for other industrial purposes (Figure 3). Fish oil used for direct human consumption is mainly in the form of concentrated EPA and DHA omega-3-fatty acid products and food products fortified with these essential fatty acids (functional food). The market for human consumption of fish oil is growing rapidly. It was estimated that 63% of the world production of fish meal in 2009 was used in various aquaculture productions (data from IFFO). The remaining fish meal was used in terrestrial animal feed production, mainly pig (25%) and poultry production (8%).

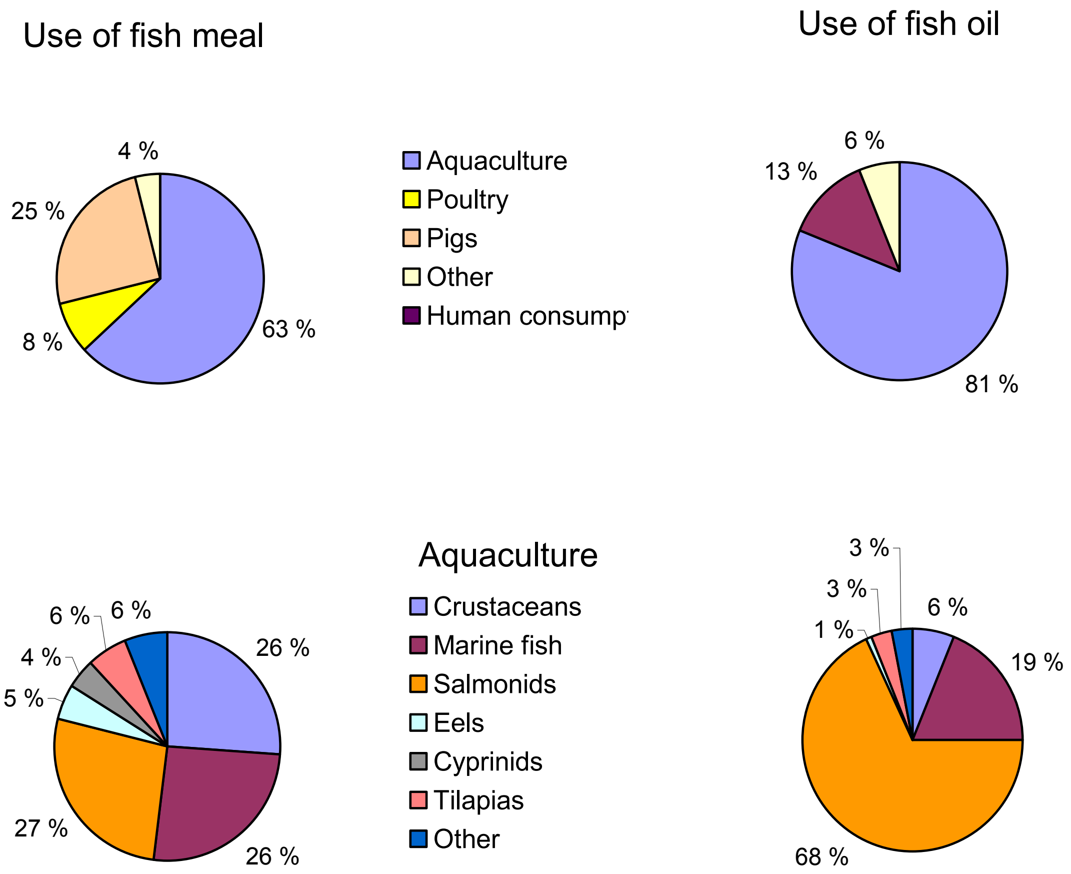


Figure 3   Use of fish meal and fish oil in different markets and aquaculture productions in 2009 (data from IFFO).

1.1.2 Sustainable food production, how can it be defined?

According to the UN, global warming, ozone depletion, pollution, overexploitation of marine resources, loss of biological diversity, land deterioration and access to drinking water are the main global environmental challenges at present. All food production has environmental consequences. The growth in the aquaculture industry has raised concerns about the environmental impacts and sustainability of fish farming among consumers, retailers, non-governmental organisations (NGO's) and authorities. In particular, the use of marine ingredients in the fish feed has been subject for debate. Forage fish are often small pelagic fish at lower trophic levels that are important prey for species higher up in the food chain (Fréon, 2005). Farming of carnivorous finfish such as Atlantic salmon has been considered as negative due to the presumed large amounts of small pelagic fish used in production that could potentially be used as human food, thus presumably reducing the amount of marine protein available for human consumption (Naylor et al., 2000, Naylor and Burke, 2005, Naylor et al., 2009). Aquaculture also has potential environmental impacts, even though the extent of the impacts is debated. Examples from the salmon farming industry are potential genetic effects of escapees on wild salmon populations and spreading of salmon lice, use of anti-fouling agents and medicines, land and energy use in all parts of the value chain and discharge of organic and inorganic material. Production of feed is a major input factor in salmon production (Ellingsen et al., 2009, Pelletier et al., 2009), so an understanding of the resource and energy consumption in food production and how different feed formulations affect resource utilisation and environmental impacts is important for making strategic decisions about future production regimes.

Crop and livestock production have a profound impact on the environment, both locally and globally. Agriculture is the main source of water pollution by nitrates, phosphates and pesticides. Livestock production consumes 8% of the global human water use and is by far the single largest anthropogenic user of land. Livestock production is also the major source of the greenhouse gasses (18% of the world total measured as CO_2 equivalents) (Gerber et al., 2007). The global meat production increases with around 3.6% per year (Figure 4) and has nearly doubled between 1980 and 2004 (FAO, 2005). It is expected to double again within 2050 as a result of population growth and a shift in consumption habits associated with urbanisation and increased per capita income (Bruinsma, 2003). The changes include a shift from cereal based diets to more energy dense diets with a high content of animal protein. The per capita meat consumption was 15 kg in 1982 and 28 kg in 2002, and is expected to reach 37 kg in 2030 (FAO, 2005). There is also a shift from grazing systems to more intensive production systems depending on concentrate feeds that are being traded internationally. In 2007, 750 million tons of cereals, (35% of the world's total production) were used as animal feed (FAOSTAT 2009). Maize is the dominating feed commodity, 60% of the world production of maize in 2009 was used as animal feed (Figure 5).

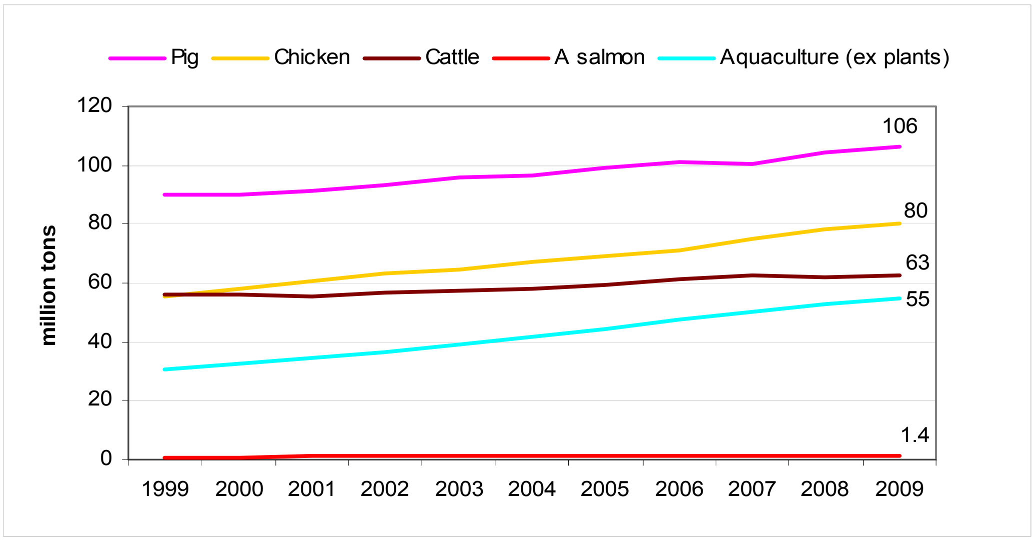
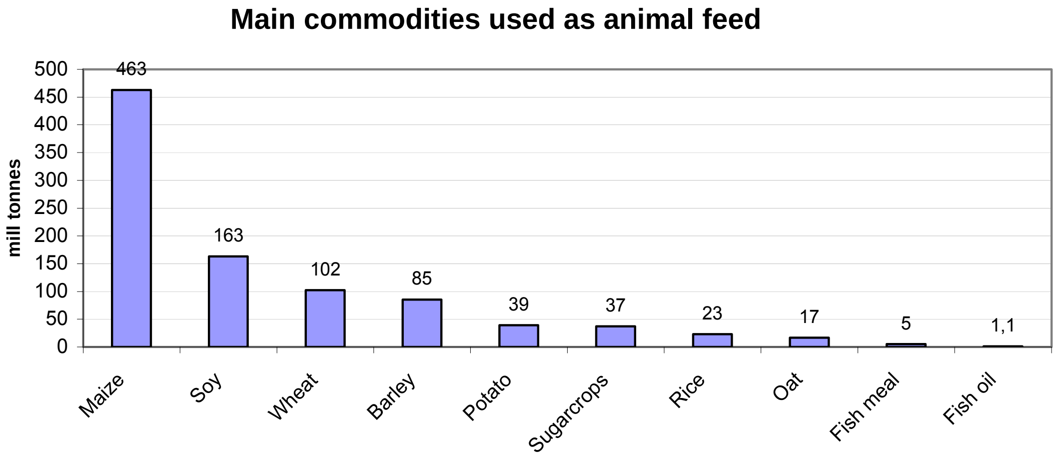


Figure 4 *Increase in world production of cattle, pig, chicken, Atlantic salmon and world aquaculture meat production from 1999 to 2009.*



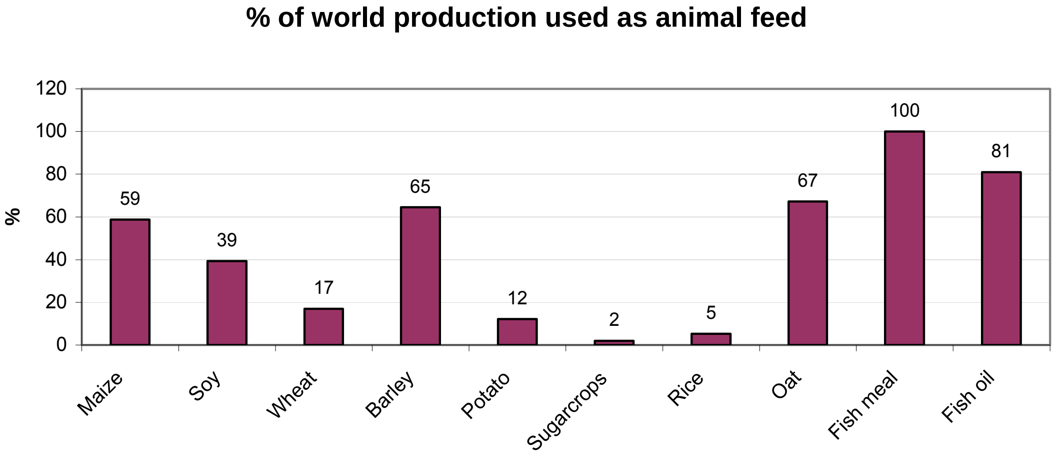


Figure 5 Upper panel: The volume of the major commodities used as animal feed in 2009. Lower panel: The % of the total world production of each commodity used as animal feed.

The report from United Nations Brundtland commission (WCED 1987), defines a sustainable development as “a development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs” (WCED, 1987:43). Included in this definition is not only a development that secures the global resource base and the environment, but also includes a social and economic aspect with responsibility for securing the basic needs of the present and future population (Figure 4). Sustainability, therefore, is an anthropocentric notion: it means that human induced changes in ecosystems must not threaten the exchange processes between society and its natural environment in ways that affect society’s survival or well-being.

Access to sufficient food with a satisfactory nutritional quality is a basic human need, and one of the major challenges in the next 30-40 years will be to increase the worlds food production to support a population of 9-11 billion people on earth in 2050 (United Nations).

The world's population is currently increasing by 80 million people each year, and FAO has estimated that food production must increase by 70% within 2050 to meet the increased demand for food. Food will have to be produced more efficiently using as little as possible of the available resource pool to produce as much nutrients as possible with minimal environmental impact. Thus, when comparing sustainability of food productions, a key issue is the ratio between energy produced and energy consumed in the production process. In addition, use of fossil energy causes serious environmental problems due to release of CO_2, NO_x and SO_x. The industrialization of agriculture has caused several serious problems including deforestation resulting in soil erosion, pollution and nutrient enrichment of rivers and lakes due to the use of pesticides and fertilizers, depletion of ground water resources and increased soil salinity, potential effects of gene modification of plants and microorganisms, and extinction of wild plants and animals due to fragmentation and destruction of habitats. According to Torrissen et al. (2011) at least three criteria should be considered when assessing sustainability of food production systems: (1) Will the process cause long term impact on the ecosystem (for centuries)? (2) Will the operation consume non-renewable resources, or is the use of resources unacceptably high? (3) Are the impacts of effluents on the ecosystem unacceptable? Eagle et al. (2004) defined an ecologically sustainable food production as a production that maintains the natural capital which it depends upon and in principle can continue indefinitely. However, according to this strict definition, no industrial food production is truly sustainable today because it is depending on non-renewable energy sources such as oil and gas as well as non-renewable phosphorous sources. Industrial food productions are variable in their energy yield per industrial energy input (Tyedmers et al., 2007). Thus, when the sustainability of food productions is evaluated it has to be seen in the context of maximising the nutritional output for human consumption with minimal input of resources (organic and inorganic) and the lowest possible impact on the environment. Whereas the nutritional content of a food product is easy to calculate, it is more challenging to quantify the use of natural resources and assessing the environmental effects of different food production systems (Schau and Fet, 2008).

At the United Nations 2005 World Summit it was noted that this requires the reconciliation of environmental, social and economic demands - the "three pillars" of sustainability (Figure 6). This view has been expressed as an illustration using three overlapping ellipses indicating that the three pillars of sustainability are not mutually exclusive and can be mutually reinforcing. The three pillars have served as a common ground for numerous sustainability standards and certification systems in recent years, in particular in the food industry. The ecological, social and economic development is restricted by the limits set by the environment, which consist of available resources and the capacity of the environment to absorb waste and emissions.

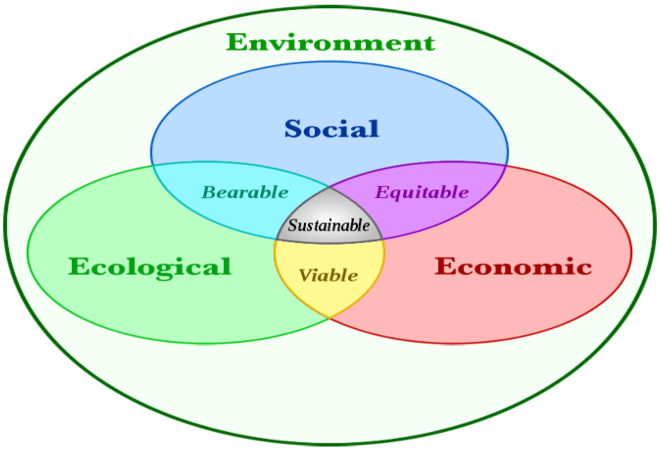


Figure 6 Development can be classified as sustainable, viable, bearable and sustainable and has elements of social and economic aspects in addition to ecological aspects.

1.2 Limiting resources

1.2.1 Land area and fresh water

The worlds cultivated area has increased by 12% the last 50 years and most of the earths land area that is suitable for agriculture is already utilised, 11% of the earths land area is used for crop production (FAO 2011 B). Thus, less new land will be available for agriculture in the future, so the majority of the increase in production must come from intensification (increase in yields and shorter fallow periods). This will also demand irrigation of new areas, and there is concern that the global freshwater supplies are being overexploited. Agriculture is presently responsible for 70% of the water withdrawn for human use and whereas there is enough water on a global scale, the water situation is becoming serious in some regions. In large areas of India and China the ground water levels are falling 1-3 meters per year, and by 2030, 20% of the developing countries will face water scarcity (FAO, 2011 C). In addition to the direct consumption of water for drinking and irrigation of crops, agriculture and livestock production in particular contribute to the pollution of water resources worldwide. According to FAO, the global feed production must increase by 30% within 2030 to keep up with the population growth. The livestock sector is already using 30% of the earth's land area (Gerber et al., 2007). Agriculture production has complex global and regional impacts on water use and depletion (Figure 7). This has led to the development of the concept of "virtual water" and the calculation of water footprints of different food products. Production of cereals uses 1644 l/kg whereas producing chicken and pig consumes 4325 and 5990 l/kg respectively (www.waterfootprint.org).

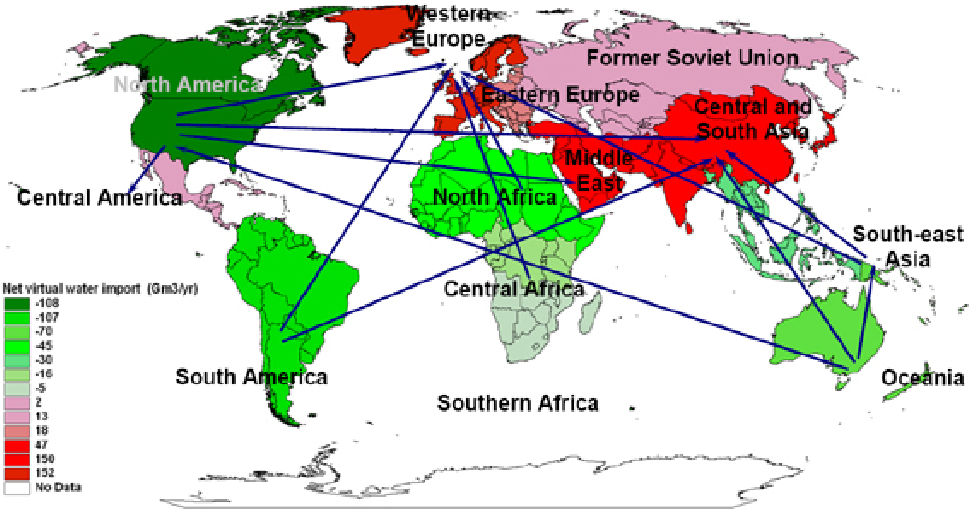


Figure 7 *Regional virtual water balances and net interregional virtual water flows related to the trade in agricultural products. Net exporters are shown in green and net importers in red. Period: 1997-2001. Only the biggest net flows (>10 Gm3/yr) are shown (Source: www.waterfootprint.*org)

1.2.2 Phosphorous resources

There has been a lot of focus on the limited availability of fossil energy sources in the near future whereas there has been less attention to the fact that the global food supply is totally dependant on the use of a finite resource of phosphorus (P). The low P concentration in soil in large parts of the world makes it a limiting factor for plant growth on entire continents such as Africa and Australia and in large countries like Brazil and India. Phosphorus is thus essential for global food production, and agriculture consumed almost 90% of P used in 2010, 82% were used in fertilisers and 7% was used in animal feed supplements (Schröder et al., 2009). In 2012, the amount of P used as fertilizer is estimated to be around 20 million tonnes (Smit et al.,2009). The rest of the P (11%) is used in industry and as detergents (Figure 8). The consumption of phosphate rock has increased by 3.4% per year the last 100 years and is expected to increase by 2.7-4.4% per year in the next decades as a result of the demand for increased food production due to the increasing world population and a shift to diets with more meat and dairy products (Van Enk et al., 2011). A meat-rich diet consumes 3 times as much P as a vegetarian diet, and for a world population of 7.7 billion people, a 20% increase in P-fertiliser would be required without changes in the world diet whereas the increase would have to be 64% if the whole world population would have a diet that resemble the diet in developed countries (Smit et al., 2009). Global P demand will also be influenced by the production of bioenergy and biofuel crops. Estimates based on different growth scenarios show that the P reserves available at the current price level may be depleted within 30 to 200 years (Van Enk et al., 2011, Figure 8, Table 1). However, the size of the future reserve base that may become available at higher market prices is not accounted for in these calculations. The size of the future reserve base also depends on the future phosphate prices. The estimated volume of the total resource base of P is also somewhat uncertain (Schröder et al., 2009, Van Vuuren et al., 2010.

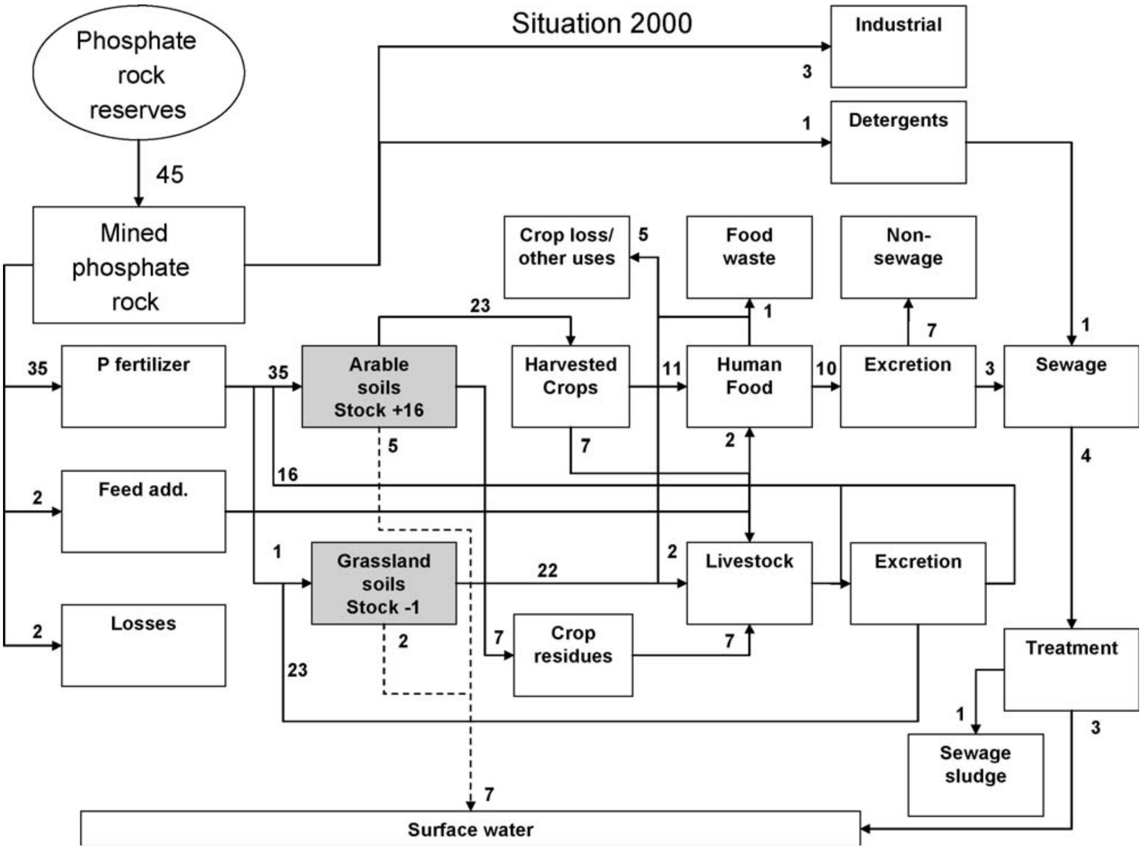


Figure 8 *Global P flows through the agricultural, food and sewage systems (from Van Vuuren et al., 2010).*

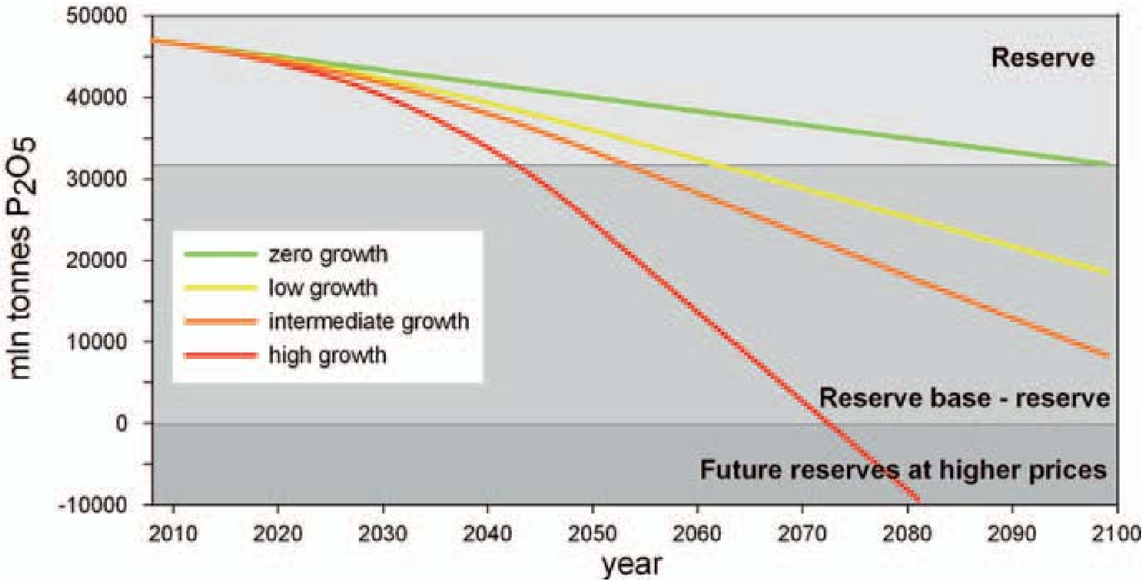


Figure 9 *Depletion of the global phosphate reserves and reserve base under zero, low, intermediate and high growth scenarios (from Van Enk et al., 2011)*

In two recent reports "Sustainable use of phosphorus" and "Phosphorous in agriculture", it is concluded that the current use of P is not sustainable due to losses at all stages from mining to crop field to human consumption. Less than 20% of the mined P is consumed by humans, and the majority of what is eaten is excreted, around 3 Mt P/y is present in human excreta and 12 Mt P/y is present in animal excreta (Smit et al., 2009). P is not cycled at present, but moves through an open one way system where the final losses end up in the ocean. Only a very small amount of the 16 Mt of P lost to the oceans is recovered (0.3 Mt/y in fish harvests), the rest ends up in ocean sediments where the P becomes unavailable for millions of years until tectonic movements lifts the ocean floor to dry land and erosion makes the P accessible to plants. Thus there is a need to reduce the global use of P and increased recycling of the P that is used (Schröder et al., 2009, Smit et al., 2009).

Table 1 Calculated phosphate rock consumption in 2050 and sufficiency of reserves available with current phosphorous prices (= reserves) and remaining reserve base available with an increase in price of phosphorous under various growth scenarios. Future reserves that may become available with new technology (=resource base) are not included (from Van Enk et al., 2011)

Growth scenario	Consumption in 2050 (Mt/y)	Year of depletion of reserves	Year of depletion of reserve base
Zero	167	2100	>2200
Low	356	2060	2150
Intermediate	511	2050	2110
High	1093	2040	2070

1.2.3 Marine resources

With less space and water resources available on land, growing food in the ocean is an attractive option. Aquaculture now accounts for almost half of the total food fish supply and the percentage is increasing every year (FAO, 2010). Capture fisheries and aquaculture supplied the world with 145 million tons of fish in 2009 of which 115 million tons were used as human food, resulting in a per capita food fish supply of 17 kg (FAO 2010). The dependence of the aquaculture feed industry on fish meal and fish oil and the consequences this may have for wild fish stocks is often used as an argument against sustainability of salmon production (Naylor et al., 2000, Deutch et al., 2007, Tacon and Metian 2008). In 2008, 53% of the world's fish stocks were fully exploited, 28% were overexploited, 3% depleted and 1% were recovering from depletion and the remaining 15% were underexploited or moderately exploited (FAO, 2010). Thus, a further growth in the production of salmon and aquaculture can not depend on an increase in the catch volume of wild fish beyond sustainable limits, but must rather rely on a further increase in the use of alternative sources of lipid and protein. There is however still a potential for increased utilisation of discards and by-products from processing of fishery products for human consumption. Worldwide, approximately 25% of the fishmeal produced originates from trimmings, but the potential is larger considering that around 120 million tons of fish are consumed by humans, and if the edible portion is around 50%, there are roughly 60 million tons of trimmings and by-products potentially available for production of fish oil and fish meal. In addition there are 38 million tons of unreported by-catch that can potentially be utilized for human consumption or for production of fish meal and oil. Improved management and regulation of the capture fisheries is necessary for a sustainable utilisation of the wild fish resources.

Marine products such as fish and seafood are a major source of the long chain unsaturated fatty acids EPA and DHA. These fatty acids, also known as omega 3,are indicated to possess several positive health effects, hence, humans are advised to consume more marine fish and less meat for health benefits . The nutritional requirement of these fatty acids is uncertain, but is assumed to be between 0.25-0.5 mg per day for humans (EFSA, ISSFAL). These requirements can be fulfilled in several ways. Marine fish and seafood contain variable amounts of these fatty acids, so consumption of seafood, either from fisheries or from aquaculture is the main source of EPA and DHA in human nutrition. Salmon and trout are effective in retaining these fatty acids from their diet, and recent studies suggest that they may even be net producers of omega 3-acids (Turchini et al., 2010, Sanden et al., 2011). Alternatively, omega 3 rich concentrates made from marine fish or by-products can be ingested in the form of capsules or in liquid form or used to fortify other food products with omega 3 (functional food).

1.3 Methods for measuring eco-efficiency

At present there are few indicators and standards for what can be defined as sustainable food production, and a given indicator does not demonstrate if a production is sustainable unless a reference value or threshold for sustainability is defined (Lancker and Nijkamp, 2000). Thus, there is a need to develop models, metrics and tools to decide whether an activity is sustainable or not. Sustainability indicators and composite indicators are increasingly recognised as a useful tool for policy making and public communication in environmental performance (Singh et al., 2009). The main purpose of environmental indicators is to summarise, focus and condense the complexity of our environment to a manageable amount of meaningful information. This will then provide decision-makers with a tool to determine which actions should or should not be taken to make society sustainable (Kates et al., 2001). To be able to make strategic decisions on how to produce enough food in the future in a safe and sustainable way it is useful to be able to assess and compare how different food producing systems utilize biotic and abiotic resources and generate waste. A major problem in the current public debate is the lack of defined criteria and reference points for determining what an environmental sustainable food production is. Several methods are currently being used to measure environmental performance of products and these methods focus on different impact factors. For example, ecological footprint and water footprint analysis can be regarded as complementary in the sustainability debate (Hoekstra, 2008. In addition, most of the methods are developed for land based production systems and industrial production systems, and the impact categories chosen are not always suited to address important environmental issues that are unique to the aquaculture industry, such as use of pelagic fish species for production of fish meal and oil and potential transmission of parasites and genetic material to wild populations (see Pelletier et al. 2007 for a review). Both local impacts such as eutrophication and global impacts (e.g. climate change) should be taken into account and it is also necessary to focus on the management of the reduction fisheries. There are currently several independent certification schemes for sustainable fisheries, the Marine Stewardship Council (MSC) has developed a standard with principles and criteria for sustainable fishing and FAO also has a Code of Conduct for Responsible Fisheries. The International Council for Exploration of the Sea (ICES) also provides scientifically based advice on the status and sustainable quotas on fish stocks in the North Atlantic Ocean.

Fish are generally more efficient converters of feed energy to bodyweight than warm blooded animals. In nature, homeotherms have a low production efficiency compared to poikilotherms due to high maintenance and respiratory costs. On average, only 2% of the consumed energy is used for biomass production in homoetherms whereas poikilotherms convert on average 17% of the consumed energy to biomass (Smith, 1992). Aquatic living animals have some advantages compared to land living animals in terms of energy conservation, as they excrete ammonia directly into the environment and thus spend less energy on protein metabolism than terrestrial animals that excrete urea or uric acid. Buoyancy in water also saves energy and reduces the need for a heavy skeleton, thus increasing the edible portion of the aquatic animals as compared to the terrestrial. Being a poikoilothermic aquatic carnivore, Atlantic salmon is a very efficient converter of consumed nutrients and energy into edible flesh and potentially a very efficient food producer. Culture production of animals generally improves the energy conversion since food is more available. This results in a higher feed intake and a reduction in activity which improves the growth and retention of nutrients (Bergheim and Åsgård, 1996). However, it is not only the conversion efficiency from feed to edible product that must be considered when evaluating different meat productions. The total amount of resources that are utilized in the production and the waste that is generated must also be considered. A high energy feed is more costly to produce in terms of resource use and energy consumption compared to a low-energy feed, and in industrial food productions the feed is the major impact factor in terms of energy and resource demand.

Methods for comparing the environmental cost of aquatic and terrestrial food production systems include cost-benefit analysis, material and energy flow analysis, human appropriation of net primary productivity, life cycle analysis, ecological footprint analysis, risk analysis and environmental impact assessment. To be useful for comparison, the methods should be scientifically based and comparable across different sectors, expandable to different scales, practical to implement and easily understood by managers and policy-makers (see review by Bartley et al., 2007). Any human activity, including aquaculture productions, can be evaluated in terms of its biophysical performance, meaning the influence it has on the environment and how much resources that are consumed in the process. The methods used to assess performance differ in methodology and focus on different aspects of biophysical performance. No single method is currently robust enough to capture all environmental impacts and costs associated with food production. Thus, the information derived from using these tools is complementary and should be interpreted together to obtain the broadest possible understanding of the eco-efficiency of a production system.

1.3.1 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is an ISO-standardized analytical framework for evaluating the environmental impacts of products or processes (eco-efficiency). A life cycle refers to the life span of a product from resource extraction, manufacture, use and final disposal. When complete, a LCA estimates the cumulative environmental impacts resulting from all stages in a product's life cycle. There are two ISO standards specifically designed for LCA application: ISO 14040 (Principles and framework) and ISO 14044 (Requirements and Guidelines). LCA was originally developed to evaluate the life-cycle impacts of industrially manufactured products, but is now increasingly being applied to evaluate food production systems, including aquaculture. LCA is currently the dominating method for environmental analysis. The LCA framework is used to quantify the energy and material inputs and environmental impacts associated with each stage of a product's life cycle, from resource extraction and processing, consumption, disposal and recycling. The environmental costs of a process is expressed in terms of its impact on a range of environmental problems such as global warming, acidification, biotic and abiotic resource use, ozone depletion, eutrophication, and environmental toxicity.

The main phases of an LCA are:

Definition of the goal and scope of the analysis

Inventory analysis - making a model of the product life cycle with data collection of all environmental inputs and outputs

Impact assessment – the effects of the resource use and emissions generated are grouped into impact categories which may be weighted according to their importance

Interpretation – The results of the inventory analysis and impact assessment are discussed, and conclusions are drawn

1.3.1.1 Definition of goal and scope

The goal and scope of a LCA defines the most important choices and definitions that must be made. The reasons for performing the LCA and the questions that needs to be answered are defined as well as the product and its life cycle. The primary goal of a LCA is to select the product alternative with the least harmful effects on human health and the environment. If two products are to be compared, a unit for comparison is also defined (the functional unit). Usually, the functional unit is a defined volume or mass unit, for example a kg of live animal or a kg of edible product. To trace absolutely all inputs and outputs from a system is impossible, so boundaries around the system must be defined. This is a critical step that may have large impact on the outcome of the study. An important question is whether the production and disposal of capital goods (trucks, factory equipment, fishery vessels, net pens for fish farming etc.) are included in the analysis. In modern databases capital goods are usually included, and in general, capital goods should be included if they give a significant contribution to the outcome of the LCA. An example of system boundaries for an LCA of production of salmon fillet is shown below (Figure 10).

When agricultural systems are analyzed it must be defined whether the agricultural land is seen as a part of nature or as a production system. If it is defined as nature, all pesticides applied are considered as an emission. On the other hand, when considered as an economic production system, only the pesticides that leak out from the area are considered as emissions.

1.3.1.2 Inventory analysis

In the inventory analysis, the products lifecycle is defined and all material and energy requirements as well as all emissions to air, water and soil are quantified. The steps involved in the inventory analysis are creation of a flow diagram (Figure 9), data collection and modelling multi-output processes and reporting. The data are obtained through direct information and measurements and from databases such As Ecoinvent 95.

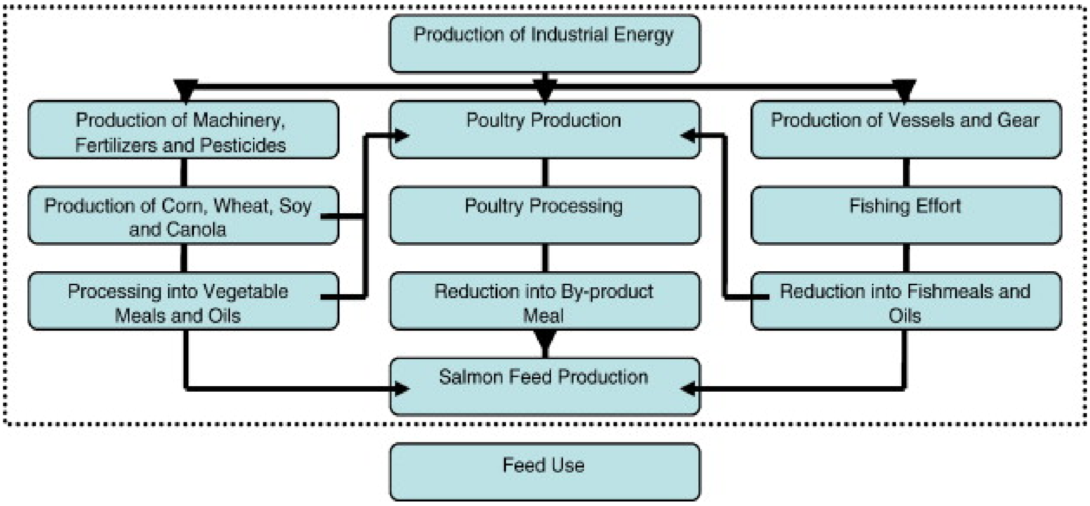


Figure 10 Example of a simplified flow diagram with system boundaries for production of salmon feed in Canada (from Pelletier and Tyedmers, 2007).

1.3.1.3 Allocation

Most industrial food production systems result in more than one product. Thus, flows of materials and energy as well as the environmental load must be allocated to the different products. The ISO standard recommends avoiding allocation by either sub-dividing the process in two or more separate processes to isolate the component of interest, or to expand the system boundaries to include processes that would be needed to make a similar output. If it is not possible to avoid allocation, the ISO standard recommends allocating the environmental load according to an underlying physical relationship that reflects the material balances between the inputs and outputs of the system. If no physical relationship can be established, allocation may be based on some other relationship that reflects the material balance between inputs and outputs of the production system. Examples are allocation according to the mass or energy content or economic value of the products and by-products. Allocation based on mass or energy content reflects the biophysical flows through the production system and is stable over time. Economic allocation is not stable over time because the prices of products may change in response to changing availability and market demands. The choice of allocation method is one of the most controversial methodological issues in LCA because it has a large impact on the outcome of the LCA (Ayer et al., 2007, Svanes et al., 2011, Pelletier and Tyedmers, 2011) and the ISO standard states that a sensitivity analysis should be performed if there are several alternative allocation methods that may be applied.

In fisheries and aquaculture productions allocation may become necessary in the fishing stage, during processing and feed production. The economic value of main product and co-products has been used to allocate impacts between main product and by-product and express the relative importance of an output. However, using economic allocation may change the outcome of the analysis if the price of the products changes. If the price of the main product falls but the price of the by-product is not reduced accordingly, the relative contribution to the environmental burden from the main product will be reduced, and it may seem as if the main product has become more eco-effective. Mass allocation divides the contribution to environmental impact equally according to the mass of the main product and by-product. Trimmings and by-products have a lower economic value than the fillets for human consumption, but may represent more than half of the total weight and contain a major proportion of the total energy content of the fish. Svanes et al. (2011) describe a case study with Atlantic cod where they compared the effect of allocation method on the outcome of LCA results of different products from cod .They compared mass, energy and economic allocation and a novel hybrid allocation method that combined mass and economic allocation by multiplying the product categories with a set factor. Products for human consumption were multiplied with 1, products used in animal feed were multiplied with 0.5 and products that were incinerated were multiplied with 0.25. Economic allocation gave a much larger spread of impacts between the different products than mass allocation, particularly for trimmings due to the large price differences between the products for human consumption and the processing residue sold as raw material for animal feed. The global warming potential (GWP) was 7.6 and 0.15 for the loins and processing residue using economic allocation and 3.9 and 1.2 when using mass allocation respectively. Hybrid allocation gave impacts between economic and mass allocation whereas allocation based on energy content of the products gave results close to mass allocation.

The choice of allocation method is clearly important if by-products form fisheries or livestock productions are used in salmon feed production. In mass allocation, the environmental cost associated with the by-products is the same as for the products for human consumption. Thus, the use of by-products from “environmentally costly productions” such as livestock production in salmon feed production will contribute substantially to the outcome of an LCA analysis in terms of energy use and CO_2 emissions. Using mass allocation in LCA’s is beneficial for producers of products for human consumption if they can recycle their by-products into other production systems. This may create an incentive for avoiding dumping or burning of processing waste. On the other hand, economic allocation is more beneficial for the consumer of by-products and creates an incentive for using these valuable resources. Thus, there is a conflict of interest between producers and consumer of by-products regarding what allocation method is most beneficial for their product.

Despite the problems with co-allocation in LCAs, system expansion or splitting up the process in several sub-processes to avoid allocation has rarely been applied in LCA studies involving sea food products (Ayer et al., 2007). Thrane (2006) is an example of how system expansion may be used in LCA of capture fisheries.

1.3.1.4 Life Cycle Impact Assessment

During the impact assessment, the magnitude of environmental impact from different processes is quantified by using impact categories that represent environmental issues of concern. The impact may be on both global and/or local scale. The potential impacts are modelled using conversion factors to obtain one indicator for each impact category. An impact category may for instance be the global warming potential, where all gases that contribute to global warming (CO_2, N_2O, CH_4) are converted into CO_2 equivalents based on their global warming potential. Table 2 shows examples of impact categories and category indicators. An LCA may be performed for one or a selection of these impact categories. The ISO guidelines define optional and mandatory elements of the impact assessment framework. The selection of impact categories and characterization models, calculation of category indicators and classification of results are mandatory elements of the analysis, whereas normalisation (relative to a reference value), grouping and weighing of data and data quality analysis are optional (Guinee et al., 2001). Grouping means that indicators are sorted by characteristics such as emissions (air, water) or by location (local, regional, global). The weighing of impact categories is more controversial, as relative values are assigned to the various impact categories based on the anticipated importance. Thus, even though scientific methods such as multi criteria analysis may be used, there is an element of preference when ranking the importance of impact categories. Preferences may change in time and may also be different among stakeholders, so the weighted factors obtained are not strictly objective or scientific. Therefore, the ISO standard prohibits the use of weighing methods in studies that are to be disclosed to the public.

1.3.1.5 Strengths and limitations of the method

LCA is generally well suited for measuring flows of matter through production system as the method was originally developed to study industrial processes. However, some of the impact categories relevant for industrial processes are not so relevant for agriculture and aquaculture productions, whereas there are no relevant measures for some of the environmental problems associated with food productions. There are currently no sufficient methods for quantifying problems such as soil erosion, loss of biological diversity, disease and genetic transmission from cultured to wild animal populations.

An important task when evaluating environmental impacts is to identify which processes that contribute most in the outcome of the LCA. This may for instance be certain life cycle stages (e.g feed production), certain impact categories (e.g global warming), or certain inventory parameters (energy use). When comparing different products it is often difficult to get a clear answer to which products are better from an environmental point of view due to different outcomes in the impact categories considered relevant. Thus, the results may be difficult to communicate to the public. The relevance of impact factors may also vary depending on local conditions. For example, the eutrophication potential may be important when assessing the effect of a fish farm located in a freshwater lake but may be irrelevant for a fish farm located in the open sea. And water consumption may not be a problem in an area where water is plentiful, but could constitute a serious environmental impact factor in areas where water is scarce and ground water reservoirs are becoming depleted. Thus, the choice becomes subjective as to what impact is considered the most serious depending on local conditions. However, the information obtained may still be useful for a deeper understanding of the environmental impacts of the processes involved and identifying potential hazards. The sensitivity of choice of allocation method and the practice of using mass units as functional units in LCA studies might be the most serious limitations of the model when applied to food producing systems. Using mass as functional unit makes LCA unsuitable for measuring the retention efficiency of nutrients in food production systems. Because the main function of food is to provide nutrients, it would be more useful to use the nutritional value of a product as a basis for comparison between products. The nutritional value of a product may be defined as a sum of all the ratios: (nutrient gained/daily requirement) for a kg of a certain product. The nutritional value has been suggested used as a normalisation factor when assessing impacts of a production (Mungkung and Gheewala, 2007).

Table 2 Impact categories and category indicators often used in LCA analyses

Impact category	**Scale**	**Category indicators**
Climate change	global	Global warming potential expressed as CO_2 equivalents
Ozone depletion	global	Ozone depletion potential expressed as CFC-11 equivalents
Acidification	regional/local	Acidification potential expressed as SO_2 equivalents
Eutrophication	local	Eutrophication potential expressed as PO_4 equivalents
Toxicity (human/ecosystem)	global/continental	Contributes to conditions toxic to marine flora/fauna Expressed as 1,4-DCB equivalents
Photochemical oxidant formation	local	Photochemical ozone formation potential, expressed as ethylene (C_2H_4) equivalents
Land use	global/regional/local	Land occupation, expressed as m^2/year
Biotic resource use	global	Appropriation of net primary productivity (NPP) carbon appropriated
Abiotic resource depletion	global	Depletion of minerals and fossil fuels, expressed as Sb (Antimony) equivalents or MJ for energy use
Water use	Global, regional, local	Expressed as litre/year or litre/kg

1.3.1.6 Examples of LCA analysis of salmon farming

The LCA methodology is becoming the dominating method for assessing the eco-efficiency of different food productions, both land based, and fishery and aquaculture productions (Thrane, 2006, Pelletier, 2008, Pelletier et al., 2008, 2010, Schau et al., 2009, Schmidt, 2010). LCA methodology is also used by the aquaculture feed industry to make strategic decisions (Gundersen et al., 2010, Buttle et al., 2011). Several studies that have focused on different aspects of Atlantic salmon and salmonid production (diet composition, production system) have been published in recent years. The published studies have compared the impact of salmon farming with other animal productions, such as chicken (Ellingsen and Aanondsen, 2006) and cod fisheries (Ellingsen and Aanondsen, 2006, Winther et al., 2009). Other studies have compared different salmonid diets and production systems (Papatryphon et al., 2004, Pelletier and Tyedmers 2007, Ayer and Tyedmers, 2009 Pelletier et al., 2009, Boissy et al., 2011, Hall et al., 2011) (Table 3). All of the published studies used mass as functional unit and none of them tried to relate the environmental impact to the nutritional value of the product.

Although many of the same impact categories are applied and the results of the different studies are therefore not directly comparable due to different system boundaries and allocation methods used, some general conclusions can be made. Most studies performed on aquaculture productions so far have excluded environmental costs associated with infrastructure, seed production, packaging and processing of product, transport of feed and product, cooking of product and disposal of waste. This is due to the fact that the bulk of the environmental emissions and consumption of resources lies within the boundaries shown in Figure 8 (Pelletier and Tyedmers 2007, Pelletier et al., 2009). In aquaculture productions using high energy and dense pelleted feeds, feed production is particularly resource demanding and may account for up to 80-90% of the total energy consumption and environmental impacts (Ellingsen and Aanondsen, 2006, Tyedmers et al., 2007, Ellingsen et al., 2009, Pelletier et al., 2009, Boissy et al., 2011). The use of plant derived ingredients increases terrestrial land occupation but reduces the biotic resource use (measured as net primary production) compared to diets with high levels of marine ingredients (Papatryphon et al., 2004, Boissy et al., 2011). There was no effect of replacing marine ingredients with plant ingredients on the energy use and climate impact, but the terrestrial toxicity potential, water use, and acidification potential increased when a high level of plant ingredients were included in the diet (Boissy et al., 2011). Although fisheries are generally more energy intensive than farming operations, crop production is dependent on nitrogen fertilizer which is highly energy demanding to produce. The plant ingredients used are also very variable with respect to environmental impacts. Production of camelina oil, for instance, uses more water and energy than the production of rapeseed and palm oil (Boissy et al., 2011). Also, in a study comparing rapeseed oil and palm oil, it was concluded that palm oil was preferable to rapeseed oil in terms of land use, ozone depletion, acidification, eutrophication and photochemical smog whereas it was unclear which oil was preferable in terms of global warming, biodiversity and ecotoxicity (Schmidt, 2010). The use of mass or energy content as allocation method, results in a higher environmental impact of feeds containing by-products from land animal productions (Pelletier and Tyedmers, 2007, Pelletier et al., 2009) due to the high input of energy and primary production required to produce livestock. Using economic allocation reduced the average life cycle environmental impacts with 60% for diets containing poultry by-products (Pelletier and Tyedmers 2007). Feed efficiency (FCR) is a key factor in reducing the sum of environmental impacts (Papatryphon et al., 2004, Pelletier et al., 2009). Therefore, selective breeding (Thodesen et al., 2001, farm management practices, diet composition and reduction of production losses are all important focus areas for reducing environmental effects, both locally and globally.

Ellingsen and Aanondsen (2006) compared the energy use in salmon production with production of chicken and wild caught cod and found chicken to be the most energy effective whereas wild caught cod was comparable to farmed salmon. When the marine ingredients were replaced with plant ingredients the energy demand of salmon production was reduced to a lower level than for chicken production. However, while salmon and cod are similar in protein content and in the amino acid profile of the protein, they are very different in fillet lipid content and cod contain far less of the essential omega 3 fatty acids EPA and DHA.

Table 3 Summary of LCA studies involving Atlantic salmon and salmonids

Authors	Aim	Impact categories	Allocation method	Functional unit
Ayer and Tyedmers, 2009	Compare culture systems	Abiotic depletion Global warming Human toxicity Marine toxicity Acidification Eutrophication Energy demand	Gross nutritional energy content	1 ton of live salmon
Boissy et al., 2011	Effect of diet formulation Plant ingredients versus Marine ingredients	Energy demand Water use Land use NPPU Terrestrial ecotoxicity Global warming Eutrophication Acidification	Economic	1 ton of salmon feed, 1 ton of live salmon
Ellingsen and Aanondsen 2006	Comparison of wild caught cod, farmed salmon and chicken, effect of diet and energy source	Energy demand Antifouling Land use	Economic and mass	1 kg salmon fillet
Ellingsen et al., 2009		Global warming	Economic and mass	1 kg salmon fillet
Pelletier and Tyedmers 2007	Comparing organic and conventional salmon production	Energy demand Marine toxicity Eutrophication Acidification Global warming Biotic resource use	Gross nutritional energy content	Feed to grow 1 ton of salmon
Pelletier et al., 2009	Comparing global salmon farming systems	Energy demand Biotic resource use Global warming Eutrophication Acidification	Gross nutritional energy content	1 ton of live salmon
Hall et al., 2011	Comparing global salmon farming systems	Energy demand Global warming Eutrophication Acidification Land use Biotic depletion (forage fish)		1 ton of live salmon

1.3.2 The ecological footprint model (EF)

The ecological footprint model was developed in the 1990's by Rees and Wackernagel (1994). The EF is a measure of the demand human activities require from the biosphere. It measures the area of biologically productive land and water area required to produce all the resources an individual, a population or an activity consumes and the area required to absorb the waste that is generated. The EF calculation is based on the assumption that most of the resource and waste flows generated by human activities can be measured in terms of the biologically productive area necessary to sustain them. Resource and waste flows that can not be quantified in terms of biologically productive areas are excluded from the analysis, leading to an underestimation of the total demand these flows require from the ecosystem. The land and water area is scaled according to its biological productivity which makes it possible to compare ecosystems with different productivity in different areas of the world using the same unit, namely the global hectare. The global hectare represents a hectare with a global average productivity. Because the productivity of different land types vary widely on a global scale, yield factors are calculated for different countries and ecosystems. Hence a local area can be converted to a global hectare. The global hectare is used to express both the demand on the ecosystem (footprint) and the biocapacity of an ecosystem. The biocapacity of an ecosystem is defined as the productive area available to generate the resources and to absorb the waste generated. Thus, human demand (measured as the EF) can be compared to global, regional or national biocapacity. If the demands of an area exceed the available biocapacity this is referred to as overshoot. Standards and methodology for calculating EF have been developed by the Global Footprint Network by a committee-based process. The Standards Committee, comprised of representatives from Global Footprint Network partner organisations, issued the first Ecological Footprint Standards in 2006. The standards focus on the use of source data, derivation of conversion factors, and establishment of study boundaries. The details of the latest accounting method are described in Ewing et al. (2008b). The 2008 Edition of the National Footprints Account distinguishes six categories of land-use:

Cropland: The area used to produce food for human consumption and feed for livestock and fibre and rubber production.

Grazing land: The area used to raise livestock for meat, dairy and wool products.

Forest for timber and fuelwood: The area used to produce lumber, pulp, timber products and fuelwood.

Built-up land: The area covered by human infrastructure (housing, transport, industry etc)

Fishing ground: The estimated area needed to sustain a fishery based on calculations of the primary productivity requirement (PPR) to produce the fish caught. The PPR is calculated from the average trophic level of the species in question, assuming a 90% loss of energy between trophic levels. This means that fish at higher trophic levels require much more input of primary production and consequently will have much larger ecological footprints compared to species at lower tropic levels. Furthermore, because the average productivity of the oceans is much lower than the productivity on land, the footprints of fisheries will be much higher than terrestrial productions

Forest for carbon sequestration: The area of bioproductive forest needed to store the CO_2 emissions generated from burning fossil fuels and land-use change (deforestation) after subtracting the amount sequestered in the ocean. The area calculated for carbon sequestration is in many cases the dominating part of the ecological footprint.

Equivalence factors are developed to translate a specific area type into a global hectare (Table 4).

Table 4 Equivalence factors 2005, global area and global biocapacity of the different land use categories (Source: The ecological footprint atlas 2008)

Area type	**Equivalence factor (global ha/ha)**	**Global area (billion ha)**	**Biocapacity (billion global ha)**
Cropland	2.64	1.5	3.2
Forest	1.33	3.8	5.2
Grazing land	0.50	3.5	1.6
Fisheries	0.40	2.3	0.8
Built-up land	2.2	0.3	0.6
Total	1.0	11.4	11.4

1.3.2.1 Strengths and limitations of the EF model

The EF model calculates a single indicator measuring accumulated effects and it is therefore easy to communicate. The EF model can be applied to many levels and scales (regional, national, global). Because the model can estimate the regional or global biocapacity it can be used to predict environmental overshoot. The EF has been used to estimate the global ecological overshoot. In 2005 it was estimated that the global overshoot was 30%, meaning that the human population used 1.3 Earths to support its consumption and that 10 nations could be attributed to 50% of the global footprint (Ewing et al., 2008a). The EF methodology has also been used to assess eco-efficiency of food production systems, including fisheries and aquaculture operations (Larsson et al., 1994, Berg et al., 1996, Folke et al., 1998) and an EF model is also used in the aquaculture feed industry to assess environmental impact of different feed formulations as a basis for making strategic decisions (Buttle et al., 2011).

Although the EF model is used as an indicator of sustainability, some important impact categories are not included in the model and some aspects are hard to quantify with present methodology. The footprint does not measure depletion of non-renewable resources such as oil, coal, gas, minerals and metal deposits. It only quantifies the energy use in terms of the area required to absorb the CO_2 emissions generated by burning fossil energy sources. However, the footprint does not measure the emissions of other greenhouse gases such as methane and SO_x and NO_x generated by combustion of fossil fuels. Further, the footprint does not measure the release of heavy metals, radioactive compounds and other environmental toxins such as the persistent synthetic compounds PCBs, dioxins, PVCs, CFCs etc. In addition, the model does not directly measure loss of productive land due to soil erosion and salinity increase due to irrigation. However, the loss of productive land area may be reflected in reduced biocapacity in the future. The use of freshwater is thus only indirectly included in the model, and there is currently a lack of data linking freshwater use with loss of bioproductive capacity. Also, the model does not distinguish between area productivity before and after the area is changed from natural environments to cropland and cultural forests, and thus does not distinguish between the natural and man made productivity which is important when assessing biocapacity.

1.3.3 Material and energy flow analysis – nutrient balance models

The purpose of material flow accounting is to quantify material inputs and outputs of socio-economic systems in a similar way that flows of matter and energy are quantified in natural ecosystems (Haberl and Weisz, 2007). Material flow analysis (MFA) can be applied to various scales and type of systems, from households, companies, production systems, economic sectors, national economies, states and regions. National MFA's were developed in the late 1960s, and during the 1990s and until today, a growing number of EU countries have implemented MFA in their official environmental accounting program. Among the policies of MFA are focus on the management of material flows and land management, evaluation of resource scarcity and identifying substitution potentials (Haberl and Weisz, 2007). Recently, a comprehensive report on the flow of phosphorous in the EU region was released (Schröder et al., 2009).

MFA tracks the use of materials from extraction to manufacturing, to final use and disposal of emissions and waste and has a life cycle perspective (Figure 11). Energy flow analysis is used to account for the energy throughput of socio-economic systems based on energy content of all flows in and out of the defined system. However, the materials released at the different stages are not converted into impact categories like in the LCA methodology, so the environmental effects are not quantified as in LCA's. However, MFA can be used to quantify material requirements and release of substances from specific production systems, and may thus generate information about the environmental impact a production system has on its surroundings. The flows are measured in physical units, usually metric tonnes per year. Efficiency in the production system (conversion of feed to edible product) is highly important for the amount of biological material that is released to the surrounding environment (Figure 9). Nutrient balance models based on bioenergetic models have been used for estimating outputs of phosphorus, nitrogen and suspended solids (Einen et al., 1995, Kaushik, 1998, Papatryphon et al., 2005, Roque d'Orbcastel et al., 2008, Hua et al., 2008).

Nutrient-balance accounting can provide information on the environmental impacts of the farming activity and efficiency of resource utilisation. The efficiency is affected by feeding routines and diet composition. Efficiency in the production system, measured as conversion of feed to edible product, is highly important for the amount of biological material that is released to the surrounding environment. The feed conversion ration (FCR) is the amount of feed (kg) required to produce a kg of fish (round weight). The biological feed conversion factor is based on feed eaten whereas the economic feed conversion (eFCR) also include production losses (uneaten feed, mortalities, escapees) and is therefore higher than the biological FCR. The assimilation efficiency of nutrients is also important for the waste output; both the amount of nutrients digested and the amount of the digested nutrients that are retained in the fish. An optimal energy/protein ratio and covering the amino acids requirements are crucial for obtaining maximum growth and feed utilisation. The retention efficiency of nutrients is normally calculated in % of the amount eaten. Fish retain around 30% of the protein in the feed they eat whereas chicken and pork retain around 25 and 13% respectively (Åsgård and Austreng, 1995, Åsgård et al., 1999, Bjørkli, 2002). The ratio of total industrial energy invested in food production relative to the edible protein energy return has been used as a measure of the energy efficiency of food production systems, and is also suggested as a sustainability indicator (Troell et al., 2004, Table 5). However, the energy from fat should also be accounted for.

Table 5 Ranking of industrial energy input/per protein energy output in capture fisheries, agriculture and aquaculture productions (data from Troell et al., 2004)

Food production	**Industrial energy input/protein energy output (J/J)**
Herring (purse seine, North Atlantic)	2-3
Vegetable crops	2-4
Tilapia (extensive, Indonesia)	8
Sheep	10
Beef (rangeland farming)	10
Cod fisheries (trawl and long line, North A tlantic)	10-12
Milk (USA)	14
Catfish culture (ponds, USA=	25
Eggs (USA)	26
Broiler production	34
Atlantic salmon (Pens, Canada)	40-50
Intensive shrimp culture (Thailand)	70

1.3.3.1 Strengths and limitations of the MFA method

Analysis of material flow through a system quantifies inputs and outputs and can generate information that is comparable over time and across scales. It can also be used to improve and compare ecological efficiency in a life cycle perspective. The method only measures flow of different materials; it does not measure or reflect environmental impacts but can be combined with other methods such as risk assessment and environmental impact assessment to draw conclusions about potential environmental effects. The method can be more useful for measuring local impacts from emissions from aquaculture farms compared to LCA analysis that tend to focus more on emissions that have global impacts. The method is also very useful for measuring the efficiency in terms of nutrient yield and retention of nutrients in a farming system, an issue the LCA analysis and ecological footprints do not address. Analysis of nutrient flows can be combined with LCA analysis to get a full picture of the efficiency of resource utilisation and the environmental impacts of a food production system.

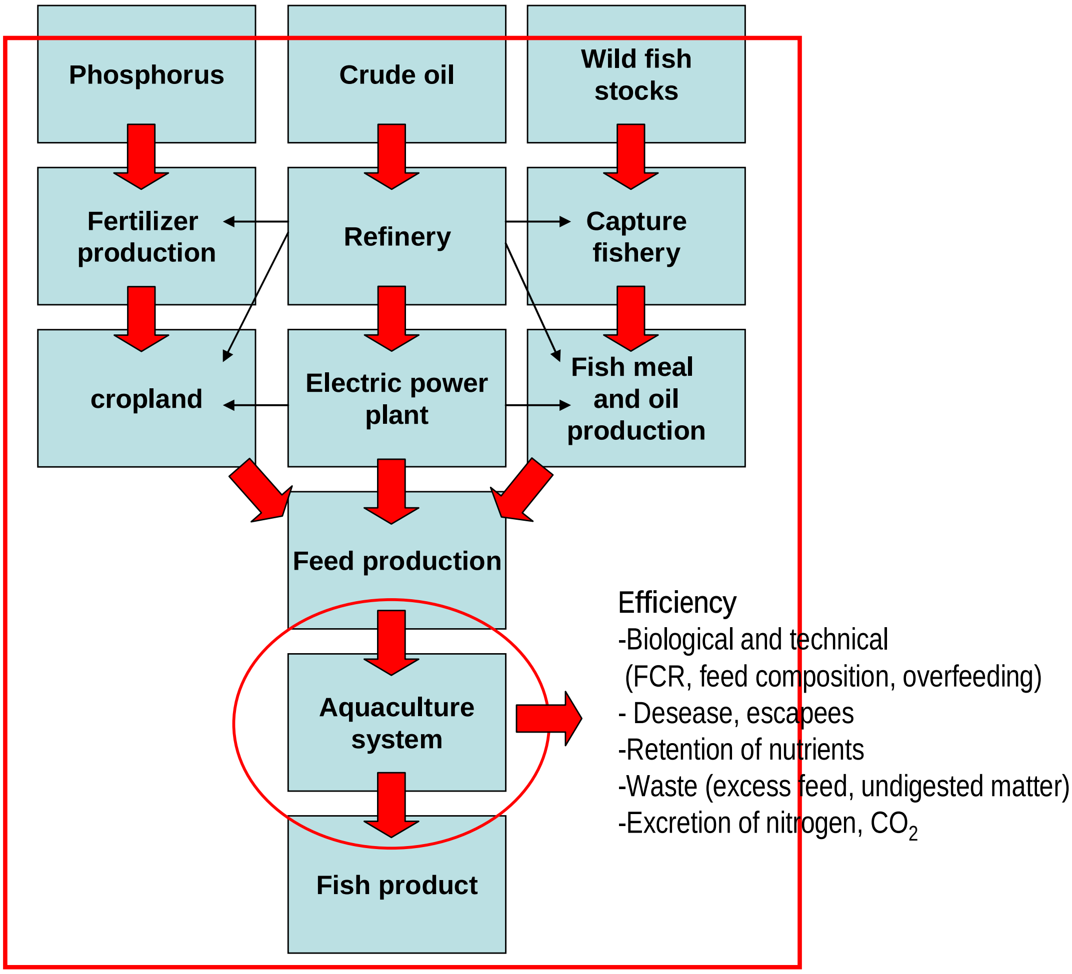


Figure 11 Flow of energy and biological matter in an aquaculture production system. Between each level there is input of energy and output of matter. (See text for details).

1.4 Summary Part 1

The population growth combined with increased urbanisation and higher per capita income in large parts of the world changes consumption habits and puts pressure on the limited resource pool. The per capita meat consumption was 15 kg in 1982, when the world population was 4.5 billion, and is expected to reach 37 kg in 2030, when the population is expected to have increased to 9 billion people. This will have large impact on the environment and the available resources of land area, fresh water, and phosphorus.

All food production has environmental consequences. Crop and livestock production have a profound impact on the environment, both locally and globally. Agriculture is the main source of water pollution by nitrates, phosphates and pesticides, and livestock production is a major source of greenhouse gasses. Livestock production uses large amounts of fresh water and land areas. The global meat production increases with around 3.6% per year and has nearly doubled between 1980 and 2004 and is expected to double again within 2030. There is also a shift from extensive grazing systems to more intensive production systems depending on concentrate feeds that are being traded internationally. More than 30% of the world cereal production is currently used in feed for livestock.

The majority of wild fish stocks are already fully exploited, so potential for increasing the food consumption from fisheries seems limited. Aquaculture is the fastest growing animal food producing sector with an annual growth rate of 6.6% between 1970 and 2008. Aquaculture now accounts for almost half of the total food fish supply (China included). The growth in the aquaculture industry has raised concerns about the environmental impacts and sustainability of fish farming. The use of small pelagic fish species as forage fish has been subject for debate. Like agriculture, aquaculture also has environmental impacts, eventhough the extent of the impact is debated. Examples from the salmon farming industry are potential genetic effects of escapees on wild salmon populations and spreading of salmon lice, use of anti-fouling agents and medicines, land and energy use in all parts of the value chain and discharge of organic and inorganic material. Production of feed is a major input factor in salmon production so an understanding of how resources and energy use in food production and how different feed formulations affect resource utilisation and environmental impacts is important for making strategic decisions.

The challenges related to the worlds food supply in the coming decades has led to increased focus on sustainable and efficient food production, and several methods are currently used to evaluate and compare the eco-efficiency of food prediction systems. The principles and strength and weaknesses of three methods were evaluated: 1) the LCA methodology, 2) the ecological footprint model, 3) material and energy balance flow models.

The Life cycle assessment (LCA) methodology is becoming the most frequently used method for assessing environmental performance of food production systems. Life Cycle Assessment (LCA) is an ISO-standardized analytical framework for evaluating the environmental impacts of products or processes (eco-efficiency). A life cycle refers to the life span of a product from resource extraction, manufacture, use and final disposal. The environmental costs of a process is expressed in terms of its impact on a range of environmental problems such as global warming, acidification, biotic and abiotic resource use, ozone depletion, eutrophication, and environmental toxicity. Thus, the results may be difficult to communicate to the public. The method also requires substantial data input. Some of the impact categories relevant for industrial processes are not so relevant for agriculture and aquaculture productions, whereas there are no relevant measures for some of the environmental problems associated with food productions. There are currently no good methods of quantifying problems such as soil erosion, loss of biological diversity, disease and genetic transmission to wild animal populations.

The sensitivity to choice of allocation method and the practice of using mass units as functional units in LCA studies are maybe the most serious limitations of the model when applied to food producing systems. Because the main function of food is to provide nutrients, it would be more useful to use the nutritional value of a product as a basis for comparison between products. Thus there is a need for further development of the method to make it better suited for application in aquaculture and agricultural productions by developing nutrient-related functional units and to develop methodology for system expansion to avoid allocation between co-products.

The ecological footprint (EF) model calculate the area of biologically productive land and water area required to produce all the resources an individual, a population or a production consumes and the area required to absorb the CO_2 that is generated. The area is given as the number of global hectares. Being given as an aggregated measure the ecological footprint is easy to communicate. However, comparing aquaculture productions using capture fish in the feed production with land animal productions is difficult because the ocean has a relatively much lower productivity than the terrestrial production systems. There are also a number of flows that are not included in the EF model. For instance, the footprint does not measure the emissions of other greenhouse gases such as methane and SO_x and NO_x generated by combustion of fossil fuels. Nor does the footprint measure the release of heavy metals, radioactive compounds and other environmental toxins such as persistent synthetic compounds such as PCBs, dioxins, PVCs, CFCs etc. Further, the footprint does not measure depletion of non-renewable resources such as oil, coal, gas, minerals and metal deposits.

Material flow analysis (MFA) tracks the use of materials from extraction to manufacturing, to final use and disposal of emissions and waste in a life cycle perspective. The flows are measured in physical units, usually metric tonnes per year, but energy content or amount of nutrients may be used in the study of food production systems. The materials released at the different stages are not converted into impact categories like in the LCA methodology, so the environmental effects are not quantified as in LCA. However, MFA can be used to quantify material requirements and release of substances from specific production systems, and may thus generate information about the environmental impact a production system has on its surroundings through the development of nutrient balance models. Thus, the method can be more useful for measuring local impacts from release of material from aquaculture farms compared to LCA analysis that tend to focus more on emissions that have global impacts. The method is also very useful for measuring the efficiency in terms of nutrient yield and retention of nutrients in a farming system, an issue the LCA analysis and ecological footprints do not address. Analysis of nutrient flows can be combined with LCA analysis to get a full picture of the efficiency of resource utilisation and the environmental impacts of a food production system.

In conclusion, there is currently no single method that is robust enough to cover all possible environmental impacts related to food production. Several methods may be used in combination to gather information about a production system. Nutrient balance models may be used for assessing local impacts and nutrient retention efficiency whereas LCA may be used to study the regional or global impacts of the product.

2 Part 2

2.1 Indicators of marine resource use

One of the main concerns raised against the increase in salmon production is the use of wild fish stocks for production of fish meal and oil. The concern is based on the assumption that aquaculture production is consuming large amounts of pelagic fish for feed that could have been used as human food, and therefore that the salmon industry is reducing the amount of marine protein available for human consumption (Naylor et al., 2000, 2009, Naylor and Burke, 2005). Other authors claim that the use of marine resources in aquaculture feeds are a sustainable way of providing marine nutrients for human consumption (Shepard et al., 2005, Welch et al., 2010). To quantify the use of marine resources in aquaculture productions several indicators for the use of forage fish in aquaculture productions have been developed.

2.1.1 The fish in-fish out ratio (FIFO)

The fish in/fish out ratio transforms the amount of fish meal and oil that is used to produce one weight equivalent of farmed fish back to wild fish weight equivalents (usually a kg or ton), and it is often 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). In this process 90% of the water in the forage fish is condensed, and based on a global average, 1 kg of forage fish is turned into 225 g of fish meal and 50-100 g of fish oil (IFFO, 2010). Thus, condensation efficiency is a more appropriate term. The second conversion ratio is the amount of feed (kg) consumed to produce one kg of salmon (economic feed conversion ratio, eFCR):

$$\mathrm{FIFO} = \left[\frac{\text{Diet FM (g/kg)}}{\text{FM reduction efficiency (g/kg)}} + \frac{\text{Diet FO (g/kg)}}{\text{FO reduction efficiency (g/kg)}} \right] \cdot \mathrm{eFCR}$$

(Equation 1)

However, because the relationship between meal and oil yield from reduction fish is approximately 5:1, it is the amount of fish oil in the diet that will determine the dependency of reduction fish and the FIFO ratio, so the FIFO ratio should be calculated separately for fish oil and fish meal:

$$\mathrm{FIFO}_{\text{(FM or FO)}} = \left[\frac{\text{Diet FM or FO (g/kg)}}{\text{FM or FO reduction efficiency (g/kg)}} + \right] \cdot \mathrm{eFCR}$$

(Equation 2)

Improvements in production technology has lead to a greater protein recovery from whole fish and the latest yield figures from the industry range from 23.5-24.5% fish meal from whole fish (Jackson, 2009, Péron et al., 2010). However, the oil yield will vary with the fat content between different species and also within species during the year (Figure 13 a,b). An oil yield of 9.3% (weighed mean) was estimated for fish oil used in Norwegian salmon production in 2010 based on data of fat content of the species used in the production of fish oil and 10% residual fat in the fish meal.

The FIFO for fish oil is very sensitive to the oil yield in production of fish oil. Doubling the oil yield from the forage fish will reduce the FIFO ratio for fish oil by half (Figure 12). Thus, using herring and capelin with high fat content in fish oil production will reduce the FIFO ratio whereas using oil from leaner species such as anchovies (5% oil yield) will increase the FIFO ratio for fish oil.

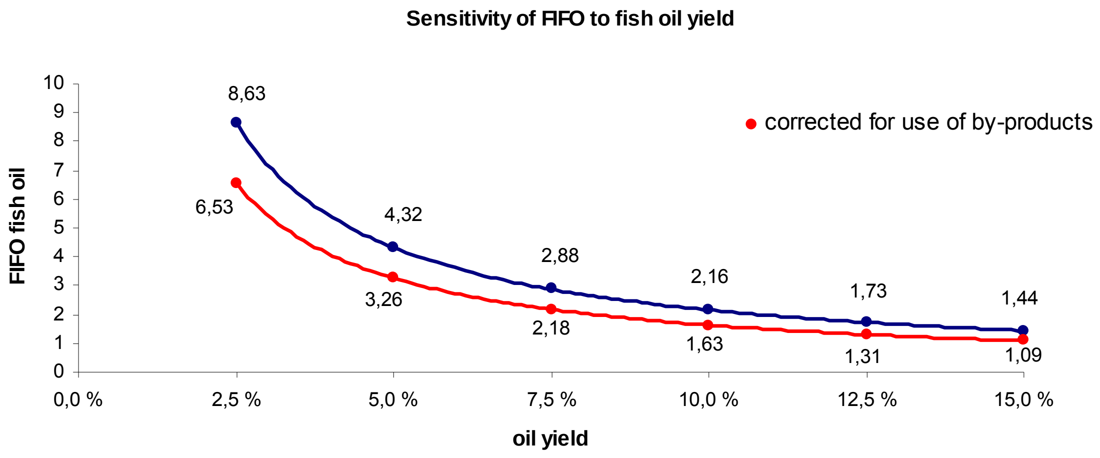


Figure 12 FIFO as a function of the conversion efficiency of reduction fish into fish oil. Data from 2010 are used in the calculations (FCR = 1.3, inclusion level of fish oil was 16.6% of which 24% came from trimmings and by products). The blue line indicate the FIFO calculated based on the total amount of fish oil in the diet and the red line indicate the FIFO calculated based only on the amount of fish oil coming from forage fish.

To achieve a FIFO of 1 for fish oil the dietary inclusion level of fish oil from forage fish must be reduced to 7% with a fish oil yield of 9.3%, whereas for fish meal, an inclusion level of 17% fish meal in the diet from forage fisheries corresponds to a FIFO of 1 with a reduction efficiency of 22.5% (Figure 14).

Using Equation 2, the FIFO for fish meal and oil in Norwegian salmon production in 2010 can be estimated. For fish meal a mean yield of 22.5% was used (IFFO) and for fish oil a yield of 9.3% was used. The feed conversion ratio was 1.3 in Norwegian salmon farming industry in 2010 and the mean inclusion levels of fish oil and meal were 16.6 and 24.8 %, in salmon diets in 2010.

$$\text{FIFO}_{(\text{FO 2010})} = [\ 166\ (\text{g/kg}) / 93\ (\text{g/kg})\ ]\ *\ 1.3 = \underline{2.32}$$

$$\text{FIFO}_{(\text{FM 2010})} = [\ 248\ (\text{g/kg}) / 225\ (\text{g/kg})\ ]\ *\ 1.3 = \underline{1.40}$$

24% of the total fish oil and 21% of the fish meal used were made from trimmings and fish silage from fish species caught for human consumption. Subtracting this amount from the total amount of fish oil and meal used in the diet reduces the FIFO for fish oil and meal from wild fish to 1.8 and 1.1 respectively for the 2010 salmon production in Norway.

The development of FIFO for FM and FO in Norwegian aquaculture over the past two decades is shown in Figure 15.

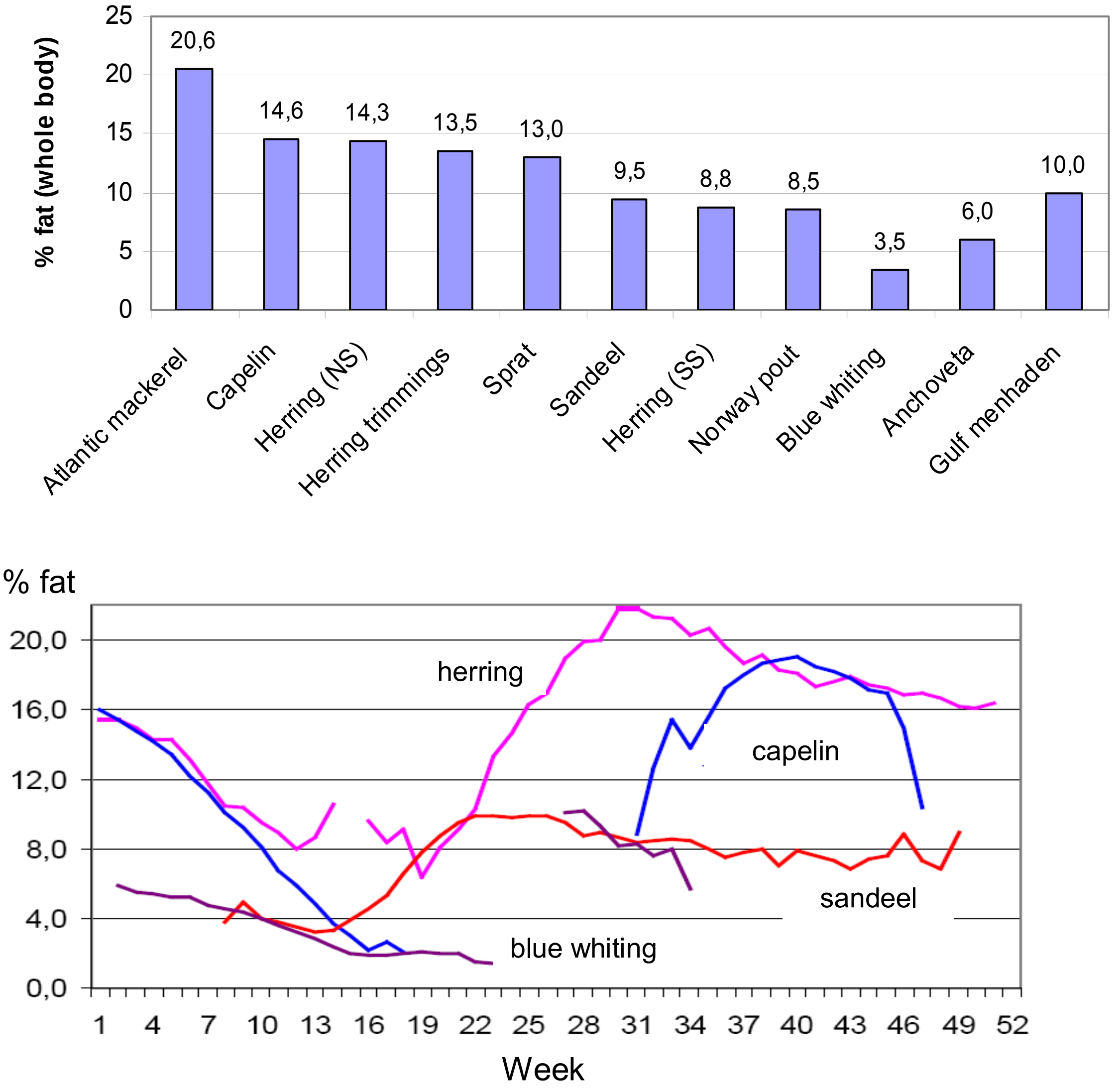


Figure 13 a) Variation in mean fat content (upper panel), and b) Seasonal variation in fat content in some species in some of the species used in fish meal and oil for production of Atlantic salmon in Norway in 2010 (lower panel). (Data taken from Fiskeriforskning-SSF, 2004)

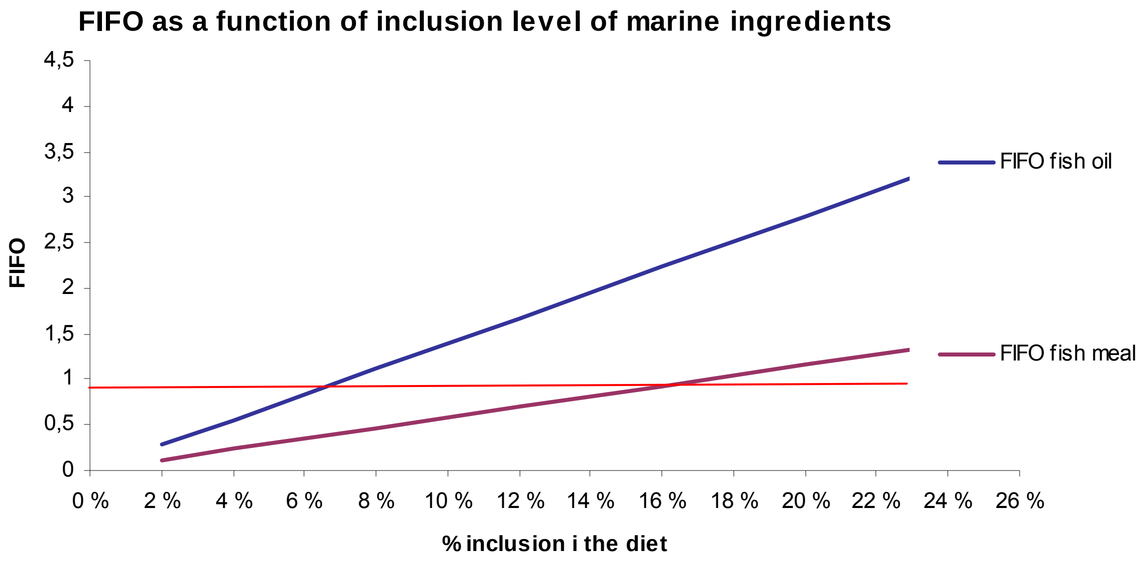


Figure 14 FIFO ratio as a function of the inclusion level of fish meal and oil in the diet (in % of the total diet). The fish meal and oil yield from forage fish is 22.5 and 9.3 % respectively.

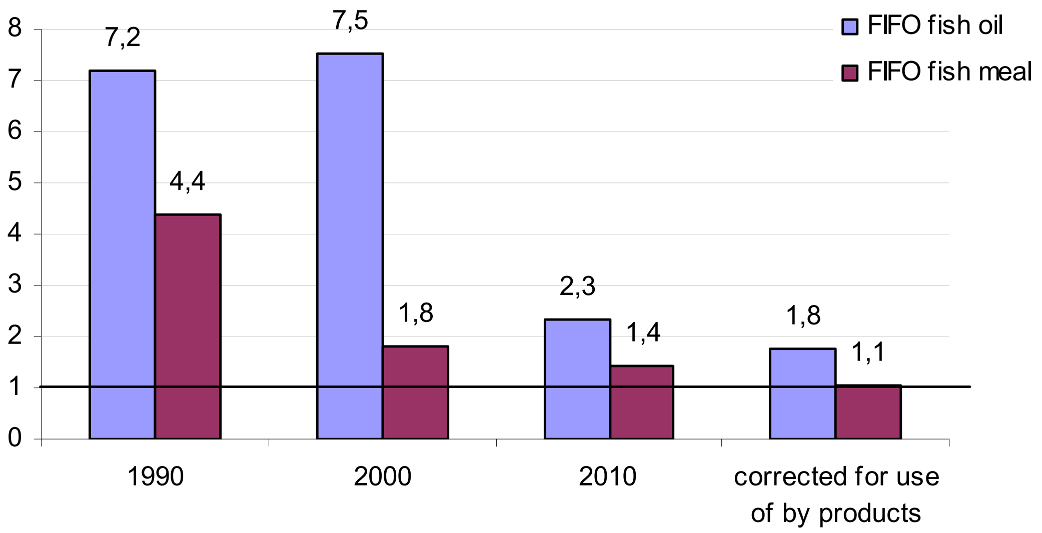


Figure 15 FIFO ratio for fish meal and oil in Norwegian salmon farming the last 20 years. Since 1990, the FIFO ratio is reduced by 68 % both for fish oil and meal (the reduction is 75% if the use of trimmings and by-products is subtracted).

The FIFO ratio is often used, both in scientific publications (Tacon and Metian, 2008, Naylor et al., 2009) and in the public debate because it seems easy to relate to. However, published FIFO values for salmon production during the last decade range from less than 2 to 8.5 (Tacon and Metian, 2008, Jackson, 2009, Naylor et al., 2009, Bendiksen et al., 2011) and this large variation in reported values makes the FIFO ratio unreliable as a measure of the amount of forage fish used in the production of fish meal and oil. The variation in reported FIFO values is a result of authors using different inclusion levels of marine ingredients, different feed conversion ratios and different conversion efficiencies of industrial fish into fish oil and meal. There are also currently several ways of calculating the FIFO ratio. Kaushik and Troell (2010) calculate a FIFO based on either fish meal or oil in accordance with what is done in the present report. Tacon and Metian (2008) also calculate a separate FIFO for fish oil in a similar way, but subtract the possible fish oil yield from the fish meal transformation. However, Naylor et al. (2009) calculate one reduction fish equivalent for meal ($\mathrm{RFE}_{(\mathrm{FM})}$) and one for additional fish oil used ($\mathrm{RFE}_{(\mathrm{AO})}$) and sum up these values to give a combined FIFO required to produce a kg of farmed fish. The oil in the fish meal (8%) and the oil that can be extracted from the reduction fish equivalent for fish meal (5%) are subtracted from the additional oil.

$$\mathrm{RFE}_{(\mathrm{FM})} = \mathrm{FCR} \cdot \left[\frac{\text{Diet FM (g/kg)}}{\text{FM reduction efficiency (g/kg)}} \right]$$

(from Naylor et al., 2009, Equation 3)

The additional oil is calculated as:

$$\mathrm{RFE}_{(\mathrm{AO})} = \left[\mathrm{FCR} \cdot \frac{(\text{Diet FO (g/kg)} - (0.08 \cdot \text{Diet FM (g/kg)})}{0.08} \right] - \left[0.08 \cdot \mathrm{RFE}_{(\mathrm{FM})} \right]$$

(from Naylor et al., 2009, Equation 4)

Using this way of calculating the FIFO for the 2010 salmon production in Norway

$\mathrm{RFE}_{(\mathrm{FM})}$ = 1.3 * (0.248/0.225) = 1.43

$\mathrm{RFE}_{(\mathrm{AO})}$ = [1.3* (0.166-0.08*0.248)/0.08] - (0.08 * 1.39) = 2.38

FIFO = 1.43 + 2.33 = <u>3.81</u>

However, this way of calculating FIFO does not take into consideration that the 2.19 kg of forage fish used to produce the 166 g of fish oil in the diet will also yield 490 g of fish meal which is almost twice as much as is used in the diet. Thus, there is no need to add a separate reduction equivalent for fish meal in the equation, because the need for fish meal in the diet is already covered. This way of calculating FIFO is in fact double counting of the amount of marine resources that are used in the production of salmon feed.

Neither Tacon and Metian (2008) or Naylor et al. (2009) subtract the amount of fish meal and oil made from trimmings and by products from the total budget. In a recent study by

Bendiksen et al. (2011) half of the 109-180 g fish oil in the diet was replaced with fish oil made from trimmings and by products reducing the FIFO ratios by 50% from around 3.4 to 1.7. The increasing use of trimmings and by products from aquaculture productions in feeds for aquaculture makes the use of FIFO ratios less reliable as a measure of the amount of marine resources that is consumed by the aquaculture industry.

Jackson (2009) proposed another approach to address this issue in a more global perspective for several aquaculture productions with different demand for fish oil and fish meal. Thus, a FIFO ratio is calculated for a combination of several aquaculture productions with different dependencies on fish meal and oil. The argument for this is that the surplus of fish meal from the production of salmon feed is used in the aquaculture production of other species such as shrimp or carp that have a higher requirement for fish meal than fish oil in the diet. In theory, this way of calculating a FIFO ratio for an aquaculture production will reflect what is actually consumed of marine ingredients.

$$\text{FIFO ratio} = \text{FCR} \cdot \left[\frac{\text{Diet FM} + \text{Diet FO}}{\text{FM reduction efficiency} + \text{FO reduction efficiency}} \right]$$

(from Jackson 2009, Equation 5)

Using Equation 5, the FIFO ratio for the 2010 salmon production in Norway becomes

FIFO ratio = 1.3* [(24.8% + 16.6%)/(22.5% + 9.3%)] = <u>1.70</u>

When this calculation method is used on the total global aquaculture production, the estimated volume of wild fish consumed as fish meal and oil is in agreement with what is estimated by FAO (20.2 million tons of wild fish in 2006). Thus, this method gives a more realistic estimate of the amount of wild fish that is used in an aquaculture production than the calculation used by Naylor et al. (2009).

Irrespective of what calculation method is used to estimate FIFO, the FIFO ratio is not an indicator of sustainable use of marine resources, because sustainability must be based on a responsible harvest of fish species that are used for fish oil and fish meal according to international fishery regulations.

Furthermore, a weight-to-weight ratio does not take into account the difference in nutrient and energy content of the forage fish and the salmon product, and it is not a measure of how effective the marine resources are utilised. The FIFO ratio does not consider the edible yield of the forage fish and of the salmon product. Herring meal is used for fishmeal production when the landings exceed the capacity for processing the herring for human consumption. For skin and boneless fillet, the fillet yield of herring is 35% whereas the fillet yield of salmon is around 60%. When the FIFO for salmon is corrected for edible yield, a FIFO 2:1 for the fish oil, becomes 1.16:1 and a FIFO of 1:1 for fishmeal becomes 0.58:1. Thus, edible FIFO for salmon is 1.16 and 0.58 for fish oil and fish meal respectively when the edible yield of the forage fish is 35%.

2.1.2 Forage fish dependency ratio calculation

The Salmon Aquaculture Dialogue (SAD) has included the Forage Fish Dependency Ratios for fish meal and oil as one of its indicators of performance. These ratios calculate the quantity of forage fish required to produce the amount of fishmeal and oil used to produce a unit of farmed salmon. Fishmeal and fish oil that originate from trimmings are excluded from the calculation as long as they do not originate from species that are endangered or vulnerable in the IUCN Red List of Threatened species. The amount of fish meal in the diet is calculated back to live fish weight by using a yield of 24% (Péron et al., 2010). The amount of fish oil in the diet is calculated back to forage fish live weight by using a 5% yield of fish oil for fish originating from Peru, Chile and the Gulf of Mexico and a 7% oil yield for fish originating from the North Atlantic.

$$FFDR_{FM} = \frac{\text{(\% Fishmeal in feed from forage fisheries)* eFCR}}{24.0}$$

(Equation 6)

$$FFDR_{FO} = \frac{\text{(\% Fishoil in feed from forage fisheries)* eFCR}}{5.0}$$

(Equation 7)

The SAD standards for $FFDR_{FM}$ and $FFDR_{FO}$ are <1.35 and <2.95 respectively.

For the Norwegian salmon production in 2010 (12.5% of the fish oil and 19.6% of the fish meal came from wild forage fish and 60 % of the oil came from the North Atlantic) the ratios are well below the defined standards:

$$FFDR_{FM} = (19.6 * 1.3) / 24 = \underline{1.06}$$

$$FFDR_{FO} = (12.5 * 1.3) / 6.3 = \underline{2.59}$$

2.1.3 Marine nutrient dependency ratios (MNDR)

It has been suggested that the amount of marine resources consumed can be expressed more accurately by calculating nutrient-to-nutrient ratios. Crampton et al. (2010) suggested to use a “Marine nutrient dependency ratio” (MNDR) as an alternative to the FIFO ratio. The Marine nutrient dependency ratio (MNDR) is the ratio of each marine-derived nutrient used to feed salmon divided by the amount of each marine nutrient produced as a result of salmon farming (Crampton et al., 2010). Thus, it estimates the amount of marine protein and oil produced in salmon farming relative to how much is consumed. Dietary protein sources and oils or lipids from all capture fish, shellfish or zooplankton are classified as marine sources. The lipids contained in fishmeal and other marine sources are counted as part of the dietary marine oils. Marine Protein Dependency Ratio (MPDR) and Marine Oil Dependency Ratios (MODR) are calculated as:

$$\text{MPDR} = \frac{(\text{\% MP in feed}) \cdot (\text{\% protein in MP}) \cdot (\text{kg feed eaten})}{(\text{BW(f)} \cdot \text{\% body protein}) - (\text{BW(i)} \cdot \text{\% body protein})}$$

(Equation 8)

$$\text{MODR} = \frac{[\%\,\text{FO in feed} + (\%\,\text{FM in feed} \cdot \%\,\text{fat in FM})] \cdot (\text{kg feed eaten})}{(\text{BW(f)} \cdot \%\,\text{body fat}) - (\text{BW(i)} \cdot \%\,\text{body fat})}$$

(Equation 9)

where MP is the marine protein sources (e.g. fishmeal) in the feed and FO is the fish oil, BW(f) is the slaughter weight of salmon and BW(i) is the initial bodyweight.

The mean protein and fat concentration in the fish meal is 70% and 10% respectively, and the inclusion level of fish meal and fish oil is 24.8 and 16.6. Whole body lipid and protein concentration was 22.4 and 17% (see part 2, resource budget) and the initial protein and lipid concentration was assumed to be 18 and 10% respectively The eFCR was 1.3 in 2010.

The MPDR and MODR for the salmon production in Norway in 2010 are shown in Figure 16. Values corrected for inclusion of fish meal and oil from trimmings and by-products are also shown.

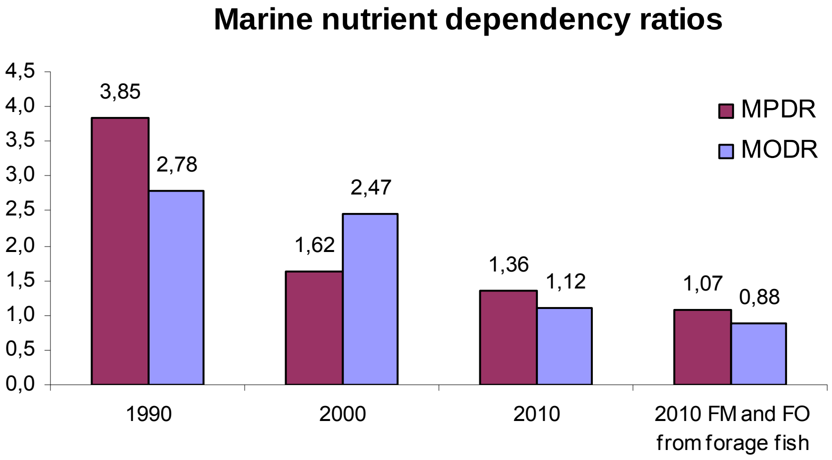


Figure 16 Marine nutrient dependency ratios for marine protein and oil for the Norwegian salmon production in 1990, 2000 and 2010. The bars representing 2010 FM and FO from forage fish is corrected for inclusion of fish meal and fish oil from trimmings and by-products.

3 Part 3

3.1 Resource budget for Norwegian salmon production in 2010

3.1.1 Ingredients used in 2010

In 2010, the three major feed companies in Norway, BioMar, Ewos and Skretting, used around 1 300 000 tons of ingredients to produce aquaculture feed in Norway. 545 000 tons (41.4 %) were of marine origin and 741 000 (56.4 %) were crop derived. Micro ingredients accounted for 2.2% of the total ingredients (Figure 17).

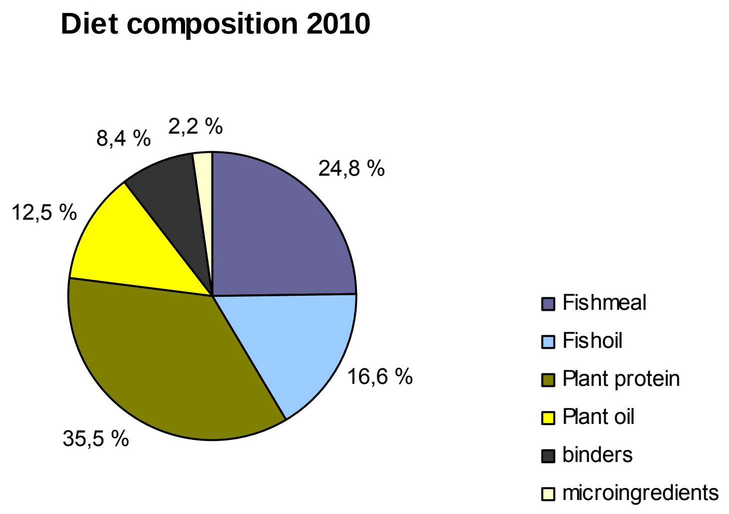


Figure 17 Composition of salmon feed in Norway in 2010. Values are % of the total amount of ingredients used.

The content of fish meal and fish oil was 24.8 and 16.6% respectively, and 21% of the fish meal and 24.4 % of the fish oil used in 2010 came from fish silage and trimmings. Thus, fish meal and oil from reduction fisheries made up 19.6 and 12.5% of the salmon diet in 2010, respectively. 52% of the fish oil and the 47% of the fish meal was of North Atlantic origin (Figure 18). In total, the Norwegian salmon feed industry consumed 218 670 tons of fish oil and 325 460 tons of fish meal in 2010 which is 22 and 6% of the global production of fish oil and meal respectively.

Table 6 Plant ingredients used in Norwegian salmon feed production in 2010. The data are the sum of ingredients used by Biomar, EWOS and Skretting

Plant ingredients in Norwegian salmon feed 2010		**tonnes**	**% of total diet**
Protein sources	Soy protein concentrate	257 580	19.6
	Wheat gluten	84 387	6.4
	Sunflowermeal	64 588	4.9
	Peaprotein concentrate	26 203	2.0
	Fababeans	33 198	2.5
Sum plant protein sources		*465 955*	*35.5*
Oil sources	Rapeseed oil	162 346	12.4
	Other plant oils	2 367	0.2
Sum plant oil		*164 713*	*12.6*
Binders	Wheat	110 625	8.4
Sum plant ingredients		**741 294**	**56.4**

Table 7 Marine species used for production of fish meal and oil used in Norwegian salmon feed production in 2010

Species	**Fish meal (tonnes)**	**Fish oil (tonnes)**	**Sum**	**% of marine ingredients**
Anchoveta	81 832	24 655	106 487	19.6
Blue whiting	22 007	2 223	24 230	4.5
Sprat (brisling)	21 492	45 731	67 223	12.4
Norway pout	14 753	4 508	19 261	3.5
Atlantic herring - Norwegian spring-spawning	10 828	8 581	19 408	3.6
Atlantic herring - North Sea	11 243	12 699	23 942	4.4
Atlantic herring - Icelandic summer-spawning	7 166	7 479	14 645	2.7
Capelin	20 777	2 466	23 243	4.3
Sandeel	41 882	24 913	66 795	12.3
Atlantic mackerel	3 420	4 129	7 549	1.4
Chilean jack mackerel	4 805	0	4 805	0.9
Boar fish	11 886	0	11 886	2.2
Gulf menhaden	0	20 922	20 922	3.8
other/unknown species	5 077	6 970	12 047	2.2
Sum forage fisheries	*257 167*	*165 277*	*422 445*	*77.6*
Trimmings/silage	*68 292*	*53 396*	*121 687*	*22.4*
Sum marine ingredients	**325 459**	**218 673**	**544 132**	**100.0**

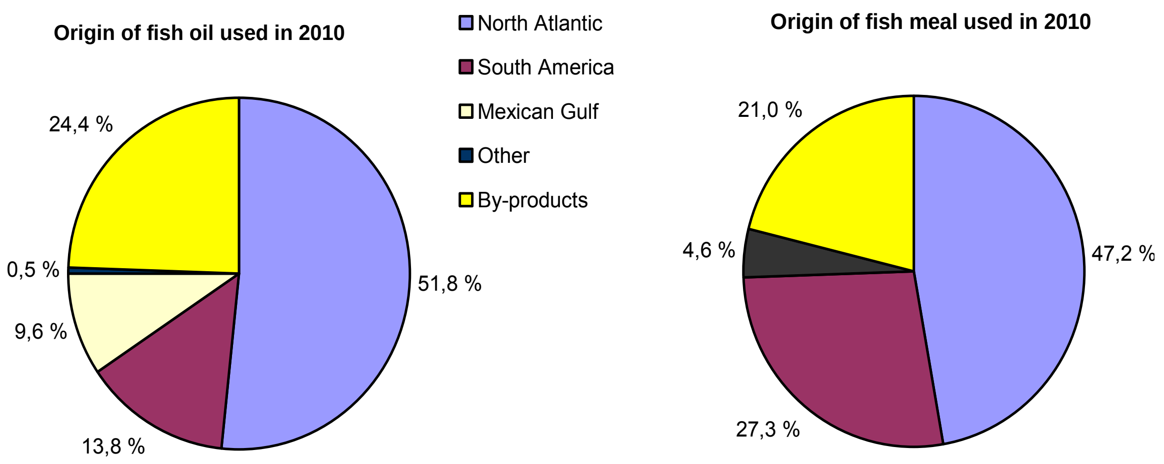


Figure 18 Geographic origin of fish meal and oil used in the production of salmon feed in Norway in 2010. Values are given as % of total amount of fish meal and oil respectively.

3.1.2 Nutrient flow in Norwegian salmon farming in 2010

Nutrient-to-nutrient ratios are a measure often used to evaluate the efficiency of food production systems. Such conversion efficiency ratios are a measure of what proportion of the dietary nutrients and energy is retained in the animal product. These calculations are commonly given for a specific study or a single production. For evaluation of the sustainability of an entire food production industry however, all relevant data must be available, which is a challenge. Norwegian aquaculture has a thorough system for reporting production data which is open to the public (www.fiskeridir, www.ssb.no, akvafakta.no). These data, and data provided by the three largest feed companies in Norway, have been used to calculate the nutrient flow in Norwegian salmon production in 2010.

An estimate of nutrients used in Norwegian salmon production in 2010 and the average composition of Norwegian aquaculture feed in 2010 are given in Table 8. The average composition of Norwegian feed is calculated based on data provided by the three largest Norwegian feed companies (BioMar, Ewos and Skretting) and reflects their use of feed ingredients for aquaculture feed in 2010, as well as chemical composition of each feed ingredient. Of the 1 346 500 tons of feed used in 2010 in Norwegian aquaculture, 1 236 000 tons, or 91.8%, was fed to Atlantic salmon (Akvafakta, 2011). When including the 66 000 tons feed used for rainbow trout (salmon and trout feeds are very similar in nutrient composition) the share fed to salmonids constitutes 96.7% of the feed used (Akvafakta, 2011). Also, the three feed companies that have provided the feed ingredient data have a market share of approximately 90% (Nordic Innovation). Thus, the estimated average composition of the total lot of aquaculture feed is considered to be representative for the average composition of Norwegian salmon feed in 2010.

Based on this, the total use of nutrients used for salmon production in Norway in 2010 (Table 8) can be estimated by multiplying the average feed composition with the total of 1 236 000 tons of salmon feed registered (Akvafakta, 2011). All batches of ingredients are not analysed, and therefore, the same chemical composition of similar ingredients is assumed. Also, not all microingredients, such as crystalline amino acids, pigment, vitamin and mineral mixes, are included. The average dry matter content of feed ingredients was 93.4%, and the same dry matter content was assumed for the feeds since there is no available data on this and dry matter content of feeds are normally close to this value. In addition, the feed ingredient data was only collected from the tree largest feed companies, and ingredients used for all aquaculture feeds were included, as described above. Thus, it is likely that there is a minor inaccuracy in the figures of the total amount of nutrients used and all calculations based on these. However, the data includes all losses, discarded feed batches, failed productions etc, and thus represents the total use of nutrients in Norwegian salmon farming industry in 2010. To our knowledge, such detailed and complete dataset for any other feed production in any country is not available. In order to increase the sustainability of food production however, similar data should be provided by other food production industries in Norway and other countries.

Table 8 Estimated average feed composition, total amount of nutrients used, and amount of nutrients from marine and plant origin in Norwegian salmon feed in 2010

	Average composition of Norwegian salmon feed in 2010 (% or MJ/kg) [1]	**Total amount of nutrients used in Norwegian salmon feed 2010 (Tons or GJ)** [2]	**Nutrients from marine ingredients (Tons or GJ)** [3]	**Nutrients from plant ingredients (Tons or GJ)** [4]
Energy	25.0	30 924 268	17 968 256	12 956 012
Protein (Nx6.25)	37.3	460 853	213 223	247 630
Lipid	33.0	408 382	313 342	95 039
EPA	2.2	27 155	27 155	0
DHA	1.8	22 218	22 218	0
Phosphorus	1.0	12 046	6 627	3 069

[1] Calculated from all ingredients used in 2010 and their chemical composition, reported by the three largest Norwegian feed companies (BioMar, Ewos and Skretting)

[2] Calculated from average composition and the total of 1 236 000 tons of feeds used in 2010 (Akvafakta, 2011). Average dry matter content in feed ingredients was 93.4%, and the same average dry matter content was assumed for feed.

[3] Fraction of nutrient of marine origin in the feed ingredients multiplied by the total amount of nutrient used in feed in 2010

[4] Fraction of nutrient of plant origin in the feed ingredients multiplied by the total amount of nutrient used in feed in 2010

In 2010, 927 876 tons of salmon were slaughtered in Norway (Statistics Norway, 2011). The additionally produced salmon that year is calculated as the difference in biomass from 31th December 2010 to 31th December 2009, and was 13 811 tons (620 531 – 606 720 tons, Directorate of Fisheries, 2011). The estimated total production of salmon in Norway was thus 941 687 tons in 2010. The 1 236 000 tons of feed (Akvafakta, 2011) registered for production of this salmon equals an estimated feed conversion factor of 1.31.

The composition of whole body and fillet of Atlantic salmon, and the total amount of nutrients in whole body, edible part and trimmings of farmed salmon produced in Norway in 2010 is shown in Table 9. These data are based on a total production volume of 941 687 tons of salmon of which 65% is utilized for human consumption (Matvaretabellen, 2006). The fillet yield will vary depending on several factors, and here the figure for edible part from Matvaretabellen is used. This represents a high fillet yield, and thus, the “true” amount of nutrients in fillet is somewhat lower than the calculated figures, and correspondingly, the amount of nutrients in trimmings higher. A corresponding error will be present in all calculations based on these figures.

Table 9 Composition of whole body and edible part of Atlantic salmon, and total amount of nutrients in whole body, edible part and trimmings of Atlantic salmon produced in Norway in 2010. Calculations of the three latter are based on a total amount of 941 687 tons of salmon produced in Norway in 2010 of which 65% is edible product (Matvaretabellen, 2006) resulting in 612 097 tons of edible salmon produced

	Whole body composition of Altantic salmon (% or MJ/kg)	**Composition of salmon fillet (% or MJ/kg)**	**Total nutrients in whole body of salmon produced in Norway in 2010 (tons or GJ)**	**Total nutrients in edible part of salmon produced in Norway in 2010 (tons or GJ)**	**Amount of nutrients in non-edible part (trimmings) of salmon produced in Norway in 2010 (tons or GJ)**
Dry matter	41.7[1]	33.0[3]	392 684[6]	201 992[7]	190 692[8]
Energy	12.3[1]	10.9[4]	11 582 752[6]	6 646 390[7]	4 936 362[8]
Protein (Nx6.25)	16.9[1]	19.9[3]	158 910[6]	121 807[7]	37 102[8]
Lipid	22.4[1]	15.6[5]	210 938[6]	95 487[7]	115 451[8]
EPA+DHA	3.0[2]	2.109[5]	28 517[6]	12 909[7]	15 608[8]
Phosphorus	0.35[1]	0.245[3]	3 263[6]	1 500[7]	1 763[8]

[1] Mean values of salmon (5.1 kg) fed 3 different commercial diets. Data from Marine Harvest, not published.

[2] Not analysed, calculated from total lipid concentration, assuming the portion of DHA+EPA to be the same as in fillet

[3] Matvaretabellen, 2006 (”Laks oppdrett, rå” – in Norwegian. Translated: ”Farmed salmon, uncooked”)

[4] Calculated from energy content in fat (39.5 kJ/g) and protein (23.6 kJ/g)

[5] NIFES Sjømatdata, 2010 (”Atlantisk laks – oppdrett (*Salmo salar*)” – in Norwegian. Translated: ”Atlantic salmon – farmed (*Salmo salar*)”).

[6] Data for whole body composition multiplied by total salmon production in 2010 (941 687 tons)

[7] Data for fillet composition multiplied by total salmon fillet production in 2010 (941 687 tons salmon x 65% edible part /100 = 612 097 tons fillet)

[8] Nutrients in total salmon produced minus nutrients in edible part produced in 2010.

The amount (%) of nutrients and energy from the feed used that is retained in the animal (whole body or edible part) product can be calculated as

$$\text{Nutrient retention}(\%) = 100 \cdot \frac{\text{Amount of nutrient or energy incorporated in animal}}{\text{Amount of nutrient used in feed}}$$

(Equation 10)

The retention data for Norwegian production of Atlantic salmon in 2010 is shown in Table 10. The calculation is based on figures from Table 8 and 9. The sources of inaccuracy described for the total amount of nutrients used and fillet yield (above) also apply for the retention data. Furthermore, the retention data are based on feed consumption during one year and salmon production during one year. Thus, the calculation of retention assumes a constant use of feed and production of salmon over a few years, since the production cycle of salmon is more than one year.

The retention data includes, in addition to all loss of feed and feed ingredients, all loss of fish (mortality and escapees) and poor and failed productions of both feed and salmon. Thus, the data show the retention of the total amount of nutrients in Norwegian salmon production in 2010. Consequently, these retention data can not be compared to data from controlled, single productions of salmon or other species which is often reported in the literature.

It should be noted that the given retention values for lipids, EPA and DHA includes the salmon's production of these from non-lipid precursors. Since fatty acids can be produced from carbohydrates and amino acids, 'retention' of lipids, EPA and DHA with the given calculation is not a strictly correct term. For simplicity however, the term is still used here since it shows the net flow of these nutrients from feed to salmon fillet. The retention of protein and lipid is sometimes referred to as protein productive value (PPV) and lipid productive value (LPV).

Table 10 Retention (%) of nutrients and energy in whole body, edible part (fillet) and trimmings of Atlantic salmon, and not retained (lost) nutrients

	Retention in whole body of salmon	**Retention in edible part of salmon**	**Retention in trimmings [1]**	**Not retained – loss [2]**
Energy	37	21	16	63
Protein (Nx6.25)	34	26	8	66
Lipid [3]	52	23	28	48
EPA+DHA [3]	58	26	32	42
Phosphorus	27	12	15	73

[1] Retention in whole body (%) – retention in edible part (%)
[2] 100 (%) – retention in whole body (%)
[3] Includes lipids produced from non-lipid precursors

Carbohydrates are not included in the overview of the nutrient flow, partly due to lack of data from analyses. Most of the carbohydrates from feed will either end up as part of the lipid fraction or as energy not retained. It should be noted however, that the increased use of protein ingredients of vegetable origin, which contain indigestible carbohydrates, results in decreased energy retention compared to the previously used fish meal based feeds.

3.1.2.1 Retention of protein and energy

As the data in Table 10 show, 21% of the energy and 26% of the protein (nitrogen) used in Norwegian salmon farming in 2010 was incorporated into the edible part of salmon to be used for human consumption. As explained above, it is difficult to find comparable data for other animal productions. Austreng (1994), Åsgård and Austreng (1995), Åsgård et al., (1999) and Bjørkli (2002) have compared the retention of protein and energy in Atlantic salmon, chicken and pig. The data from Bjørkli (Table 9) deviates from the data shown above due to a different method of calculation. However, Bjørkli's calculations are the same for all species, and can be used to compare the different animal productions to each other. According to Bjørkli (2002), protein and energy is most efficiently retained in salmon, whereas chicken retain more protein but less energy than pig.

Table 11 Comparison of the retention of energy and protein in Atlantic salmon, chicken and pig by Bjørkli (2002).

	Retention in salmon fillet	**Retention in chicken, edible part, skin included**	**Retention in chicken, edible part, no skin**	**Retention in pig, edible part**
Energy	23.0	12.1	10.2	14.1
Protein (Nx6.25)	31.4	21.2	20.7	17.9

Although the concept 'retention' is often referred to in the calculations above, it is also used as a collective term for any calculation of efficiency of energy or nutrient utilisation from feed into food product. Another commonly used way to describe protein utilization, is the protein efficiency ratio (PER), which is a measure of weight increase per amount of protein fed:

$$\mathrm{PER} = \frac{\text{Body weight or biomass produced (kg or tons)}}{\text{Protein fed (kg or tons)}}$$

(Equation 11)

Producing 941 687 tons of salmon from 460 853 tons of protein (Nx6.25) result in a PER value of 2,04 in Norwegian farmed salmon in 2010. Using the same calculation for the 612 097 tons of edible part of salmon produced, the PER value for the edible part of salmon in 2010 was 1.33.

The similar calculation for energy efficiency ratio (EER) gives an EER in whole salmon of 3.05, and 1.98 in the edible part of salmon.

The corresponding estimate can be given for lipid efficiency ratio (LER). For whole salmon and salmon fillet the LER values are 2.31 and 1.50, respectively. Although the calculation uses the amount of nutrient (protein or lipid) in feed, the increase in body weight is used for measurement of utilisation. As for FIFO, the PER (and EER and LER) does not distinguish between differences in body composition between species. Besides, protein and lipid retention and PER and LER are expressions of total protein and lipid retention, and do not separate between origin of the feed ingredients such as marine or vegetable ingredients, or offal. These calculations of PER and LER can, as the retention data, not be compared to PER and LER data obtained for single productions or in studies.

Whereas the health benefits of consumption of Atlantic salmon are often ascribed to its high content of long-chain polyunsaturated fat, the protein in fish is also beneficial for human health (Wergedahl *et al.*, 2004, Bergeron and Jacques, 1989, It-Yahia *et al.*, 2003, Liaset *et* *al.*, 2009). A general increase in fish consumption is recommended in Norway, although no specific recommendations on weekly intake are given (Anonymous, 2010). Recommended daily protein intake in Norway is 15% (10-20%) of the energy intake (Anonymous, 2010). Assuming a person's daily energy intake is 10,000 kJ, and the energy content in protein is 23.7 kJ/g, the recommended daily protein intake is 63 g per day. Given a protein content in salmon of 19.9% and in 18.6% in chicken (whole chicken with skin included; Matvaretabellen, 2006), 63 g protein corresponds to 317 g salmon fillet or 339 g of chicken. Edible parts of both salmon and chicken with skin is 65% (Matvaretabellen, 2006) resulting in 487 g salmon or 521 g chicken produced to yield 63 g protein.

Globally, sufficient protein production for the world's growing population is a challenge, and protein intake is suboptimal in certain parts of the world (Muller and Krawinkel, 2005). Therefore, the protein retention in aquaculture and other food production is an important factor when assessing sustainability. During a nine month period, Torstensen et al. (2008) found similar protein retention and PER in Atlantic salmon fed a pure marine feed and feeds with up to 80% of the fish meal and 70% of the fish oil replaced by vegetable ingredients (and some krill meal). The protein retention given for salmon fed the marine-based feed was 0.5, and the PER given for three separate periods was 2.80, 3.03 and 2.81 (Torstensen *et al.*, 2008). In accordance, Bendiksen et al. (2011) found no significant difference in PER in Atlantic salmon fed diets containing from 10% to 20% fish meal, and 50% of the oil from vegetable origin. In that study, the PER for the salmon fed the highest fish meal inclusion was 2.73. Both these studies show that Atlantic salmon can be produced with feeds containing high inclusion of ingredients of vegetable origin, and only low amounts of marine ingredients. However, the sustainability of exchanging marine ingredients (fish meal and fish oil) with plant ingredients should be assessed thoroughly, since production of plant ingredients requires water, fertilizers, phosphorus, pesticides, land area and transportation and contributes to depletion of the soil. Most plant ingredients can also be used for human consumption, and the benefit of substituting marine ingredients produced from well managed fisheries is not obvious. This is further addressed in Part 4.

3.1.2.2 Retention of EPA and DHA

EPA and DHA are nutritionally important for human consumption, and salmon is an important dietary source of these fatty acids in Norway. From a consumer perspective, high concentration of EPA and DHA in salmon, and thus in feed, is desired. Marine ingredients were the sources of EPA and DHA in Norwegian salmon feed in 2010, and since fish meal and fish oil are limited resources, both retention of EPA and DHA and the utilisation of these from offal are important aspects. As shown in Table 8, 27 155 and 22 218 tons of EPA and DHA, respectively, were used in Norwegian salmon feed in 2010. In whole salmon 58% of EPA+DHA was retained. In fillet, 26% was retained and 32% was retained in trimmings, whereas 42% of EPA+DHA from the feed were lost. These retention values include the salmon's production of EPA+DHA.

3.1.2.3 Retention of phosphorus

Phosphorus is a required nutrient for both plants and animals, and is therefore added in both agricultural fertilizers and animal feeds. The world's currently available phosphorus sources are limited and phosphorus is considered to be a limited resource for food production in near future (see Part 1). The ingredients used by the three feed companies BioMar, Ewos and Skretting for aquaculture feed production in 2010 contained 12 654 tons of phosphorus, of which 6 962 tons (55%), originated from marine ingredients, 3 224 tons (25%) originated from plant ingredients, and the remaining 2,468 tons (20%) was added as crystalline mineral compounds. The calculations in Table 6 which is based on total registered feed consumption show that for salmon feed, 12,046 tons of phosphorus was used in 2010. 27 % of the dietary phosphorus was retained in the salmon (Table 8), meaning that 73% of the feed's phosphorus was released to the sea. Thus, of the 12,046 tons of phosphorus in the feed, 73% loss amounts to 8,794 tons. This is more than what originate from the marine ingredients in all aquaculture feed used. Consequently, much of the phosphorus used for growing crops for feed ingredients is transferred to the sea, and therefore, increased use of plant ingredients in fish feed increases the drain of phosphorus from land to sea. Furthermore, some plant ingredients contain components such as phytic acid which decrease phosphorus absorption in the salmon's intestine, thus increasing the need for added phosphorus. From a phosphorus sustainability perspective, plant ingredients are therefore not beneficial unless phosphorus discharged from aquaculture is effectively captured and reused. Improving availability of phosphorus from the marine ingredients in particular and all sources in general, would improve the resource balance of phosphorus.

3.2 Alternative use of ingredients in salmon feed

In 2009, 63% of the total fishmeal production of around 6 million tonnes was used in aquaculture productions, whereas 8% (0.5 tonnes) was used in chicken production and 25 % (1.5 tonnes) was used in pork production. A small amount (4%) was used for other purposes. Of the total fish oil production in 2009, 81% was used for aquaculture productions, 13% for human consumtion and 6% for other purposes (Figure 19).

3.2.1 Marine oil sources for human consumption

The market for human consumption of omega 3 rich fish oil products has increased by 15-20% the last couple of years and this growth is expected to continue in the coming years (Rubin report 210, 2011). The global market for omega 3 products for human consumption is estimated to 49 000 tonnes with a value of 700 billion $ (Rubin report 144, 2007). Globally, fish oils were the basis for 75% of the products for human consumption whereas 19% were made from marine algae and the rest was made from linseed oil (Brownlie, 2005). In the European and US market, codliver oil made up 6% of the market, South American (18:12) fish oils 45% and concentrated EPA+DHA products 49% of the market (Frost & Sullivan 2004, 2005). Products for human consumption fall under three categories: 1) supplements (cod liver oil and other dietary supplements), 2) ingredients in food (functional foods), and 3) pharmaceutical products.

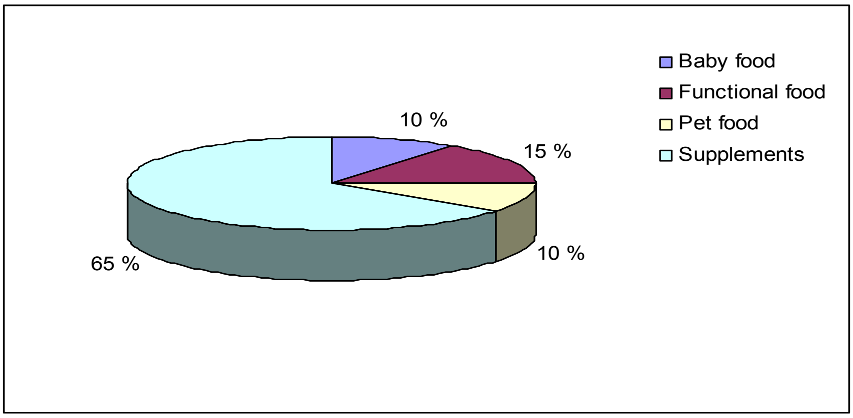


Figure 19 Distribution of fish oil consumption in the human sector, including pet food (data from Rubin report 144, 2007).

The market for functional foods is growing rapidly, (7-10 % per year compared to 2-3% per year for other food commodities) and was estimated to have a value of 34.2 billion $ in 2010 (Rubin report 144, 2007). Omega 3 is an important supplement to functional foods and the number of products supplemented with omega 3 is rapidly increasing and include a number of food products including dairy products, bread, juice and fish products (Figure 20).

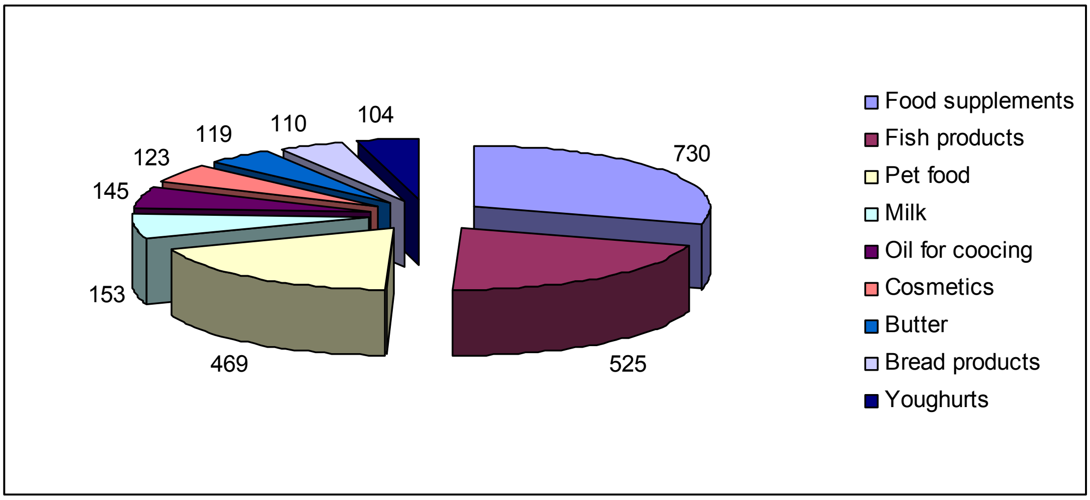


Figure 20 Number of products fortified with omega 3 in different product categories (data from Ebeltoft, 2006).

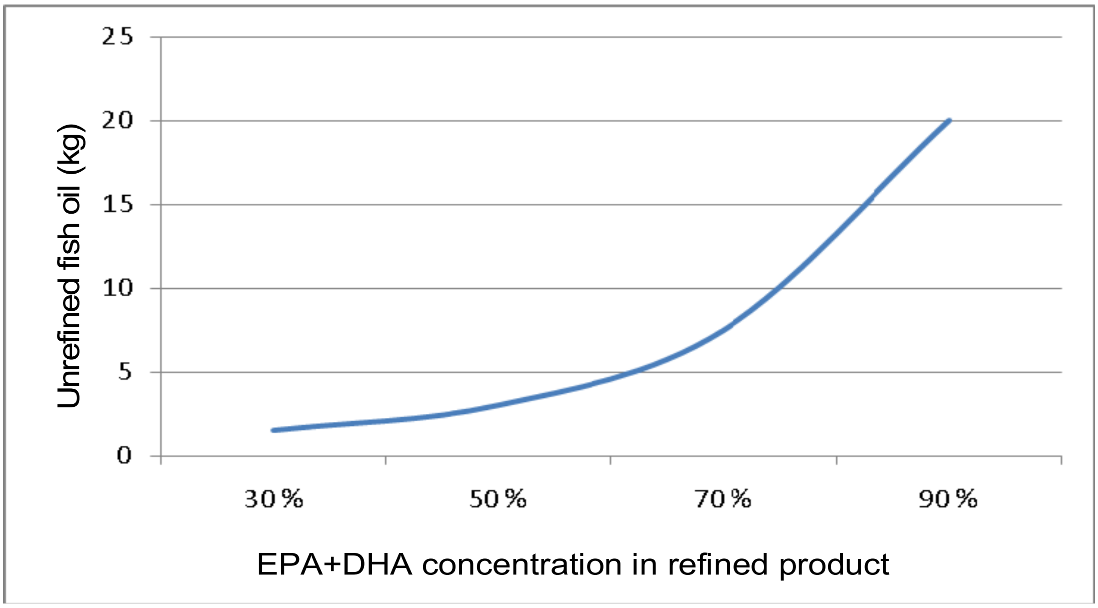


Figure 21 Estimated amount of unraffined fish oil needed to produce 1 kg of raffined fish oil with different EPA+DHA concentrations (data from Global organisation for EPA and DHA Omega 3, GOED, 2010).

The growing market for dietary supplements and food products fortified with EPA and DHA leads to an increasing production of refined fish oil with high concentration of EPA and DHA (>70% EPA and DHA). In 2001, 20 000 tonnes of refined oil was produced, and in 2009 the volume had increased to 90 000 tonnes. The volume is expected to increase to 200 000 tonnes in 2014. This process consumes large amounts of fish oil, to produce 1 kg of refined oil with 90% omega 3 fatty acid concentration requires 20 kg of raw fish oil (Figure 21). The excess oil from the refining process is not suitable for aquaculture production and is currently used as bio fuels or as fertilizer.

The relationship in figure 21 shows how much of the EPA and DHA that is available for human consumption after the refining and concentration process. Typically, a South American fish oil (containing 18% EPA and 12% DHA) is often used for manufacture of omega 3 food supplements. If this 18:12 fish oil is used as an example, we find that when 20 kg of fish oil with 30% EPA and DHA is concentrated to 1 kg of fish oil with 90% EPA and DHA it will contain 900 g of EPA and DHA (according to figure 21). Thus, 85% of the EPA and DHA originally present in the 20 kg of fish oil is lost in the process (Figure 22). If 20 kg of the same fish oil is used for producing salmon feed instead, 120 kg of salmon feed could be produced if 16 % of the diet was fish oil (2010 diet in Norway). With an economic feed conversion ratio of 1.3 in 2010, 93 kg of salmon could be produced from this feed, yielding 56 kg of salmon fillet. The retention of EPA and DHA in Norwegian salmon farming in 2010 was 58% in whole body and 26% in the fillet. This corresponds to 1560 g EPA and DHA in the fillet. If these figures are used to calculate losses of EPA and DHA we find that 3480 of the 6000 g of EPA and DHA in the fish oil is retained in the salmon. However, the 74% loss from feed to fillets is not lost for human or animal consumption because 100% of the by-products are recycled in other animal feeds (fur production, pet food,) and some is also used for making high quality oils for the human marked. In addition to higher recovery of EPA and

DHA, 56 kg of salmon fillets also contain more than 11 kg marine protein and 615 MJ of energy.

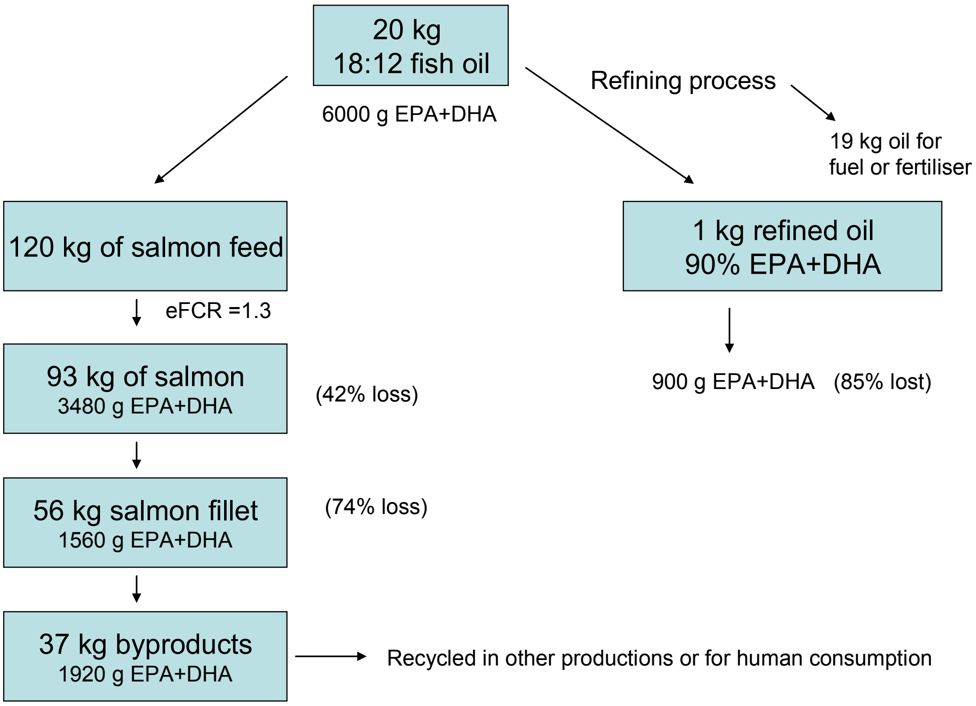


Figure 22 Calculation of EPA+DHA recovery when using a South American fish oil containing 30% EPA and DHA (18% EPA and 12%DHA) for production of salmon or when refining the oil to 90% EPA and DHA concentration. Data from the 2010 production of Norwegian salmon were used in the calculations for salmon (see text for details).

3.2.2 Alternative nutrient flows from capture fisheries

The potential available catch of marine fish is around 90 million tonnes per year. Capture fisheries are a valuable source of marine protein and the long chain omega 3 fatty acids in the human diet. In 2009, around 70 million tonnes of wild caught fish was consumed by humans corresponding to a per capita supply of 10 kg per year. There are however large regional differences in fish consumption patterns. In large parts of the world the consumption of fish is low and the intake of the omega 3 fatty acids EPA and DHA is far below the recommended daily intake for healthy adults of 0.25-0.5 g per day (recommendations from EFSA and ISSFAL respectively). If the entire world population today of 7 billion people should get sufficient EPA and DHA to cover their need based on these recommendations a total amount of between 0.6-1.3 million tonnes of EPA and DHA would be required. The potential yield of EPA and DHA from wild fisheries can be estimated to around 0.9 million tonnes per year if the entire fish is eaten (assuming a mean fat content of 6% and EPA and DHA comprise 15% of the total fat). However, the entire fish is rarely eaten; often less than

50% is destined for human consumption. Considering that the majority of the fat is in the proportion of the fish that is discarded, the amount potentially available for human consumption may be less than 0.4 million tonnes. The amount available from wild fish can not be expected to increase in the future because the majority of wild fish stocks are already fully exploited. Thus, the EPA/DHA shortage will become even larger as the world population increase towards 9 billion in 2050. It is therefore important to consider how the wild fish resources can be utilised most optimal for human consumption. For small pelagic fish species at lower trophic levels three alternative nutrient flows can be compared, 1) use for human consumption (provided there is a market willing to pay for the product), 2) as food source for species at higher trophic levels that is harvested for human consumption, 3) as a source for fish meal and oil that can be used in aquaculture productions such as Atlantic salmon. In natural ecosystems, there is generally a 90% loss in energy between each trophic level. It has been argued that feeding fish to fish in aquaculture productions is not an efficient use of the wild fish resources because to much protein, and energy is lost by adding another step in the food chain. However, because the aquaculture diets include a high proportion of plant ingredients and the farmed fish spend a lot less energy on foraging compared to fish in a natural environment, aquaculture may be an efficient way of producing marine protein for human consumption.

The Northeast Arctic cod (Gadhus morhua) is an important fishery resource, 865 000 tonnes were landed in total in 2009 (FAO fisheries statistics). It has been estimated that the standing biomass of cod the Barents Sea is approximately 2 million tonnes consuming a biomass of 6 million tonnes of fish per year (Ressursoversikt, 1997). The harvestable amount of cod was estimated to be 0.7 million tonnes per year. Capelin is an important prey for cod but it may also be used for production of fish meal and fish oil included in salmon diets. Traditionally, capelin has not been much used for human consumption. An estimate of the nutrient flow trough these alternative production systems for marine protein are shown in Figure 23. When the flow and retention of nutrients are calculated in these alternative production systems it is clear that harvesting low in the marine food web may potentially be very efficient for providing nutrients for human consumption. In this example it was assumed that 50% of the capelin biomass was utilised as edible product. The proportion that is consumed is however very species dependent, some small species such as sardines are consumed as whole fish, whereas other fish must be processed further before they can be consumed by humans. For the majority of species used for fish meal and oil production there is currently a limited marked for human consumption. It is also seen that harvesting fish higher in the marine food web, such as cod, is far less efficient in providing marine nutrients for human consumption compared to harvesting the capelin and producing capelin meal and oil used in salmon production. Using the capelin resource to produce salmon gave nearly 10 times more marine protein, 15 times more energy and 6 times more EPA and DHA for human consumption. (including the cod liver oil) compared to harvesting the cod resource. If the daily requirement of EPA and DHA is 0.5 g/day, producing salmon would cover the requirements of 154 million people for a year. The surplus fish meal may be used in other aquaculture or land based meat productions further increasing the output for human consumption.

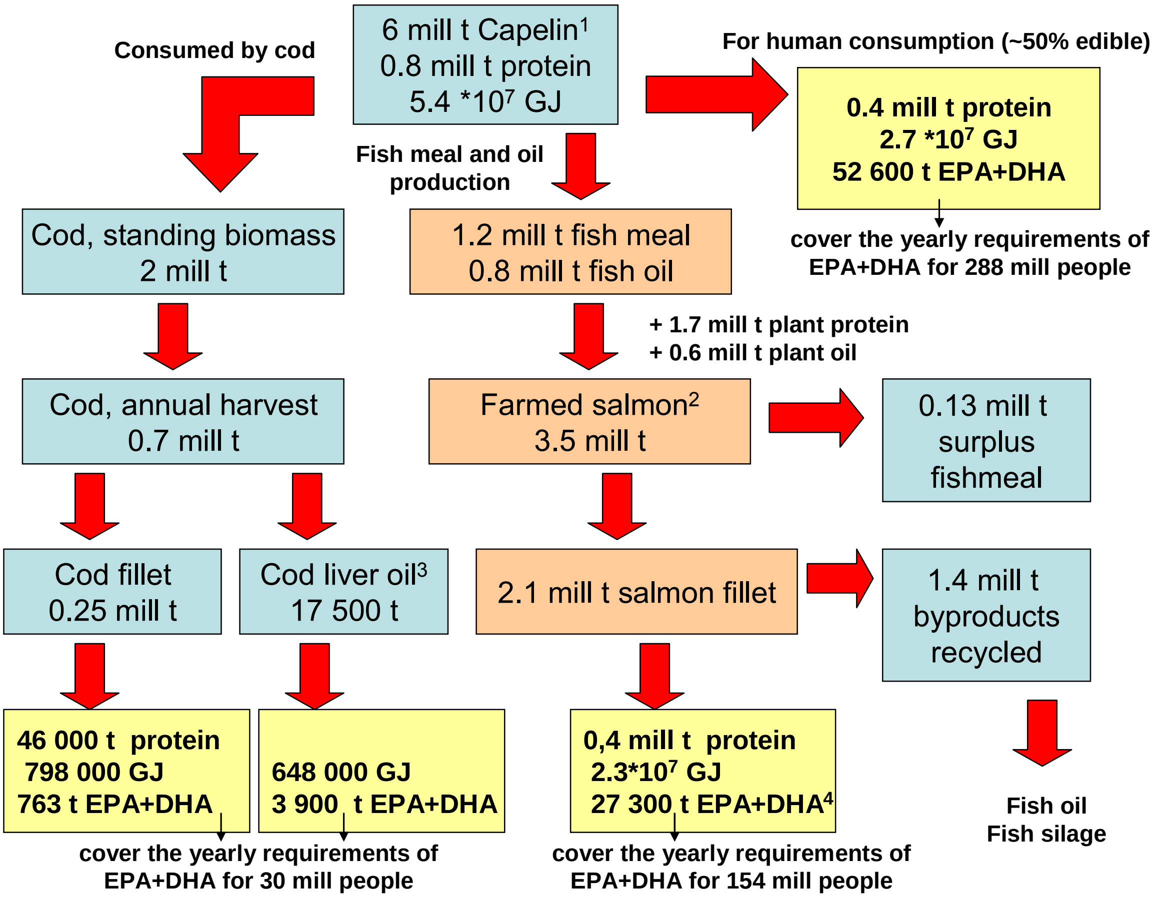


Figure 23 Theoretical nutrient flows for alternative ways of using the capture fish resources.

[1] The capelin contained 14.6% fat (15% EPA+DHAof total fat) and 13.5% protein,

[2] The composition of the salmon diet and FCR was identical to the 2010 production in Norway (16.6% fish oil, 24.8% fish meal, eFCR 1.3).

[3] The retention of EPA and DHA in the fillet was assumed to be 26% as for the 2010 production of salmon in Norway (EPA+DHA concentration of 4% in the 2010 diet). The retention may be higher in this case study where the calculated feed concentration of EPA and DHA was 2.5%

Daily requirements for EPA and DHA was as recommended by ISSFAL, 0.5 g/day.

[4] The liver yield was 5% of body weight and the yield of cod liver oil was 50% of liver weight (Rubin reports nr 144 and 202)

It is interesting to note that when 50% of the capelin is considered edible, the marine protein available for human consumption is the same if the capelin is consumed directly as when the capelin is converted to fish meal and oil used to produce salmon whereas the energy output is slightly higher. The EPA and DHA output is potentially larger when consuming capelin compared to producing salmon. However in this scenario it is assumed that EPA and DHA are evenly distributed in the capelin. It is likely that a major part of the EPA and DHA is found in the trimmings so that less than 50% of the EPA and DHA in the capelin are available for human consumption.

A further positive contribution to the nutrient flow in the production of salmon is that all the by-products are recycled and used in other animal productions or for human consumption. If the whole body retention of EPA and DHA is around 60% (2010 data for Norwegian salmon production) the amount of these fatty acids in the by-products would be around 35 000 tonnes. The majority of processing residue from cod fisheries is at present dumped at sea

(66%) while approximately 10% is used for fish meal and fish silage products (Rubin 2010. Thus, there is a large potential for increased use of this resource, either for fish meal and oil production in products for human consumption.

When LCA was used to compare the industrial energy input per kg fish produced in salmon farming and cod fisheries, Ellingsen and Aanondsen (2006) found very similar values for the two products (salmon, 66 MJ/kg, cod 67.5 MJ/kg) and the carbon footprints of salmon and cod fillets are also very similar (Winther et al., 2009). So whereas the farmed salmon and the captured cod is comparable when LCA methodology is applied to compare the environmental impacts of the products the nutritional output of marine protein and essential fatty acids for human consumption of these two alternative ways of using the capelin resource is quite different.

4 Part 4

4.1 LCA analysis of Norwegian salmon production 2010

LCA analysis was used to calculate the carbon footprint, and quantify resource use in terms of cumulative energy demand, occupation of cropland and marine primary production measured as sea area required for production of 1 kg of edible salmon product. Details regarding the methodology and system boundaries are given in appendix 1. The effect of diet composition on the parameters mentioned above was also studied by comparing 5 different diet formulations:

1. The 2010 diet in Norwegian salmon farming
2. A diet with 88% marine ingredients (High Marine Ingredient, HMI)
3. The 2010 formulation with marine ingredients only from the North-Atlantic (North Atlantic Marine Ingredients, NAMI)
4. A diet containing by-products from land animal productions (poultry) and fish oil from herring trimmings (2020 Land Animal Protein, LAP)
5. A diet with a high content (85%) of plant ingredients (2020 VEG)

The occupation of cropland and carbon footprint was also calculated for the Swedish production of pork and chicken in 2005. The total pork production (Carcass weight) was 275 130 tonnes with an economic feed conversion factor of 2.9 (feed to live weight) and the chicken production was 98 600 tonnes with an eFCR of 2.2. The average live weight for chicken was 1,9 kg and the carcass weight was 1,3 kg, the edible portion was 51,3% of live weight and 75% of carcass weight respectively. The average carcass weight was 87 kg for pig of which 59% was considered edible (see Cederberg et al., 2009 for a detailed description of the input data). 80% of the chicken diet was made up of wheat (58.6%), soy (18.2%) and rapeseed (3%). These ingredients also comprise 83% of the plant ingredients in the 2010 diet for farmed Norwegian salmon and 60% of the diet for the 2005 production of Swedish pig.

The carbon footprint of the Norwegian 2010 salmon production was 2.6 CO_2e/kg edible product. The corresponding values for Swedish chicken and pig were 3.4 and 3.9 respectively. The increase in carbon footprint for farmed salmon compared to in the study of Winther et al., (2009, 2.0 CO_2e/kg) is due to a small increase in the eFCR and to the inclusion of the climate effect of land use change of Brazilian soy. This was also included for chicken and pig in the current study. Harvest, processing and transport of marine and plant ingredients contributed 39% and 47% of the total carbon footprint of the total carbon footprint of the 2010 Norwegian farmed salmon respectively. In total, production and transport of feed ingredients and feed accounted for 96% of the total carbon footprint in 2010.

Considerable changes in the salmon diet only caused minor changes in the carbon footprint of salmon except for salmon produced on a diet containing a high amount of poultry by-products (2020 LAP) which had a carbon footprint similar to Swedish chicken (3.4 CO_2e/kg). This is a consequence of allocating the carbon footprint from poultry production to the poultry by-products according to their mass. Changing the diet composition from 85% plant ingredients to 88% marine ingredients resulted in almost the same carbon footprint (2.47 and 2.40 CO_2e/kg respectively). Excluding marine ingredients from South America and the Mexican Gulf from the 2010 diet increased the carbon footprint with 7% to 2.75 CO_2e/kg.

The cumulative energy demand for the Norwegian 2010 salmon was 25.3 MJe/kg edible product which was almost the same as for a salmon fed the 2020 VEG diet (24.5 MJe/kg). Increasing the content of marine ingredients to 88% of the diet (HMI) increased the cumulative energy demand to 42.3 MJe/kg and switching from marine ingredients of American origin to North Atlantic origin in the 2010 diet also led to a marginal increase in the energy demand (27.5 MJe/kg) because the American fisheries are quite energy efficient.

The agricultural area required for the 2010 Norwegian salmon was 3.3 m^2 agricultural land per kg edible product whereas Swedish chicken and pig occupied 7.0 and 8.4 m^2 agricultural land per kg edible product (13.2 and 19.4 m^2 per kg live weight) respectively, (table 12). Even the salmon fed a diet with high content of plant ingredients (2020 VEG) occupies less agricultural land than production of chicken and pig (5.6 m^2 land/kg). The high marine ingredient (HMI) diet occupied only 0.3 m^2 agricultural land/kg edible product. The sea area required to sustain the primary production necessary for production of the marine ingredients in the 2010 diet was 115 m^2/kg edible product. Using only marine ingredients from the North-Atlantic would increase the area to 153 m^2sea area/kg edible product because the North-Atlantic species used in production of fish meal and oil occupy higher trophic levels in the marine food web compared to the South-American forage species. The HMI diet would require an area of 253 m^2/kg whereas the 2020 VEG diet would require only 44 m^2sea area/kg edible product. It is however important to keep in mind that the sea area and cropland area are fundamentally different with respect to productivity, the land area is cultivated for food production whereas the sea area is not.

When the results for the 2010 diet is used to calculate the total amount of land area and energy used for the entire Norwegian salmon production of 941 700 tonnes in 2010 we find that a total area of 5440 km^2 cropland and 188 000 km^2 sea area is required to sustain this production (Figure 24). The total industrial energy input was 41 455 TJ, of which 32% was used for harvesting, processing and transport of plant ingredients and 54% was used for harvest, processing and transport of marine ingredients. 8.5% of the energy input was used for production and transport of feed and only 5% was used for the salmon production phase. The ratio of industrial energy input per kg salmon produced/energy output in the product (per kg whole salmon) was 3.57. For the edible energy output the ratio was 8.1. The total amount of CO_2 equivalents released for the 2010 Norwegian salmon production was 4.2 million tonnes (Table 12).

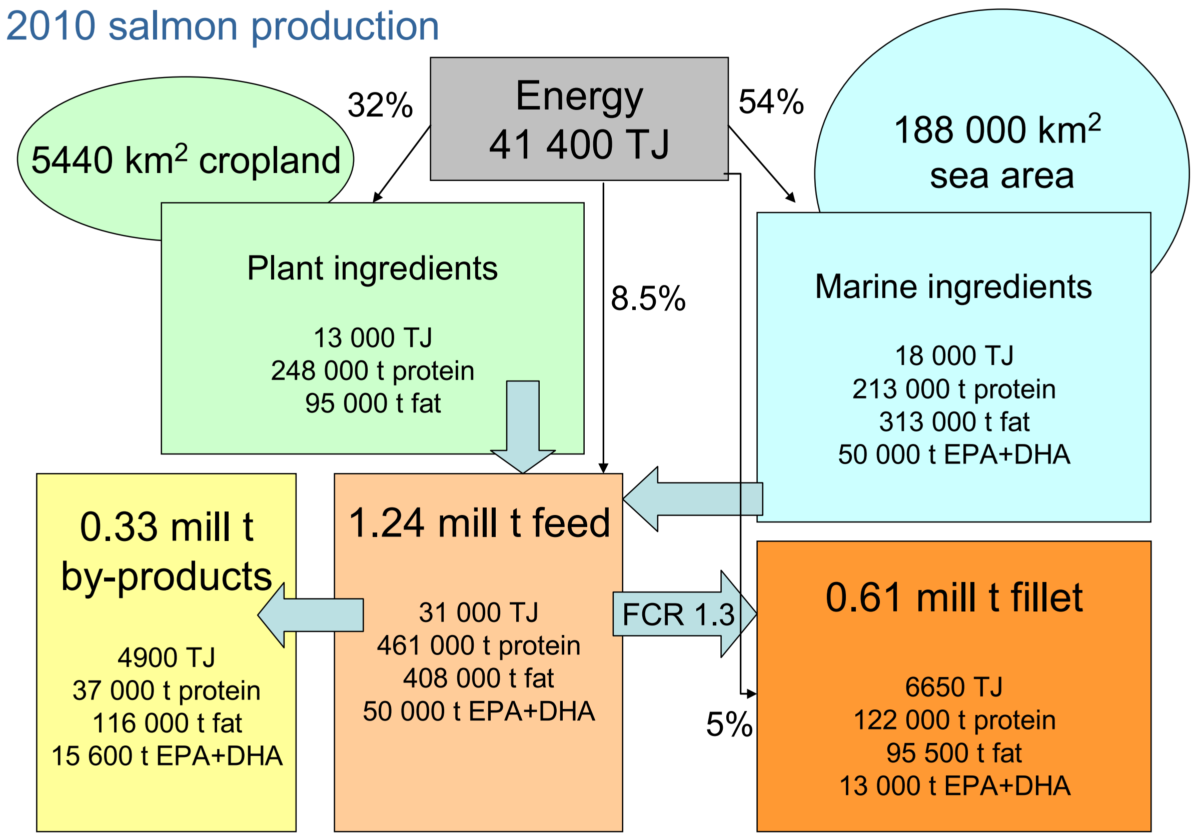


Figure 24 Overview of the nutrient flows and energy use in Norwegian salmon production in 2010.

4.2 Phosphorus utilisation in salmon, pig and chicken

The global average in use of phosphorus fertilizer was 13 kg P/ha in 2008 and is estimated to be 19.8 kg P/ha in 2012 (Smit et al., 2009). Using data from FAO for P use in wheat, soy, sunflower production (FAO 2004, 2005b, 2006) and data from the SIK database for rapeseed and pea production (Flysjö et al., 2008) the average phosphorus use in fertiliser for production of the plant ingredients in the 2010 salmon diet was estimated to be 18.6 kg P/ha. This value was also used for calculations involving chicken and pork production because the same plant ingredients comprised the major part of the diets for salmon, chicken and pig. 10 098 tonnes of P fertilizer was used for growing the plant ingredients used in the 2010 diet for Norwegian farmed salmon. The use of phosphorus fertilizer will naturally increase with increasing amount of plant ingredients in the salmon diet (Table 12).

Table 12 Total cropland area, sea area, use of phosphorus fertilizer, industrial energy use and CO_2 equivalents for the production of 941 000 tonnes of salmon with the 2010 diet formulation and a formulation with a high inclusion level of plant ingredients (85%) and marine ingredients (88%)

	2010 diet in Norway	**2020 VEG (85% plant ingredients)**	**2010 HMI (88% marine ingredients)**
Total cropland, km^2	5440	9116	657
Sea area (m^2/kg live weight)	200	77	440
Total sea area, km^2	188 432	72 437	415 568
Total phosphorus (fertilizer)	10 098	16 923	1 220
MJe/kg live weight	44	43	74
Total industrial energy input (TJ)	41 455	40 144	69 310
Kg CO_2e/kg live weight	4.5	4.3	4.2
Total CO_2e (million tonnes)	4.24	4.05	3.93

The phosphorus fertilizer consumption per kg animal product produced is 2-2.5 times higher for chicken and pig than for salmon fed the 2010 diet. The marine ingredients have a higher P content than the plant ingredients, and P from plant sources are mainly in the form of phytic acid which has a very low bioavailability for both fish and terrestric animals. Animal and salmon diets are supplemented with inorganic phosphorus, mainly in the form of mono-calcium phosphate (MCP). The total P content of salmon, chicken and pork diets is given in Table 11. The salmon diet has a higher P content than chicken and pig diets, but the amount of P consumed per kg weight gain is similar for salmon, pig and chicken due to the lower feed conversion ratio in salmon. However, the retention of P in the edible part of the animal was approximately twice as high in salmon compared to in chicken end pig. The phosphorus budget for the 2010 salmon production in Norway is shown in Figure 25. 73%, (8800 tons) of the 12 050 tonnes of consumed P is not retained in salmon and is released to the water. Thus, increasing the availability of phosphorus in the diet is crucial for improving the efficiency in utilisation of phosphorus. Developing methods for collecting faecal matter is another approach that will contribute to P recycling. Phosphorus is a finite resource that is not renewable but only recyclable. By 2100, 20-60% of the resource base may be depleted depending on the future increase in P consumption (Van Vuuren et al., 2010). Only partial depletion of the resource base can have large consequences for the sustainability of agriculture because the prices of P fertilizer will increase. Thus, there is a need to focus on more efficient use and increased recovering and recycling of phosphorus, and better data on the P flows in agro-ecosystems is needed. Replacing some of the livestock and dairy products in the human diet with salmon would contribute to lower the demand for phosphorus. It would also contribute to reduce the accumulation of P in agricultural soil in areas with intensive livestock production. P pollution of surface waters causing eutrophication and algal blooms is mainly a result of soil erosion and surface runoff from croplands. The release of P to the sea can also cause eutrophication and algal blooms and concerns have been raised regarding the release of phosphorus and nitrogen from the salmon industry in Norway. However, in a recent report examining the situation in two fjord systems with a lot of salmon farming activity (Hardangerfjorden and Boknafjorden) there were no signs of increased eutrophication and the concentration of nutrients were characterised as good-very good in both fjords (Anon 2011). The P-concentrations were closer to the limit for less good than the N-concentrations.

Table 13 g P fertilizer used per kg edible product and per kg live weight for salmon fed different diet formulations compared to chicken and pork production. The P retention in the edible portion of the animal is also given. Data on feed composition of chicken and pig are taken from Cederberg et al., 2009. Phosphorus content in the feed ingredients is taken from "Nutrient Requirements of Fish and Shrimp" (NRC, 2011). Phosphorus content in edible parts of salmon, chicken and pork are taken from "Matvaretabellen", (2006)

Phosphorus	**2010 diet**	**2020 VEG (85 % plants)**	**2010 HMI (88 % marine)**	**Chicken**	**Pig**
g P fertilizer/m^2 cropland	1.86	1.86	1.86	1.86	1.86
m^2 cropland/kg live weight	5.8	9.7	0.7	13.2	19.4
eFCR	1.3			2.2	2.9
g P fertilizer/per kg edible product	6.2	10.3	0.7	12.9	15.5
g P fertilizer/kg live weight	10.7	18.0	1.3	24.6	26.3
% P in the diet	1.00			0.66	0.48
g P eaten/kg gain	13.0			14.0	14.0
P retained in edible part (% of P eaten)	12.3			6.9	5.7

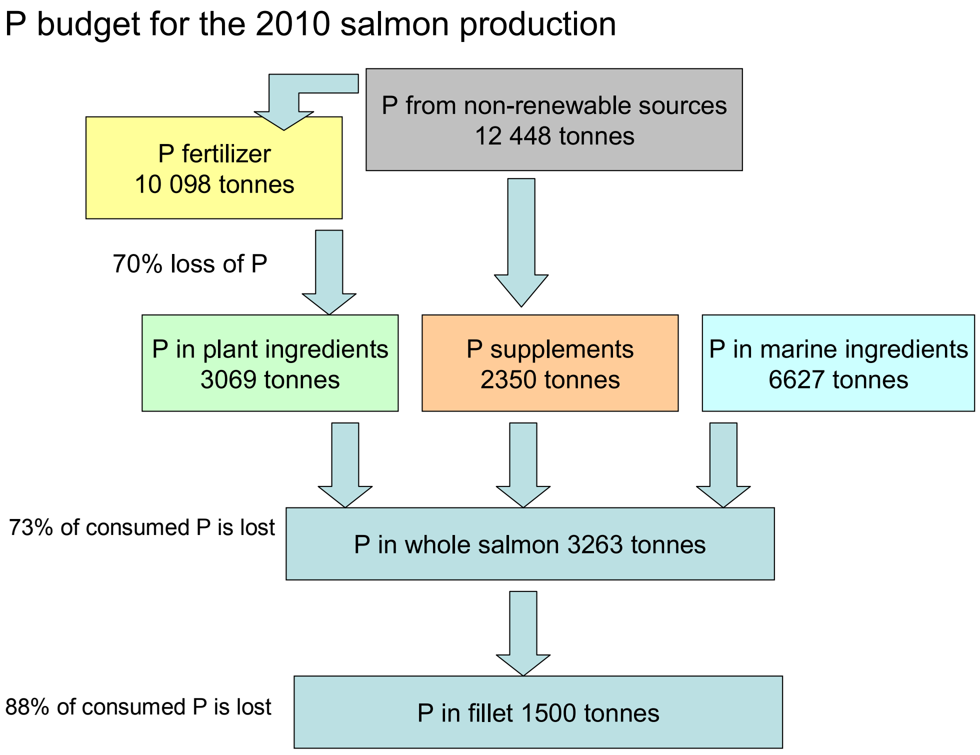


Figure 25 Phosphorus flow for the 2010 salmon production in Norway.

5 Concluding remarks

In a recent report FAO calls for urgent action in developing food systems that uses less energy and emits less greenhouse gases (FAO, 2011a). The global food sector is responsible for around 30% of the world's energy consumption and contributes to more than 20% of the global greenhouse gas (GHG) emissions (FAO, 2011b). In addition, land use changes (mainly through deforestation) contribute to another 15% of GHG emissions. FAO projects that 70% more food needs to be produced globally within 2050 to feed a population of 9 billion people. The meat consumption is projected to increase by nearly 73% and dairy products by 58% within 2050. This increase in food production will have to come through improvements in efficiency of livestock systems because most of the land area suitable for agriculture is already utilised. 30% of the worlds cereal production is currently used to feed livestock and livestock productions also consume large amounts of freshwater both for irrigation of feed crops and for drinking. Freshwater is becoming increasingly scarce and the livestock sector is probably the largest source of water pollution (FAO, 2011b). The expansion and intensification of the livestock production sector the last decades has led to degradation of 20% of the world' pastures due to overgrazing. Deforestation to grow animal feed crops has led to extinction of many plants and animals and released large amounts of carbon dioxide into the atmosphere.

The global food production is also heavily dependent on the use of phosphorus fertilizer. However, the current use of phosphorus is not sustainable due to losses at all stages from mining to crop field to human consumption. Phosphorus is not cycled at present, but moves through an open one way system where the final losses end up in the ocean. Only a very small amount of the 16 Mt of phosphorus lost to the oceans is recovered (0.3 Mt/y in fish harvests), the rest ends up in ocean sediments where it becomes unavailable for millions of years until tectonic movements lifts the ocean floor to dry land and erosion makes it accessible to plants. Thus there is a need to reduce the global use of, and increase the recycling of phosphorus.

With less space and water resources available on land, harvesting and producing food in the ocean is an attractive alternative. Capture fisheries and aquaculture supplied the world with a per capita fish supply of 17 kg in 2009, and fish accounted for 15.7% of the global intake of protein. However, in 2008, 53% of the world's fish stocks were fully exploited, 28% were overexploited, 3% depleted and 1% were recovering from depletion and the remaining 15% were underexploited or moderately exploited (FAO, 2010). Aquaculture now accounts for almost half of the total food fish supply and the percentage is increasing every year. The dependence of the aquaculture feed industry on fish meal and fish oil and the consequences this may have for wild fish stocks is often used as an argument against sustainability of salmon production. In 2010, the Norwegian salmon feed industry used 6% and 22% of the global production of fish meal and oil respectively. However, the amount of forage fish needed to produce 1 kg of farmed salmon has been reduced by 70% the last decades, and the trend of reducing the dietary content of marine ingredients is continuing.

When assessing the environmental efficiency of food production systems it is vital to identify the processes that consume most of the energy and resources and generates most of the emissions. Of the models assessed in this study, life cycle assessment methodology (LCA) has been most widely used to study the efficiency of food production systems and is also used in the current study to calculate the agricultural land use, energy consumption and carbon footprint of farmed salmon, chicken and pig. It was shown that production of salmon uses less agricultural land, less phosphorus and has a lower carbon footprint than production of chicken and pork. However, the LCA methodology has its limitations, in its current form it does not trace the flow of nutrients through food production systems and there is no consensus in how the environmental impacts should be allocated between co-products in productions with multiple outputs. Recycling of nutrients from agro-industrial by-products back into animal productions is a key factor in increasing the environmental efficiency of food production, and is positive for the overall productivity and efficiency. However, when the environmental impacts are allocated to by-products according to their mass, the use of by-products from environmentally more costly food productions such as pork and chicken in salmon feed will generate the impression that this makes the salmon less eco-efficient. In fact, not using these valuable resources to produce human food would be the greatest waste of resources. To improve the global resource use in food production it is necessary to improve the efficiency of the resource demanding livestock productions and perhaps also reduce the global production. The available resource base may instead be used to produce more plants both for direct human consumption and as ingredients in aquaculture feeds.

When tracing nutrient flows and estimating the nutrient retention efficiency mass balance models are more suited than LCA models. This study has shown that salmon farming is an efficient way of providing nutrients for human consumption compared to chicken and pork production. In addition, salmon is also a valuable source of the essential omega 3 fatty acids EPA and DHA, and salmon production may in fact be more efficient in providing these fatty acids for human consumption than capture fisheries. It is essential to be able to track the major flows of protein, lipid, minerals and fatty acids in food production systems, and knowing how efficiently the nutrients are utilised. 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, is vital for tracking the nutrient flows when making a resource budget for a food production system.

Finally it is important to have in mind that when evaluating the resource utilisation of a food production system one have to look at the entire chain from harvesting of feed ingredients and production at the farm to how much of the final product that is actually consumed by humans. FAO has estimated that 30% of the food produced in the world is not consumed by various reasons (FAO 2011a). In the developed world, retailers and consumers are responsible for most of the waste whereas in developing countries, losses occur mainly during harvest and storage of food. Avoiding these losses will reduce the demand for land, water, energy and reduce the GHG emissions. Thus, more focus should be directed towards reducing food losses after the product leaves the farm gate when the goal is to provide food for human consumption in the most efficient way from a resource utilisation perspective.

6 References

Akvafakta. 2011. http://akvafakta.fhl.no/category.php?categoryID=38. Accessed October 2011.

Anonymous. 2010. Norske anbefalinger. Norwegian Directory of Health. http://www.helsedirektoratet.no/ernaering/matvarer_og_n_ringsstoffer/n_ringsstoffanbefalinger/norske_anbefalinger. Accessed June 20th 2011.

Anonymous 2011. Vurdering av eutrofieringssituasjonen I kystområder, med særlig focus på Hardangerfjorden og Boknafjorden. Rapport fra ekspertgruppe oppnevnt av Fiskeri-og kystdepartementet i samråd med Miljøverndepartementet. 2011.

Åsgård T., & Austreng E. 1995. Optimal utilization of marine proteins and lipids for human interests. In Reinertsen and Haaland (Eds.): Sustainable fish farming. Balkema, p 79-87.

Åsgård, T, Austreng, E, Holmefjord, I, Hillestad, M & Shearer, K. 1999. Resource efficiency in the production of various species. 1999. In Svennevig et al. (Eds.): Sustainable aquaculture: food for the future. Balkema, p 171-183.

Austreng, E. 1994. Fôrutnytting hos laks samanlikna med kylling, gris og sau. Norsk fiskeoppdrett 2A, p 2-3. (In norwegian)

Ayer, N., Tyedmers, P.H. 2009. Assessing alternative aquaculture technologies: life cycle assessment of salmonid culture systems in Canada. Journal of cleaner production 17, 362-373. DOI: 10.1016/j.clepro.2008.08.002

Ayer, N.W., Tyedmers, P.H., Pelletier, N.L., Sonesson, U., Scholz, A. 2007. Co-product allocation in life cycle assessments of seafood production systems: Review of problems and strategies. Int. J. LCA 12(7), 480-487. DOI:http//dx.doi.org/10.1065/lca2006.11.284

Bartley, D.M., Brugère, C., Soto, D., Gerber, P., Harvey, B. 2007 (Eds.). Comparative assessment of the environmental costs of aquaculture and other food production sectors: methods for meaningful comparisons. FAO fisheries proceedings No.10. FAO, Rome, 241 pp.

Bendiksen, E.Å., Johnsen, C.A., Olsen, H.J., Jobling, M. 2011. Sustainable aquafeeds: Progress towards reduced reliance upon marine ingredients in diets for farmed Atlantic salmon (*Salmo salar* L.) Aquaculture. DOI:10.1016/j.aquaculture.2011.01.040

Berg, H., Michelsen, P., Troell, M., Kautsky, N. 1996. Managing aquaculture for sustainability in tropical Lake Karibia, Zimbabwe. Ecological Economics 18, 141-159

Bergeron,N. & Jacques,H. 1989. Influence of fish protein as compared to casein and soy protein on serum and liver lipids, and serum lipoprotein cholesterol levels in the rabbit. *Atherosclerosis* 78, 113-121.

Bergheim, A & Åsgård, T.. 1996. Waste production from aquaculture. In Baired et al. (Eds.): Aquaculture and water resource management. Blackwell science, p 50-80.

Bjørkli J. 2002. Protein og energiregnskap hos laks, kylling, gris og lam. (Protein and energy account in chcken, pig and lamb) Master thesis at Agricultural University of Norway. (In Norwegian)

Boissy, J., Aubin, J., Drissi, A., van der Werf, H.M.G., Bell, G.J., Kaushik, S.J. 2011. Environmental impacts of plant-based diets at feed and farm scales. Aquaculture 321, 61-70. DOI:10.1016/j.aquaculture.2011.08.033

Brownlie, K. 2005. Functional food ingridents, a strategic review of the key challenges that are shaping the industry. Frost & Sullivan. Storbritania.

Bruinsma, J. 2003. World Agriculture: towards 2015/2030: an FAO perspective. Earthscan, London, UK, 440 pp.

Buttle, L., Pelletier, N., Tyedmers, P., Robb, D. 2011. Life cycle analysis model quantifies ecological footprints of salmon feed. Global aquaculture advocate, Jan/Feb 2011.

Cederberg, C., Sonesson, U., Henriksson, M., Sund, V., Davis, J. 2009. Greenhouse gas emissions from Swedish production of meat, milk and eggs 1990 and 2005. SIK Report No 793. ISBN 978-91-7290-284-8.

Crampton, V.O., Nanton, D.A., Ruohonen, K., P.-O Skjervold, El-Mowafi, A. 2010. Demonstration of salmon farming as a net producer of fish protein and oil. Aquacult. Nutr. DOI:10.1111/j.1365-2095.2010.00780.x

Davies, R.W.D., Cripps, S.J., Nickson, A., Porter, G. 2009. Defining and estimating global marine fisheries bycatch. Marine Policy 33, 661-672.

Deutch, L., Gräslund, S., Folke, C., Troell, M., Huitric, M., Kautsky, N., Lebel, L. 2007. Feeding aquaculture growth through globalisation: Exploitation of marine ecosystems for fishmeal. Global Environmental Change 17, 238-249.

Directorate of Fisheries. 2011.

http://www.fiskeridir.no/statistikk/akvakultur/biomassestatistikk/biomassestatistikk. Accessed November 2011.Eagle, J., Naylor, R., Smith, W. 2004. Why farm salmon outcompete fishery salmon. Marine Policy 28, 259-270.

Ebbeltoft. 2006. International retail experts.

http://www.ebeltoftgroup.com/Ebeltoft/Main/Main.aspx. Accessed November 2011.

Einen, O., Holmefjord, I., Talbot, C & Åsgård, T. 1995. Auditing nutrient discharges from fish farms. Theoretical and practical considerations. Aquaculture Research 26, 701-713.

Ellingsen, H., Olaussen, J.O., Utne, I.B. 2009. Environmental analysis of the Norwegian fishery and aquaculture industry-A preliminary study focusing on farmed salmon. Marine Policy 33, 479-488. DOI:10.1016/j.marpol.2008.11.003.

Ellingsen, H., Aanondsen, S.A. 2006. Environmental impacts of wild caught cod and farmed salmon-A comparison with chicken. Int J. LCA 1, 60-65. DOI: http://dx.doi.org./10.1065/lca2006.01.236

Ewing B., Goldfinger, S., Wackernagel, M., Steckbart, M., Rizk, S.M., Reed, A., Kitzes, J. 2008 a. The Ecological footprint atlas 2008. Oakland: Global Footprint Network. http://www.footprintnetwork.org/

Ewing B., Reed, A., Rizk, S.M., Galli, M., Wackernagel, M., Kitzes, J. 2008 b. Calculation methodology for the 2008 national footprints account. Oakland: Global Footprint Network. http://www.footprintnetwork.org/

FAO. 2004. Fertilizer use by crop in Brazil. Rome, Italy.

FAO. 2005.a Livestock policy brief 02. Food and Agriculture Organization, Rome, Italy.

FAO 2005 b Fertilizer use by crop in Ukarine. Rome, Italy.

FAO 2006. Fertilizer use by crop. Rome, Italy.

FAO. 2010. *The State of the World Fisheries and Aquaculture 2010*. Food and Agriculture Organisation of the United Nations, Rome.

FAO. 2011 a. Energy-smart" food for people and climate. Food and Agriculture Organization, Rome, Italy.

FAO. 2011 b. "World livestock 2011". Food and Agriculture Organization, Rome, Italy.

FAO 2011 c. "The state of the world's land and water resources for food and agriculture. Managing systems at risk." Rome, Italy.

FAOSTAT: http://faostat.fao.org/

Fiskeridirektoratet. 2011. Nøkkeltall for havbruksnæringen. År 2010, 32 pp. (In Norwegian)

Folke, C., Kautsky, N., Berg, H., Jansson, A., Troell, M. 1998. The ecological footprint concept for sustainable seafood production: A review. Ecological Applications 8, 63-71.

Fiskeiforskning-SSF. 2004. Håndbok for fiskemelsindustrien. Råstoffbehandling. Hefte nr. 1, 54 pp. (In Norwegian)

Flysjö, A., Cederberg, C., Strid, I. 2008. LCA-databas för konventionella fodermedel (In Swedish – LCA database for conventional feeds). Version 1.1 SIK report No 772. ISBN 978-91-7290-265-7

Fréon, P., Cury, P., Shannon, L., Roy, C. 2005. Sustainable exploitation of small pelagic fish stocks challenged by by environmental and ecosystem changes: A review. Bulletin of Marine Science 76, 385-462.

Frost & Sullivan Reports. 2004. European mega-3 and Omega-6 PUFA ingredients market. 12/7 2004

Frost and Sullivan Reports. 2005. End-user analysis of the global Omega-3 PUFA markets. 22/12 2005

Gerber, P., Wassenar, T., Rosales, M., Castel, V., Steinfeld. 2007. Environmental impacts of a changing livestock production: owerview and discussion for a comparative assessment with other food production sectors. In D.M. Bartley, C. Brugère, D. Soto, P. Gerber, and B. Harvey (Eds): Comparative assessment of the environmental costs of aquaculture and other food production sectors: methods for meaningful comparisons. FAO/WFT Expert workshop, 24-28 April, Vancouver Canada. FAO Fisheries Proceedings. No 10. FAO, Rome, p 37-53.

Global organisation for EPA and DHA-Omega 3 (GOED). http//www.goedomega3.com/

Guinee, J., Gorree, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Weneger, A., Suh, S., Udo de Haes, H., de Bruin, H., Duin, R., Huijbregts, M. 2001. Life Cycle Asessment: An operational guide to the ISO Standards Part 2. Ministry of Housing, Spatial Planning and Environment, The Hague, Neteherlands.

Gundersen, V., Måsøval, K.A., Bendiksen, E.Å. 2010. Feed sustainability og high-energy feeds with graded fishmeal inclusion for Atlantic salmon (*Salmo salar* L.).Abstract 14th International Symposium on Fish Nutrition and Feeding, Qingdao, China, May 31-June 4 2010.

Haberl, H., Weisz, H. 2007. The potential use of the Materials and Energy Flow Amalysis (MEFA) framework to evaluate the environmental costs of agricultural production systems and possible applications to aquaculture. In D.M. Bartley, C. Brugère, D. Soto, P. Gerber, and B. Harvey (Eds): Comparative assessment of the environmental costs of aquaculture and other food production sectors: methods for meaningful comparisons. FAO/WFT Expert workshop, 24-28 April, Vancouver Canada. FAO Fisheries Proceedings. No 10. FAO, Rome, p 37-53.

Hall, S.J., Delaporte, A., Phillips, M.J., Beveridge, M., O'Keefe, M. 2011. Blue Frontiers. Managing the environmental costs of aquaculture. The Worldfish Center, Penang, Malaysia.

Hoekstra, A.Y. 2008. Human appropriation of natural capital: a comparison of ecological footprint and water footprint analysis.

Hua, K., de Lange, C.F.M., Niimi, A., Cole, G., Moccia, R.D., Fan, M.Z., Bureau, D. 2008. A factorial model to predict phosphorus waste output of rainbow trout (*Oncorhynchus mykiss*). Aquacult. Res. 39, 1059-1068. DOI: 10.1111/j.1365-2109.2008.01966.x

IFFO, Internationao Fishmeal and Fish Oil Organisation. http://www.iffo.net/

It-Yahia,D., Madani,S., Savelli,J.L., Prost,J., Bouchenak,M., & Belleville,J. 2003. Dietary fish protein lowers blood pressure and alters tissue polyunsaturated fatty acid composition in spontaneously hypertensive rats. *Nutrition* 19, 342-346.

Jackson, A.J., 2006. The importance of fishmeal and fish oil in aquaculture diets. International Aquafeed 9, 16-19.

Jackson, A.J., 2007. Challenges and opportunities for the fishmeal and fish oil industry Feed Technology update 2, 9 pp.

Jackson, A.J., 2009.Fish in – Fish out, Ratios explained. Aquaculture Europe 34,5-10.

Kates, R.W., Clark, W.C., Corell, R., Hall, M.J., Jaeger, C.C., Lowe, I., McCarthy, J.J., Schellnhuber, H.J., Bolin, B., Dickson, N.M., 2001. Sustainability science. Science 292, 641-642.

Kaushik, S.J. 1998. Nutritional bioenergetics and estimates of waste production in non salmonids. Aquat. Living Res. 11, 211-217.

Kaushik, S., Troell, M. 2010. Taking the fish-in fish-out ratio a step further. Aquaculture Europe 35, 15-17.

Lancker, E., Nijkamp, P. 2000. A policy Scenario analysis of sustainable agricultural development options: A case study for Nepal. Impact Assess. Project Appraisal 18 (2),111-124.

Larsson, J., Folke, C., Kautsky, N. 1994, Ecological limitations and appropriation of ecosystem support by shrimp farming in Columbia. Environmental management 18, 663-676.

Liaset,B., Madsen,L., Hao,Q., Criales,G., Mellgren,G., Marschall,H.U., Hallenborg,P., Espe,M., Frøyland,L., & Kristiansen,K. 2009. Fish protein hydrolysate elevates plasma bile acids and reduces visceral adipose tissue mass in rats. *Biochimica et Biophysica Acta (BBA) - Molecular and Cell Biology of Lipids* 1791, 254-262.

Matvaretabellen. 2006. http://matportalen.no/matvaretabellen/index_html/tabell_view?nutrients =&searchmode=%20normal&grouping=0&togglerowcol=col. Accessed August 2011.

Muller,O. & Krawinkel,M. 2005. Malnutrition and health in developing countries. *CMAJ* 173, 279-286.

Munkung, R., Gheewala, S. 2007. Use of life cycle assessment (LCA) to compare the environmental impacts of aquaculture and agri-food products. In D.M. Bartley, C. Brugère, D. Soto, P. Gerber, and B. Harvey (Eds): Comparative assessment of the environmental costs of aquaculture and other food production sectors: methods for meaningful comparisons. FAO/WFT Expert workshop, 24-28 April, Vancouver Canada. FAO Fisheries Proceedings. No 10. FAO, Rome, p 87-96.

Naylor, R. and Burke, M., 2005. Aquaculture and Ocean resources: raising tigers of the sea. Ann. Rev. Environ. Res. 30, 185-218.

Naylor, R.L., Goldburg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M.C.M., Clay, J., Folke, C., Lubchenko, J., Mooney, H., Troell, M. 2000. Effect of aquaculture on world fish supplies. Nature 405, 1017-1024.

Naylor, R.L., Hardy, R.W., Bureau, D.P., Chiu, A., Elliott, M., Farrell, A.P., Forster, I., Gatlin, D.M., Goldburg, R.J., Hua, K., Nichols, P.D. 2009. Feeding aquaculture in an era of finite resources. PNAS, 106, 15103-15110.

NIFES Sjømatdata. 2010. http://www.nifes.no/index.php?page_id=164&lang_id=1. Accessed August 2011.

NRC. 2011. Nutrient Requirements of Fish and Shrimp. Animal Nutrition Series. National Research Council. ISBN-13:978-0-309-16338-5.

Papatryphon, E., Petit, J., Kaushik, S., Van der Werf, H. 2004. Environmental impact assessment of salmonid feeds using life cycle assessment (LCA). Ambio 33, 316-323.

Papatryphon, E., Petit, J., Hayo, V., Kaushik, S.J., Claver, K. 2005. Nutrient-balance modelling as a tool for environmental management in aquaculture: the case of trout farming in France. Env. Managem. 35, 161-174.

Pelletier, N. 2008. Environmental performance in the US broiler poultry sector: Life cycle energy use and greenhouse gas, ozone depleting, acidifying and eutrophying emissions. Agricultural Systems 98, 67-73. DOI:10.1016/j. aquaculture.2007.06.024

Pelletier, N., Tyedmers, P. 2007. Feeding farmed salmon: Is organic better? Aquaculture 272, 399-416.

Pelletier, N., Tyedmers, P. 2011. An ecological economic critique of the market information in life cycle assessment research. J. Ind. Ecol. 15, 342-354. DOI:10.1111/j.1530-9290.2011.00337.x

Pelletier, N., Arsenault, N., Tyedmers, P. 2008. Scenario modelling potential eco-efficiency gains from a transition to organic agriculture: Life cycle perspectives on Canadian canola, corn, soy and wheat production. Environ. Man. DOI: 10.1007/s00267-008-9155-x

Pelletier, N., Ayer, N.W., Tyedmers, P.H., Kruse, S.A., Flysjo, A., Robillard, G., Ziegler, F., Scholz, A.J., Sonesson, U. 2007. Impact categories for life cycle assessment research of seafood production systems: Review and prospects. Int. J LCA 12, 414-421. DOI:http://dx.doi.org/10.1065/lca2006.09.275

Pelletier, N., Lammers, P., Stender, D., Pirog, R. 2010. Life cycle assessment of high- and low-profitability commodity and deep-bedded niche swine production systems in the Upper Midwestern United States. Agricult. Syst. 103, 599-608. DOI:10.1016/j.agsy.2010.07.001

Pelletier, N., Tyedmers, P., Sonesson, U., Scholz, A., Ziegler, F., Flysjo, A., Kruse, S., Cancino, B., Silvermann, H. 2009. Not all salmon are created equal: Life cycle assessment (LCA) of global salmon farming systems. Environ. Sci. Technol. 43, 8730-8736. DOI: 10.1021/es9010114

Péron, G., Mittaine, J.F., Le Gallic, B. 2010. Where do fish meal and fosh oil come from? An analysis of the conversion ratios in the global fishmeal industry. Marine Policy, 34815-820. DOI:10.1016/j.marpol.2010.01.027

Rees, W.E., Wackernagel, M. 1994. Ecological footprints and and appropriated carrying capacity: Measuring the natural capital requirements of the human economy. In: Jansson, A.M., Hammer, M., Folke, C., Costanza, R. (Eds.): Investing in Natural Capital: The Ecological Economics Approach to Sustainability. Island Press, Washington DC, p 362-390.

Ressursoversikt. 1997. Fisken og havet. Særtrykk 1. 120 pp. (In Norwegian)

Roque d'Orbcastel, E., Blancheton, J-P., Boujard, T., Aubin, J., Moutounet, Y., Przybyla, C., Belaud, A. 2008. Comparison of two methods for evaluating waste of flow through trout farm. Aquaculture 274, 72-79. DOI: 10.1016/j.aquaculture.2007.10.053.

Rubin rapport 144. 2007. Råvarekilder for omega 3 oljer. Potensialer, ernæring/helse, bærekraftighet og miljøstatus. (In Norwegian)

Rubin rapport 202. 2011. Økt utnyttelse av biråstoff fra hvitfisksektoren i Finnmark. (In Norwegian)

Rubin rapport 210. 2011. Internasjonal markeds- og industrianalyse for marine ingredienser. (In Norwegian)

Rubin varestrømsanalyse for 2010 (In Norwegian)

Sanden, M., Stubhaug, I., Berntssen, M.H.G., Lie, Ø., Torstensen, B. 2011. Atlantic salmon (*Salmo salar*) as a net producer of long-chain marine ω-3 fatty acids. J.Agric. Food Chem. DOI: dx.doi.org/10.1021/jf203289s.

Schau, E.M., Ellingsen, H., Endal, A., Aanondsen, S.Aa. 2009. Energy consumption in the Norwegian fisheries. J. Cle. Prod. 17, 325-334. DOI:10.1016/j.jclepro.2008.08.015

Schau, E.M., Fet, A,M. 2008. LCA studies of food products as background for environmental product declarations. Int. J. LCA 13(3), 255-264. DOI:http//dx.doi.org/10.1065/lca2007.12.372

Schmidt, J.H. 2010. Comparative life cycle assessment of rapeseed oil and palm oil. Int. J Life Cycle Assess. 15, 183-197. DOI: 10.1007/s11367-009-0142-0.

Schröder, J.J., Cordell, D., Smit, A.L., Rosemarin, A. 2009. Sustainable use of phosphorus. EU Tender ENV.B.1/ETU/2009/0025

Shepherd, C.J., Pike, I.H., Barlow, S.M. 2005. Sustainable feed resources of marine origin. European Aquaculture Society special publication no 35, pp 59-66.

Singh, R.K., Murty, H.R., Gupta, S.K., Dikshit, A.K. 2009. An overview of sustainability assessment methodologies. Ecological Indicators 9, 189-212. DOI:10.1016/jecolind.2008.05.011

Smit, A-L., Bindraban, P.S., Scröder, J.J., Conijn, J.G., van der Meer, H.G. 2009. Phosphorus in agriculture: global resources, trends and developments. Report to the Steering Committee Technology Assessment of the Ministry of Agriculture, Nature and Food Quality, The Netherlands, and in collaboration with the Nutrient Flow Task Group (NFTG), supported by DPRN (Development Policy Review Network).

Smith, R.L. 1992. Elements of ecology, third edition, Harper Collins Publishers Inc. 617 pp. ISBN 0-06-046328-7.

Statistics Norway. 2011. http://www.ssb.no/aarbok/tab/tab-376.html. Accessed November 2011.

Svanes, E., Vold, M., Hanssen, O.J. 2011. Effect of different allocation methods on LCA results of products from wild-caught fish and on the use of such results. Int. J. Life Cycle Asess. DOI:10.1007/s11367-011-0288-4

Tacon, A.J.G., Metian, M. 2008. Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: Trends and future prospects. Aquaculture 285, 146-158.

Thodesen, J. Gjerde, B., Grisdale-Helland, B., Storebakken, T. 2001. Genetic variation in feed intake, growth and feed utilization in Atlantic salmon (*Salmo salar*). Aquaculture 194, 273-281. doi.1016/S0044-8486(00)00527-5

Thrane, M. 2006. LCA of Danish fish products. New methods and insights. Int. J. LCA 11, 66-74. DOI: http://dx.doi.org./10.1065/lca2006.01.232

Torrissen, O., Olsen, R.E., Toresen, R., Hemre, G.I., Tacon, A.G.J., Ashe, F., Hardy, R.W., Lall, S. 2011. Atlantic salmon (*Salmo salar*): The “Super-Chicken” of the Sea? Rev. Fish Sci. 19, 257-278. DOI: 10.1080/10641262.2011.597890.

Torstensen, B., Espe, M., Sanden, M., Stubhaug, I., Waagbø, R., Hemre, G-I., Fontanillas, R., Nordgarden, U., Hevrøy, E.M., Olsvik, P., Berntssen, MHG. 2008. Novel production of Atlantic salmon (*Salmo salar*) protein based on combined replacement of fish meal and fish oil with plant meal and vegetable oil blends. Aquaculture 285, 193-200.

Troell, M., Tyedmers, P., Kautsky, N., Rönnbäck, P. 2004. Aquaculture and energy use. In C. Cleveland (Ed.). *Encyclopedia of energy*. Elsevier, San Diego, vol. 1, p 97-108.

Turchini, G.M.,Francis, D.S., Keast, R.S.J., Sinclair, A.J. 2010. Transforming salmonid aquaculturefrom a consumer to a producer of long chain ω-3 fatty acids. Food Chem. 124, 609-614.

Tyedmers, P., Pelletier, N., Ayer, N. 2007. Biophysical sustainability and approaches to marine aquaculture development policy in the United States. A report to the Marine Aquaculture Task Force.

Van Enk, R., van der Vee, G., Acera, L., Schuiling, R., Ehlert, P., de Wilt, J., de Vries, C., van Haren, R. 2011. The Phosphate balance. Current developments and future outlook. Report for the Netherlands Innovsation Network (Ministry for Economic Affairs, Agriculture and Innovation). ISBN:978-90-5059-414-1

Van Vuuren, D.P., Bouwman, A.F., Beusen, A.H.W. 2010. Phosphorus demand for the 1970-2100 period: A scenario analysis of resource depletion. Global environmental change 20, 428-439.

WCED. 1987. Our common future, World Commission on Environment and Development.

Welch, A., Hoenig, R., Stieglitz, J., Benetti, D., Tacon, A., Sims, N., O'Hanlon, B. 2010. From fishing to the sustainable farming of carnivorous marine finfish. Rev. Fish. Sci. 18, 235-247. DOI:10.1080/10641262.2010.504865

Wergedahl,H., Liaset,B., Gudbrandsen,O.A., Lied,E., Espe,M., Muna,Z., Mørk,S., & Berge,R.K. 2004. Fish Protein Hydrolysate Reduces Plasma Total Cholesterol, Increases the Proportion of HDL Cholesterol, and Lowers Acyl-CoA:Cholesterol Acyltransferase Activity in Liver of Zucker Rats. *The Journal of Nutrition* 134, 1320-1327.

Winther, U., Ziegler, F., Skontorp Hognes, E. 2009. Carbon footprint and energy use in Norwegien seafood products, SINTEF Fisheries and Aquaculture.

APPENDIX

Carbon footprint and area use of farmed Norwegian salmon

F21039- Confidential

Report

Carbon footprint and area use of farmed Norwegian salmon

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

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

SINTEF Fisheries and Aquaculture
Fisheries Technology
2011-11-14

SINTEF

SINTEF Fiskeri og havbruk AS
SINTEF Fisheries and Aquaculture

Address:
Postboks 4762 Sluppen
NO-7465 Trondheim
NORWAY

Telephone:+47 40005350
Telefax:+47 93270701

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

Report

Carbon footprint and area use of farmed Norwegian salmon

KEYWORDS:
LCA, aquaculture, carbon footprint, feed, sustainability, energy, crops, seafood, area use

VERSION Final report	**DATE** 2011-11-14

AUTHOR(S)
Erik Skontorp Hognes (SINTEF Fisheries and aquaculture)
Other authors
Friederike Ziegler and Veronica Sund (Swedish Institute for Food and Biotechnology, SIK)

CLIENT NOFIMA AS	**CLIENT'S REF.** Torbjørn Einar Åsgård
PROJECT NO. 830276	**NUMBER OF PAGES/APPENDICES:** 30 + Appendices

ABSTRACT

This report presents the carbon footprint and area use of Norwegian farmed salmon that is fed five different diets. It also compares the carbon footprint and occupation of agricultural land of Norwegian farmed salmon from 2010 with Swedish pig and chicken.
All results are calculated according to LCA methodology where the functional unit is 1 kg edible product and the system boundaries from fishing/growing of feed ingredients and until the products are at the farm gate.
Results show that changes in the content of marine ingredients can change the final carbon footprint with ± 7 %. Per kilo edible product a salmon that is fed the average Norwegian feed diet in 2010 has a carbon footprint of 2.6 kg CO_2e, it occupies 3.3 m^2 agricultural land and requires 115 m^2 of sea primary production area. Although only 40 % of the diet was of marine origin, the area needed to produce those inputs was much larger than the area used for farming.
The comparison with pig and chicken concluded that salmon has the lowest carbon footprint and occupies least agricultural land. Even an almost "vegetarian" salmon can occupy less agricultural land than chicken. Pig had the highest carbon footprint and the highest occupation of agricultural land.

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

REPORT NO. F21039	**ISBN** ISBN	**CLASSIFICATION** Confidential	**CLASSIFICATION THIS PAGE** Confidential

Document history

VERSION	DATE	VERSION DESCRIPTION
	2011-11-14	Final report

Table of contents

APPENDICES

No Appendices

1 Introduction

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

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

2 Methodology

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

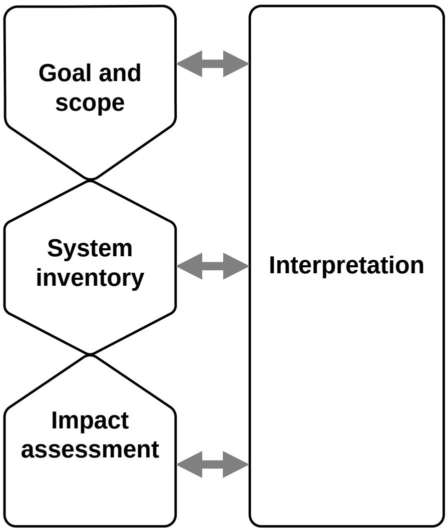


Figure 2-1 Iterative phases of LCA

2.1 Goal and scope

Functional unit

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

System boundaries

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

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

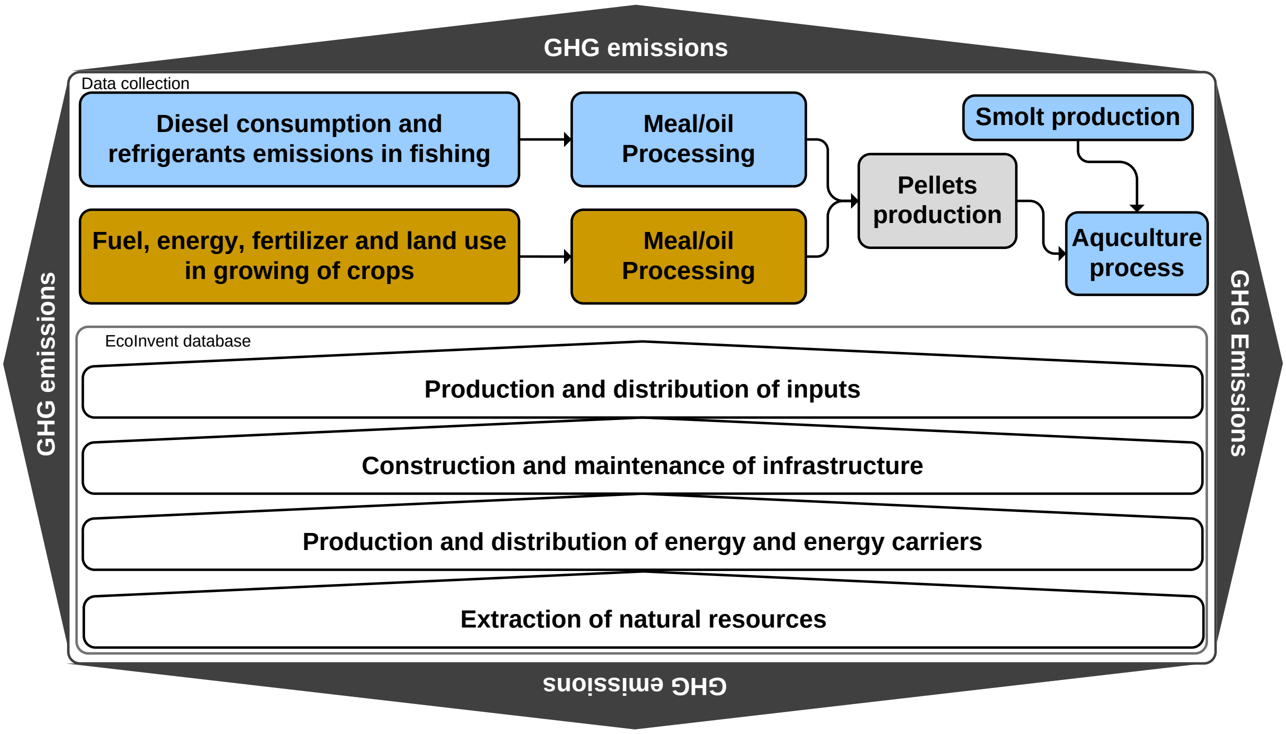


Figure 2-2 System boundaries for the impact assessment (carbon footprint and energy- and area use) for the salmon

Allocation

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

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

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

2.2 Impact assessment methodologies

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

Carbon footprint

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

Occupation agricultural land

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

Sea primary-production-required

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

The area of primary production required (PPR) to sustain the fish catch, was calculated using trophic levels for the species together with levels of primary-production-per-area in the Large Marine Ecosystem (LME) in which they are caught.

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

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

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

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

Cumulative energy demand

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

2.3 Data sources

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

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

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

2.4 Cut offs

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

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

3 System inventory

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

3.1 Feed composition scenarios

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

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

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

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

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

[1] This marine oil was modelled as purely from herring trimmings
[2] This was modelled identical to "poultry by-product meal

3.2 Composition of marine ingredients in 2010 Norwegian salmon feed

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

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

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

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

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

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

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

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

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

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

3.4 Area of primary production required by marine ingredients

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

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

3.5 Carbon footprint from energy use and refrigerant emissions in fisheries

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

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

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

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

3.6 Yields in oil and meal production

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

---

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

3.7 Transports of feed ingredients

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

3.8 Agricultural ingredients

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

Table 3-5 Data agricultural ingredients

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

Pea Protein Concentrate (PPC)

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

Soy Protein Concentrate (SPC)

Carbon footprint from Soy Protein Concentrate (SPC) from Brazil is assumed to be equal to soy meal found in the SIK database (SIK-feeddatabase-v2, 2011).
For soy production the climate impact from land use change is of special importance since soy production contributes to deforestation both directly and indirectly. The reason that this type of climate impact is only included for soy is, that among the crops that are used in this analysis, soy is to a higher extent grown on newly deforested land than the others. Here the climate impact is calculated using a method developed by the Joint Research Centre of the European Commission for calculating climate impact from land use change:

---

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

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

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

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

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

Wheat Grains/Fodder Wheat

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

Wheat gluten

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

Rape seed oil

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

Sunflower meal

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

3.9 Poultry by-product fat and meal

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

3.10 Pellets production

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

3.11 Swedish chicken and pig meat

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

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

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

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

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

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

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

4 Results

4.1 Carbon footprint

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

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

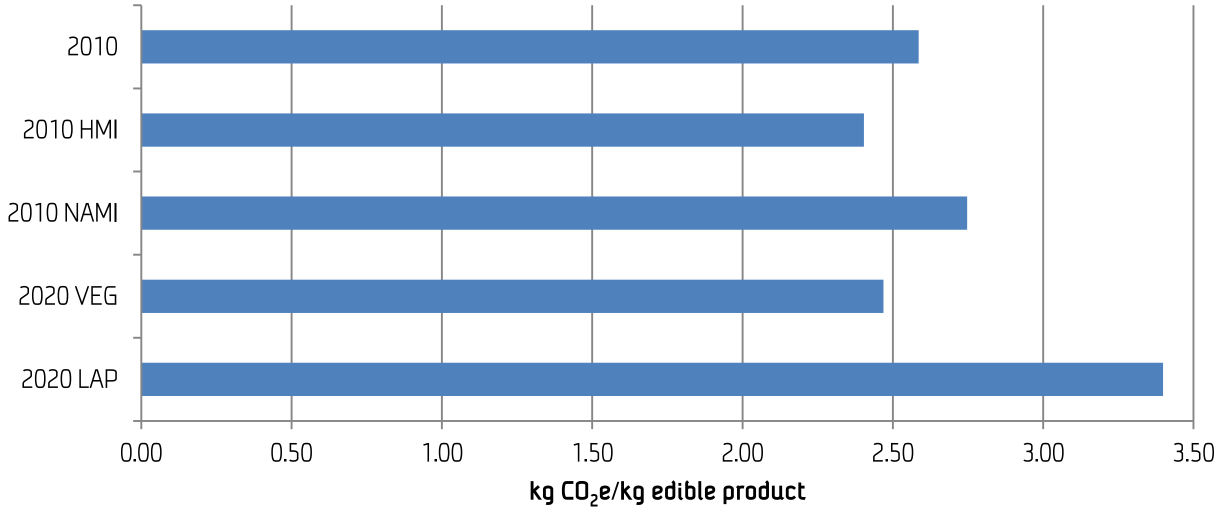


Figure 4-1 Total carbon footprint per kilo edible product for each diet

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

Climate aspects in the 2010 diet.

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

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

---

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

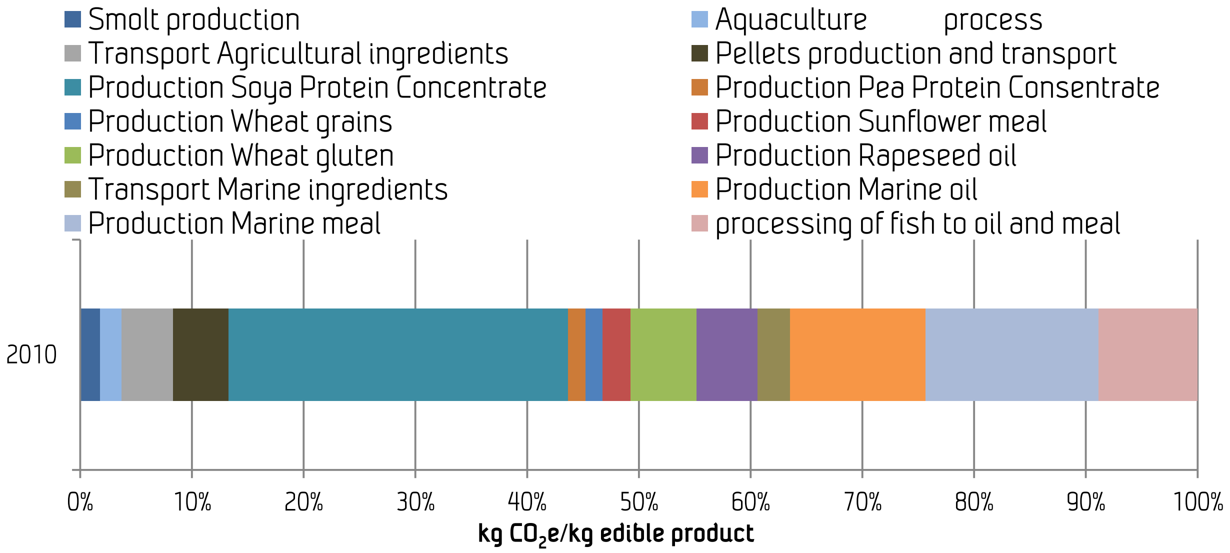


Figure 4-2 Contribution (in %) from different processes to the carbon footprint of the 2010 salmon

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

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

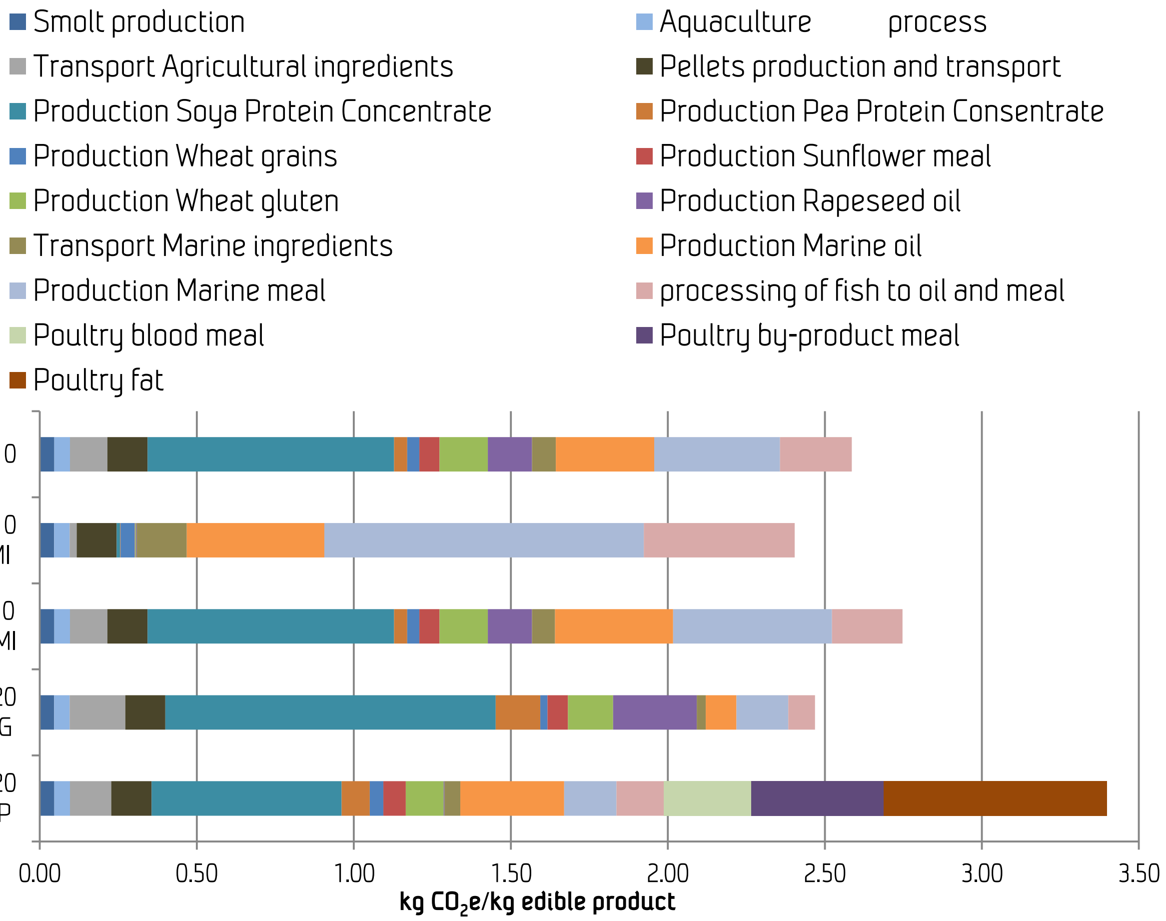


Figure 4-3 Total carbon footprint per kilo edible product for each diet

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

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

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

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

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

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

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

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

	Carbon footprint	Field area	Area of Primary Production Required (PPR)	Energy use
	kg CO_2e/kg	m^2 land/kg	m^2 sea/kg	MJe/kg
Anchoveta oil/meal	0.99	0.00	62.0	14.1
Blue whiting oil/meal	2.20	0.01	1 294	32.9
Boar fish oil/meal	1.85	0.00	176	27.5
Capelin, trimmings oil/meal	2.39	0.06	324	54.6
Capelin, Icelandic oil/meal	1.98	0.01	322	29.4
Herring, NVG oil/meal	1.54	0.00	330	23.1
Herring, silage	2.78	0.06	184	63.4
Herring, trimmings oil/meal	2.56	0.06	193	57.1
Mackerel, Atlantic oil/meal	1.31	0.00	321	19.5
Mackerel, Chilean Jack oil/meal	0.77	0.00	222	11.1
Mackerel, Horse oil/meal	2.71	0.00	314	40.8
Menhaden oil/meal	0.85	0.00	22.0	12.3
Norway pout oil/meal	1.55	0.00	149	23.3
Pearlside oil/meal	1.55	0.00	177	23.3
Pilchard oil/meal	1.60	0.00	70.0	24.0
Sand eel oil/meal	1.37	0.00	58.0	20.2
Sprat oil/meal	1.77	0.00	102	26.3
Whitefish, trimmings oil/meal	10.63	0.08	784	153.6
Pea protein concentrate (PPC)	0.92	9.54	0	14.8
Rapeseed oil	1.02	3.60	0	9.25
Soy protein concentrate (SPC)	3.20	4.06	0	5.87
Sunflower meal	1.24	12.10	0	12.75
Wheat gluten	2.08	1.83	0	36.57
Wheat grains	0.51	1.65	0	4.91
Poultry blood meal	5.79	NA	0	64.49
Poultry by-product meal	3.14	NA	0	35.59
Poultry fat	5.37	NA	0	60.59

NA = Not Available

4.2 Area use

Area use for salmon diets

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

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

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

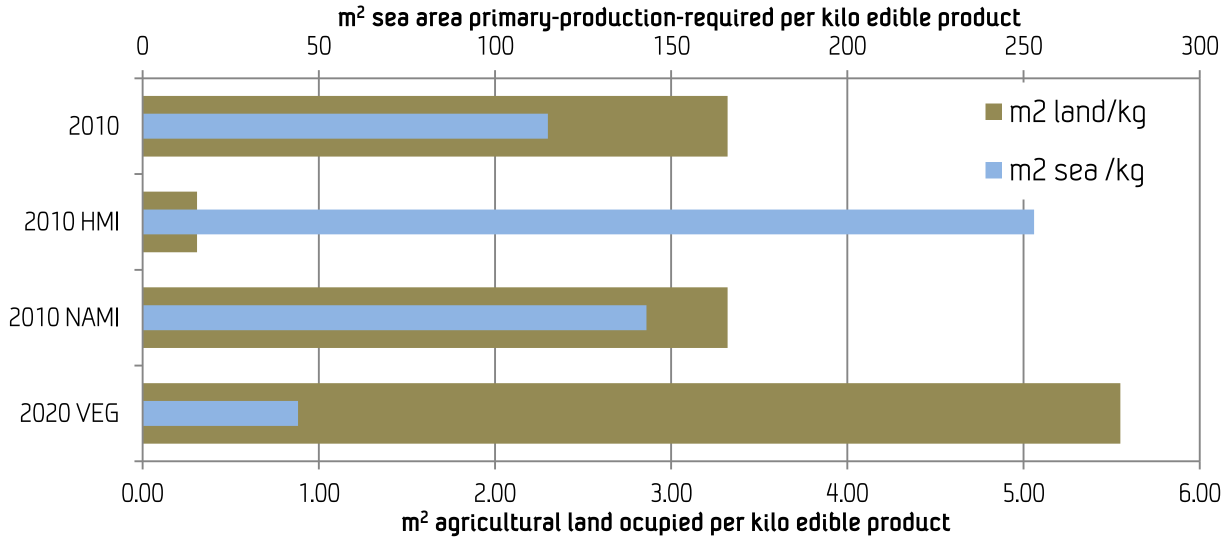


Figure 4-4 Agricultural area occupation and sea-primary-production-area required

Sea primary-production-area required

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

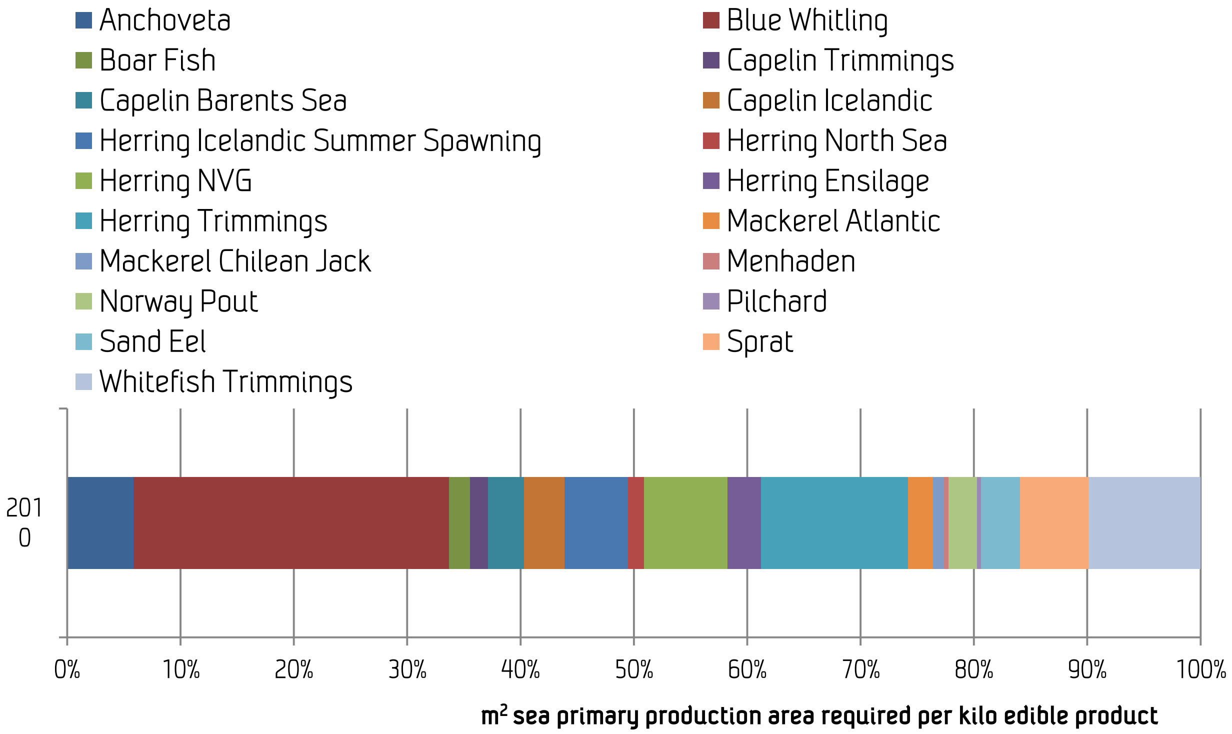


Figure 4-5 Contribution to sea primary-production-required per kilo edible salmon from 2010 diet

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

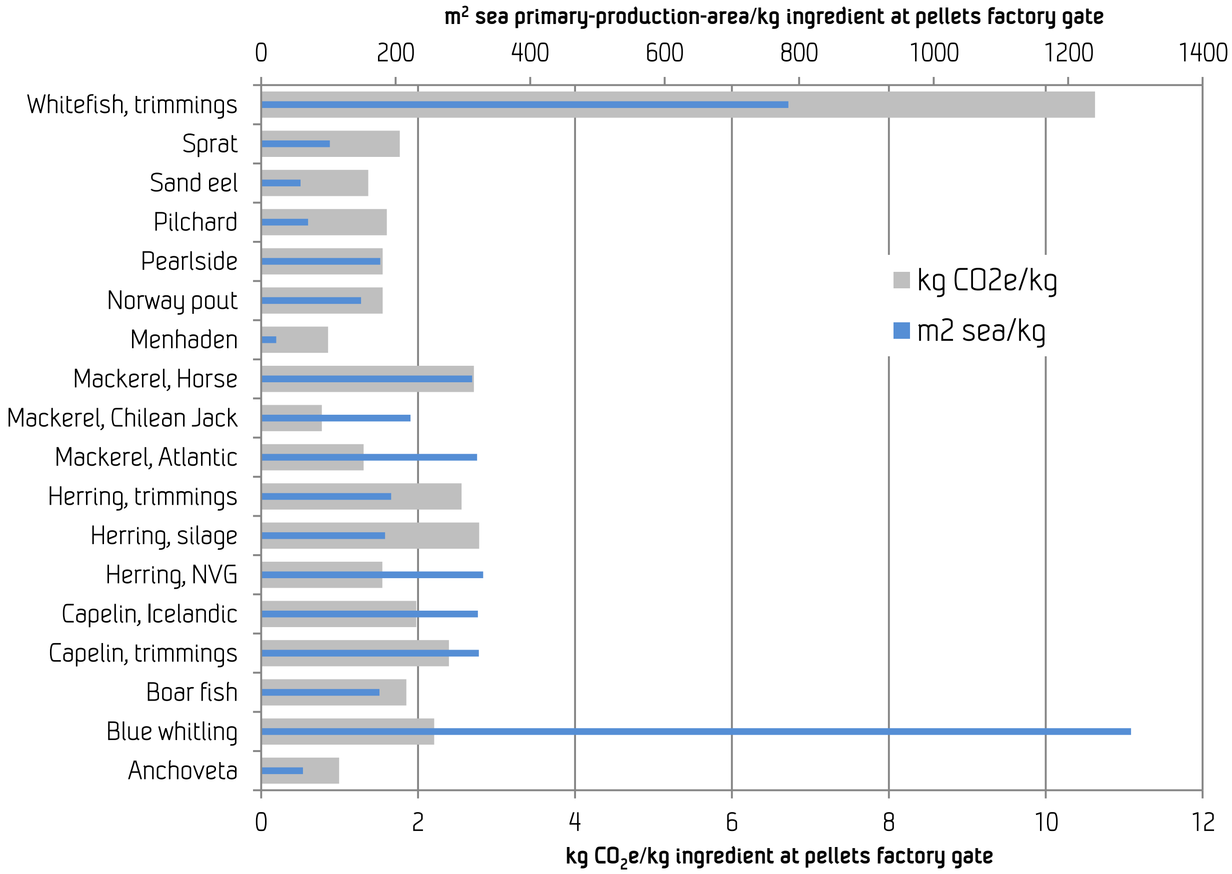


Figure 4-6 Contribution to carbon footprint and sea primary-production-area required per kilo edible salmon from 2010 diet.

4.3 Comparison Norwegian salmon and Swedish pig and chicken

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

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

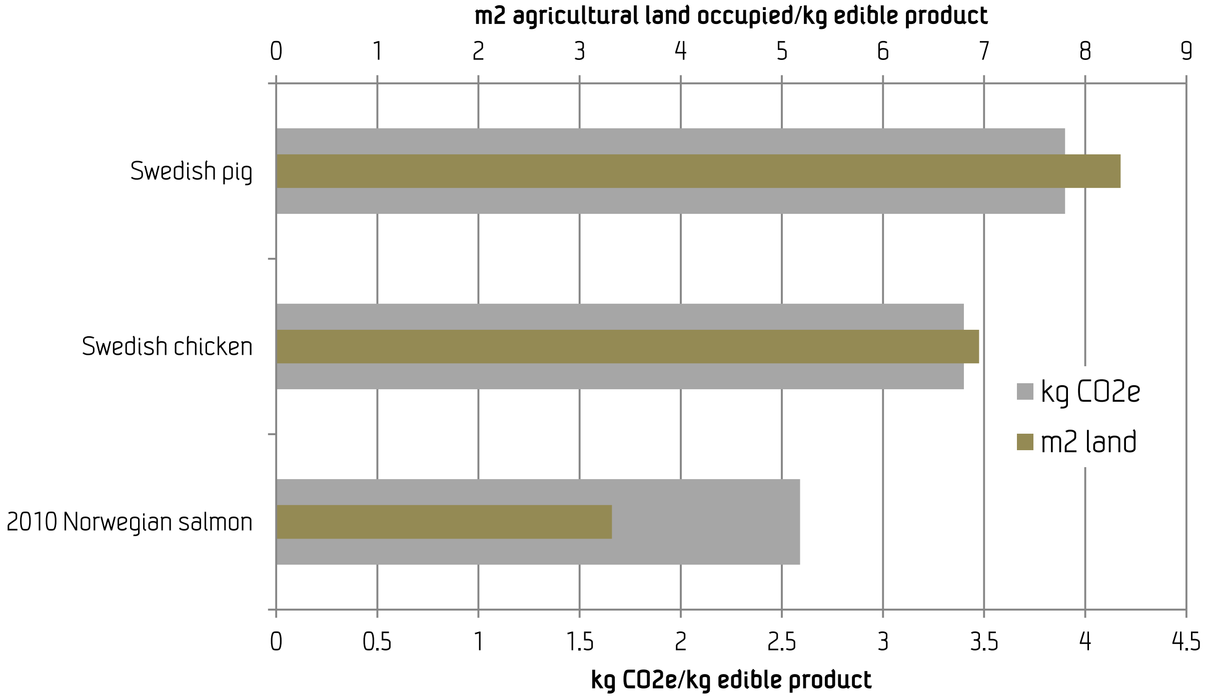


Figure 4-7 Carbon footprint and land occupation by Norwegian farmed salmon and Swedish pig and chicken

4.4 Energy use

Cumulative energy demand and carbon footprint

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

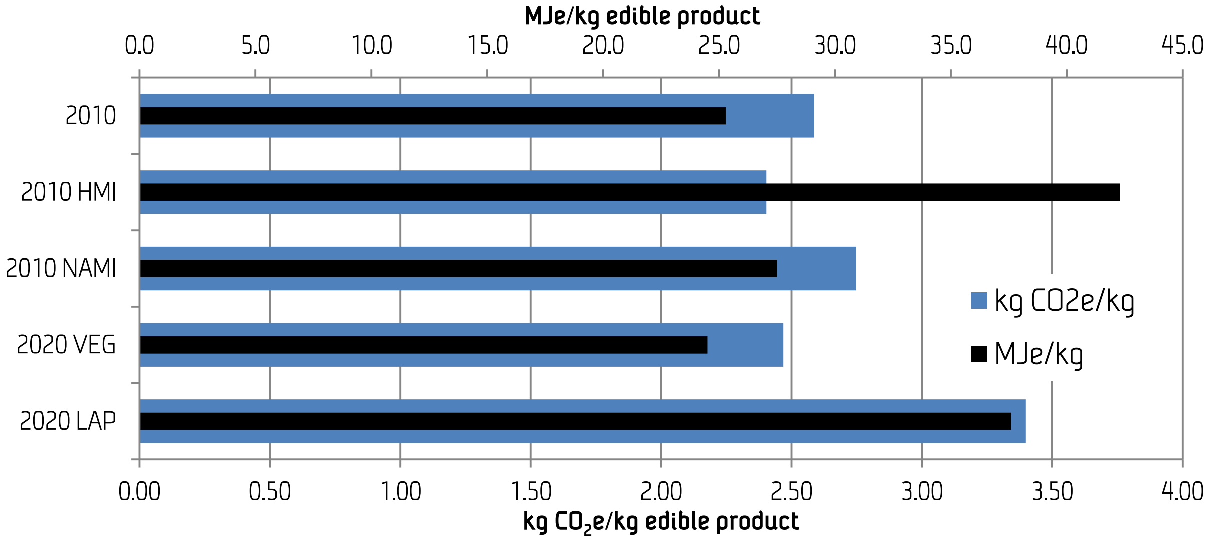


Figure 4-8 Cumulative energy demand and carbon footprint from the different diets

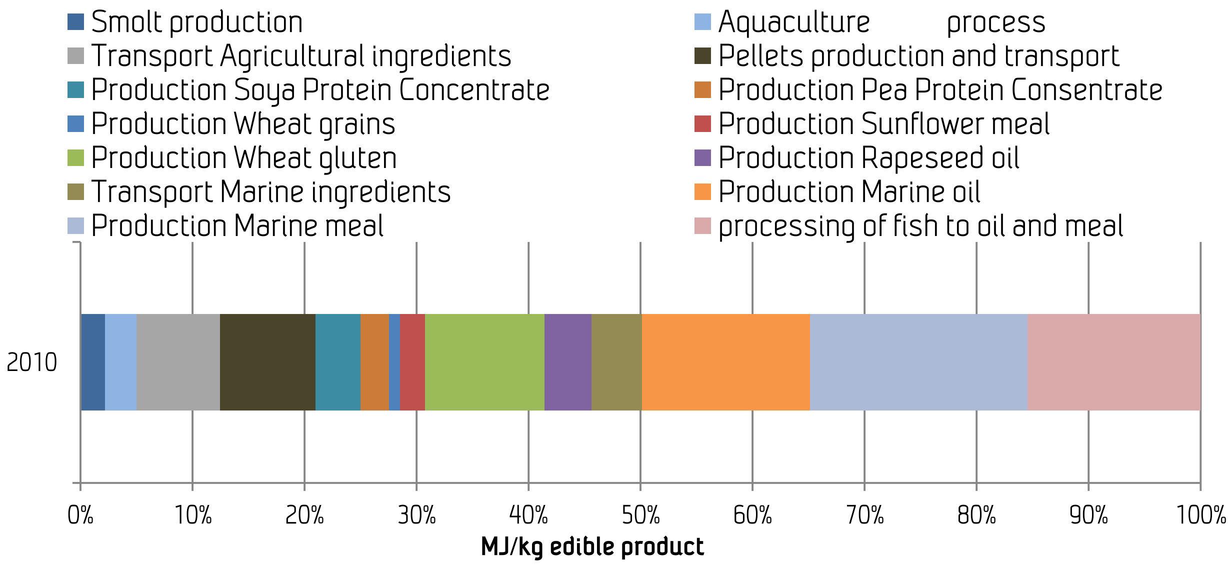


Figure 4-9 Contribution (in %) to total cumulative energy demand for 1 kilo edible salmon from the 2010 diet

Table 4-2 Results

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

NA = Not Available

5 Conclusions

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

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

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

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

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

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

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

6 References

BAUMANN, H. & TILLMAN, A. 2004. *The hitch hiker's guide to LCA: An orientation in life cycle assessment methodology and application.*, Sweden, Studentlitteratur.

CDP 2009. The Carbon Disclosure Project (CDP) http://www.cdproject.net/.

CEDERBERG, C., SONESSON, U., HENRIKSSON, M., SUND, V. & DAVIS, J. 2009. Greenhouse gas emissions from Swedish production of meat, milk and eggs 1990 and 2005. SIK – The Swedish Institute for food and Biotechnology, Göteborg, Sweden.

ELLINGSEN, H., EMANUELSSON, A., HOGNES, E. S., ZIEGLER, F. & WINTHER, U. 2009. Prosjektrapport: Energibruk og klimautslipp i eksport av norsk sjømat.

FHL 2010. Miljørapport - Tall og fakta fra norsk havbruksnæring.

FISHBASE.ORG. 2011. *www.fishbase.org/search.php* [Online]. Available: http://www.fishbase.org/search.php 20.10.2011].

FISKERIDIREKTORATET. 2008. *RE: Data from the 2007 Profitability survey on the Norwegian fishing fleet and sales statistics. Personal communication with: A. K. Stenseide at Fiskeridirektoratet.* Type to HOGNES, E. S.

FLYSJÖ, A., CEDERBERG, C. & STRID, I. 2008. LCA-databas för konventionella fodermedel - miljöpåverkan i samband med produktion Version 1 (SIK report No. 722). SIK Institutet för livsmedel och bioteknik.

FRISCHKNECHT, R., JUNGBLUTH, N. & ET.AL. 2003. Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000. Swiss Centre for LCI. Duebendorf, CH, www.ecoinvent.ch.

GERBER, P., VELLINGA, T., OPIO, C., HENDERSON, B. & STEINFELD, H. 2010. Greenhouse Gas Emissions from the Dairy Sector. A Life Cycle Assessment. Animal Production and Health Division,. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

IPCC 2007. Intergovernmental Panel on Climate Change, Fourth Assessment Report: The Physical Science Basis.

IRIBARREN, D., VÁZQUEZ-ROWE, I., HOSPIDO, A., MOREIRA, M. T. & FEIJOO, G. 2010. Estimation of the carbon footprint of the Galician fishing activity (NW Spain). *Science of The Total Environment*, 408**,** 5284-5294.

ISO 2006a. ISO 14040 Environmental management - life cycle assessment - principles and framework. ISO 14040:2006(E). International Organization for Standardization. Geneva. Switzerland.

ISO 2006b. ISO 14044 Environmental management - Life cycle assessment - Requirements and guidelines. ISO 14044:2006(E). International Organization for Standardization. Geneva. Switzerland.

JRC-IES 2010. International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance. First edition. *In:* SUSTAINABILITY, E. C.-J. R. C.-I. F. E. A. (ed.). Luxembourg.

LEIP, A., WEISS, F., WASSENAAR, T., PEREZ, I., FELLMANN, T. & LOUDJANI, P. 2010. Evaluation of the livestock sector's contribution to the EU greenhouse gas emissions (GGELS). Final report. Brussels, Belgium: Joint Research Centre (JRC), European Commission.

PAULY, D. & CHRISTENSEN, V. 1995. Primary production required to sustain global fisheries. *Nature*, 374: 255-257. [With erratum from 376: 279]

PELLETIER, N. & TYEDMERS, P. 2011. An Ecological Economic Critique of the Use of Market Information in Life Cycle Assessment Research. *Journal of Industrial Ecology*, 15**,** 342-354.

PELLETIER, N., TYEDMERS, P., SONESSON, U., SCHOLZ, A., ZIEGLER, F., FLYSJO, A., KRUSE, S., CANCINO, B. & SILVERMAN, H. 2009. Not All Salmon Are Created Equal: Life Cycle Assessment (LCA) of Global Salmon Farming Systems. *Environmental Science & Technology*, 43**,** 8730-8736.

PRÉ 2011. EcoInvent 2.2 Life Cycle Inventory (LCI) data. *In:* CENTRE, T. E. (ed.).

RECIPE. 2010. *the ReCiPe methodology for Life Cycle Assessment Impact Assessment* [Online]. Available: http://www.lcia-recipe.net/ [Accessed 21.10.2011.

RUTTAN, L. M. & TYEDMERS, P. H. 2007. Skippers, spotters and seiners: Analysis of the "skipper effect" in US menhaden (Brevoortia spp.) purse-seine fisheries. *Fisheries Research,* 83**,** 73-80.

SEAAROUNDUS.ORG. 2011. *Sea Around Us Project* [Online]. Available: http://www.seaaroundus.org/ [Accessed 20.10.2011 2011].

SIK-FEEDDATABASE-V2 2011. SIK feed database v2 - To be published in 2011 at www.sikfeed.se. *In:* BIOTEKNIK, S. I. F. L. O. (ed.). Gothenburg, Sweden.

SKRETTING 2010. Skretting Miljørapport (Social and Environmental Report). *In:* NORWAY, S. (ed.).

SVANES, E., VOLD, M. & HANSSEN, O. 2011. Effect of different allocation methods on LCA results of products from wild-caught fish and on the use of such results. *The International Journal of Life Cycle Assessment,* 16**,** 512-521.

TORRISSEN, O., OLSEN, R. E., TORESEN, R., HEMRE, G. I., TACON, A. G. J., ASCHE, F., HARDY, R. W. & LALL, S. 2011. Atlantic Salmon (Salmo salar): The “Super-Chicken” of the Sea? *Reviews in Fisheries Science,* 19**,** 257-278.

WINTHER, U., ZIEGLER, F., SKONTORP HOGNES, E., EMANUELSSON, A., SUND, V. & ELLINGSEN, H. 2009. Project report: Carbon footprint and energy use of Norwegian seafood products www.sintef.no/Fiskeri-og-Havbruk-AS/Prosjekter/2011/Miljoregnskap-og-klimasporing-av-sjomat/. Trondheim, Norrway: SINTEF Fisheries and aquaculture.

ISBN 978-82-7251-945-1 (printed)
ISBN 978-82-7251-946-8 (pdf)
ISSN 1890-579X