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Utilisation of feed resources in production of Atlantic salmon (*Salmo salar*) in Norway

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ABSTRACT

In 1990, 90% of the ingredients in Norwegian salmon feed were of marine origin, whereas in 2013 only around 30%. The contents of fish meal and fish oil in the salmon feed were 18% and 11%, respectively, in 2013. Between 2010 and 2013, salmon production in Norway increased by 30%, but due to a lower inclusion of marine ingredients in the diet, the total amount of marine ingredients used for salmon feed production was reduced from 544,000 to 466,000 tonnes. Norwegian salmon farming consumed 1.63 million tonnes of feed ingredients in 2012, containing close to 40 million GJ of energy, 580,000 tonnes of protein and 530,000 tonnes of lipid. 1.26 million tonnes of salmon was produced. Assuming an edible yield of 65%, 820,000 tonnes of salmon fillet, containing 9.44 million GJ, and 156,000 tonnes of protein were produced. The retentions of protein and energy in the edible product in 2012 were 27% and 24%, respectively. Of the 43,000 tonnes of EPA and DHA in the salmon feed in 2012, around 11,000 tonnes were retained in the edible part of salmon. The retentions of EPA and DHA were 46% in whole salmon and 26% in fillets, respectively. The *fish in/fish out ratio* (FIFO) measures the amount of fish meal and fish oil that is used to produce one weight equivalent of farmed fish back to wild fish weight equivalents, and the *forage fish dependency ratio* (FFDR) is the amount of wild caught fish used to produce the amount of fish meal and fish oil required to produce 1 kg of salmon. From 1990 to 2013, the forage fish dependency ratio for fish meal decreased from 4.4 to 0.7 in Norwegian salmon farming. However, weight-to-weight ratios such as FIFO and FFDR do not account for the different nutrient contents in the salmon product and in the forage fish used for fish meal and fish oil production. *Marine nutrient dependency ratios* express the amount of marine oil and protein required to produce 1 kg of salmon oil and protein. In 2013, 0.7 kg of marine protein was used to produce 1 kg of salmon protein, so the Norwegian farmed salmon is thus a net producer of marine protein.

Statement of relevance

This manuscript shows the retention efficiency of nutrients from feed resources to final product in the Norwegian salmon production, including limiting resources such as the omega-3 fatty acids EPA and DHA and phosphorous. It is highly relevant to compare the efficiency in commercial scale with experimental data, and this is to our knowledge the first attempt to make such calculations for an entire commercial aquaculture production.

1. Introduction

The world's population is currently increasing by 80 million each year, and is expected to reach 9 billion by the year 2050. The Food and Agricultural Organization of the United Nations (FAO) has predicted that 70% more food must be produced globally by 2050 to meet the increase in demand. 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 available resources. 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. This will have a large impact on the environment and the available resources of land area, fresh water, and phosphorus, and urgent action to develop food systems that use less energy and emit less greenhouse gases is required (FAO, 2011a). The global food sector is currently responsible for around 30% of the world's energy consumption and contributes more than 20% of the global greenhouse gas emissions (FAO, 2011b). In addition, land use changes, mainly through deforestation, contribute another 15% of greenhouse gas emissions.

Any method of food production can be evaluated in terms of the influence it has on the environment and how much natural resources are consumed in the process (Bartley et al., 2007; Kates et al., 2001; Singh et al., 2009). Eagle et al. (2004) defined *ecologically sustainable*

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food production as production that maintains the natural capital on which it depends, and that in principle can continue indefinitely. Well-managed fisheries where the catch is regulated based on stock assessment fulfil this definition. However, no industrial food production is truly sustainable today, because all such productions depend on non-renewable energy sources such as oil and gas, as well as non-renewable phosphorous sources. Industrial food productions may be evaluated in terms of energy produced in relation to the input of industrial energy (Tyedmers et al., 2007). When the sustainability of food productions is evaluated, the goal should be to maximise the nutritional output for human consumption and minimise the input of resources (organic and inorganic), with the lowest possible impact on the environment. The nutritional content of food products is easy to calculate, but it is more challenging to quantify the use of natural resources and to assess the environmental effects of different food production systems (Schau and Fet, 2008).

All food production has environmental consequences. Agriculture is the main source of water pollution by nitrates, phosphates and pesticides, and livestock production is a major source of greenhouse gases. Livestock production uses large amounts of fresh water and land areas. The global meat consumption is increasing by around 3.6% per year and has nearly doubled between 1980 and 2004. It is expected to double again by 2030 (FAO, 2011b). There is also a shift from extensive grazing systems to more intensive production systems that depend on more concentrated feeds and feed ingredients that are traded internationally. More than 30% of the world cereal production is currently used in feed for livestock. Global food production is also heavily dependent on the use of phosphorus fertilizer. The low phosphorous 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 many large countries such as Brazil and India. Phosphorus is thus essential for global food production, and agriculture consumed almost 90% of the P used in 2010, 82% was used in fertilizers and 7% was used in animal feed supplements (Schröder et al., 2009). However, the current use of phosphorus is not sustainable. Phosphorus is not recycled at present, but moves through an open one-way system in which the phosphorus ends up in the ocean. A meat-rich diet consumes three times as much P as a vegetarian diet, and for a world population of 7.7 billion people, a 20% increase in phosphorous-fertilizer would be required without changes in the world diet, whereas a 64% would be required if the complete world population were to have a diet that resembles the diet in developed countries (Smit et al., 2009).

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, 2012). The rapid growth in the aquaculture industry has raised concerns among consumers, retailers and non-governmental organisations about the environmental impact and sustainability of fish farming. The dependence of the aquaculture feed industry on fish meal and fish oil and the consequences for wild fish stocks are often used as arguments against the sustainability of salmon production (Deutch et al., 2007; Naylor et al., 2000; Tacon and Metian, 2008). Forage fish are often small pelagic fish at lower trophic levels that are important prey for species higher up in the food chain (Fréon et al., 2005). The majority of the world's fish resources are fully exploited or overexploited (FAO, 2012). A further growth in aquaculture must therefore rely on an increase in the use of alternative sources of lipid and protein. There is, however, still a potential for an increased utilisation of discards and by-products from the processing of fishery products for human consumption. Approximately 25% of the fish meal produced worldwide originates from trimmings, but the potential is larger, considering that around 120 million tonnes of fish are consumed by humans. If the edible portion is around 50%, there are roughly 60 million tonnes of trimmings and by-products available for the production of fish oil and fish meal. This is three times the amount of forage fish used for this purpose today. Improved regulation and management of the capture fisheries are necessary for a sustainable and optimal utilisation of the marine production systems.

Farming of Atlantic salmon has been seen as negative due to the use of small pelagic fish in the feed, and it has been claimed that salmon farming reduces the amount of marine protein available for human consumption (Naylor and Burke, 2005; Naylor et al., 2000, 2009). In common with all food production, aquaculture has environmental consequences, and feed production is a major input factor in salmon production (Ellingsen et al., 2009; Pelletier et al., 2009). An understanding of the environmental impact of different feed formulations and how they affect resource utilisation is thus important for making strategic decisions about food production regimes (Åsgård and Austreng, 1995; Åsgård and Hillestad, 1998; Åsgård et al., 1999; Einen et al., 1995; Torrissen et al., 2011). Several indicators and methods for measuring the sustainability and production-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 nutrient retention and nutrient flow models (Einen et al., 1995; Papatryphon et al., 2005; Roque d'Orbcastel et al., 2008). More extensive methods such as the ecological footprint model and life cycle analysis (LCA) are also used to assess the sustainability of aquaculture and other food production systems. These methods are complementary and cover different aspects of biophysical performance and resource efficiency. Evaluating the sustainability of food production methods is complicated, and many aspects must be addressed. 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 to evaluate eco-efficiency and sustainability.

2. Methods

Nutrient flow analysis can provide information about the environmental impact of food-producing activities and the efficiency of resource utilisation. The efficiency of a production method is affected by many factors, such as feeding routines and diet composition. The efficiency can also be improved by selective breeding for improved performance (Gjedrem, 2010; Grisdale-Helland et al., 2013; Thodesen et al., 1999). The conversion of feed to edible product determines the amount of biological material that is released to the surrounding environment. The *feed conversion ratio* (FCR) is the amount of feed (in kilograms) required to produce 1 kg of farmed animal (round weight). The *biological feed conversion ratio* is based on the feed eaten, whereas the *economic feed conversion ratio* (eFCR) includes also production losses (uneaten feed, mortalities, escapees), and is therefore higher than the biological FCR. The assimilation efficiency of nutrients is also crucial for the waste output — both the amount of nutrients digested and the amount of the digested nutrients that are retained in the fish. A high feed intake and an optimal energy/protein ratio are necessary for obtaining maximum growth and feed utilisation, as is also satisfying the requirements for essential amino acids, fatty acids and minerals. The retention efficiency of nutrients is normally calculated as a percentage of the amount eaten. The ratio of the total industrial energy invested in food production to the edible protein energy return has been used as a measure of the energy efficiency of food-production systems, and has been suggested also as a sustainability indicator (Troell et al., 2004). However, the energy produced in the form of fat should also be accounted for, because not only protein, but also lipid is produced and contributes to the energy output of the food production methods. An alternative is to use input and output ratios for protein, lipid and energy to assess the efficiency of food production methods.

Nutrient flow models were used to estimate the nutrient retention efficiency in Norwegian salmon production in 2012. Representative data for the nutrient content of the feed, salmon fillets and the parts of the salmon that are not utilised for human consumption must be available in order to track the nutrient flows in a resource budget for salmon. The Norwegian aquaculture industry is required to report detailed production data to public databases, and those were used to obtain information on production volumes and feed consumption (http://www.fiskeridir.no/statistikk/akvakultur/). Information about the ingredients used for feed production in 2012 and 2013 was provided by BioMar, EWOS and Skretting. These three companies have a market share of 90% of salmon feed in Norway. The nutrient compositions of some ingredients were provided by the feed manufacturers, while assumptions about the compositions of other ingredients were based on literature values. Lerøy Seafood provided data about the nutrient content in salmon that had been fed commercial feeds from the three feed companies in a benchmark trial in 2012. The salmon were around 5 kg when harvested at the beginning of September. The feeding trial and analysis of fish were performed by Nofima. The fillets and whole fish were homogenised and analysed for dry matter (DM, 105 °C, 16–18 h), crude protein (N × 6.25; semi-micro-Kjeldahl, Kjeltec-Auto System, Tecator, Höganäs, Sweden), crude lipid (diethyl ether extraction in a Fosstec analyser (Tecator, Höganäs, Sweden) after HCl-hydrolysis). Gross energy was analysed by adiabatic bomb calorimetry (Parr 1271 Bomb calorimeter, Parr, Moline IL, USA). The concentration of phosphorous was measured by inductively coupled plasma–optical-emission spectrometry (ICP–OES, Vista-PRO-radial, Varian Inc., USA) by Eurofins. The concentrations of EPA and DHA were analysed by gas chromatography after trans-methylation of the fatty acids (Hewlett Packard 6890) with a split injector, (SGE BPX70 capillary column flame ionisation detector). Helium was the carrier gas. The chemical compositions of whole salmon and fillets were used to calculate the retention of protein, lipid, energy, phosphorous, and EPA and DHA. The FIFO ratio and the marine protein and marine oil dependency ratios were used to quantify the use of marine resources in Norwegian salmon production between 1990 and 2013. Information about the species that were used in the production of fish oil and fish meal was also obtained from the three feed companies mentioned above.

2.1. The fish in/fish out ratio (FIFO) and forage fish dependency ratio (FFDR)

The fish in/fish out ratio expresses the amount of fish meal and fish oil that is used to produce one weight equivalent of farmed fish back to wild fish weight equivalents (usually a kilogram or tonne), and is often used as a measure of the amount of marine resources that are 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, the forage fish is condensed to 10% water and 90% dry matter in the meal and 100% dry matter in the oil. On average, 1 kg of forage fish is turned into 225 g of fish meal and 50–100 g of fish oil (IFFO, 2010). Improvements in production technology have increased the protein recovery from whole fish, and the latest yield figures from the industry range from 23.5 to 24.5% fish meal from whole fish (Jackson, 2009; Péron et al., 2010). However, the oil yields vary with the fat content in different species, and within species during the year, and this will have a large influence on the FIFO ratio. Doubling the oil yield from the forage fish will reduce the FIFO ratio for fish oil by half. Thus, using herring and capelin, which have high fat contents, 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. The second conversion ratio is the amount of feed (in kilograms) consumed to produce 1 kg of salmon (economic feed conversion ratio, eFCR). Thus, the FIFO is calculated separately for fish oil and fish meal according to the equation:

$$\mathrm{FIFO}_{(\mathrm{FM\ or\ FO})} = \left[\frac{\mathrm{FM\ or\ FO\ (g/kg)\ in\ the\ diet}}{\mathrm{FM\ or\ FO\ reduction\ efficiency\ (g/kg)}}\right] \cdot \mathrm{eFCR}. \tag{1}$$

The forage fish dependency ratios for fish meal and fish oil express the quantity of forage fish required to produce the amount of fish meal and fish oil used to produce one unit of farmed salmon. The Aquaculture Stewardship Council (ASC) has included the forage fish dependency ratios for fish meal and fish oil as two of its indicators of performance. These ratios express the quantity of forage fish required to produce the amount of fish meal and fish oil used to produce one unit of farmed fish. Fish meal and fish oil that originate from trimmings are excluded from the calculation as long as they do not originate from species that are listed as endangered or vulnerable in the International Union for Conservation of Nature (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% yield of fish oil for fish originating from the North Atlantic. The forage fish dependency ratios are calculated from Eqs. (2) and (3) according to the ASC standards. A weighted mean for oil yield was used, based on the origin of the fish oil. If such information was not available, a yield of 5% was assumed.

$$\mathrm{FFDR}_{\mathrm{FM}} = \frac{(\%\ \mathrm{of\ fish\ meal\ in\ feed\ from\ forage\ fisheries}) \cdot \mathrm{eFCR}}{\mathrm{Meal\ yield\ (24\%)}} \tag{2}$$

$$\mathrm{FFDR}_{\mathrm{FO}} = \frac{(\%\ \mathrm{of\ fish\ oil\ in\ feed\ from\ forage\ fisheries}) \cdot \mathrm{eFCR}}{\mathrm{Oil\ yield\ (5\ or\ 7\%).}} \tag{3}$$

The ASC standards for $\mathrm{FFDR}_{\mathrm{FM}}$ and $\mathrm{FFDR}_{\mathrm{FO}}$ are <1.35 and <2.95, respectively (http://www.asc-aqua.org/).

2.2. Marine nutrient dependency ratios (MNDR)

The amounts of marine protein and marine oil resources consumed relative to the amounts produced in aquaculture can be expressed more accurately by calculating nutrient-to-nutrient ratios in fed fish and the product. Crampton et al. (2010) suggested a *marine nutrient dependency ratio* (MNDR) as an alternative to the FIFO ratio. The MNDR is the ratio of each marine-derived nutrient used to feed salmon to the amount of each marine nutrient produced as a result of salmon farming (Crampton et al., 2010). MNDR thus accounts for the difference in nutrient concentration in the forage fish and in the salmon product. Feed protein sources and oils from all capture fish, shellfish or zooplankton are classified as marine sources. The fat in fish meal and other marine sources is included in the budget for marine oils. The marine protein dependency ratio (MPDR) and the marine oil dependency ratio (MODR) are calculated as:

$$\mathrm{MPDR} = \frac{(\%\ \mathrm{of\ MP\ in\ feed}) \cdot (\%\ \mathrm{of\ protein\ in\ MP}) \cdot (\mathrm{kg\ of\ feed\ eaten})}{(\mathrm{final\ bodyweight} \cdot \%\ \mathrm{of\ body\ protein}) - (\mathrm{initial\ bodyweight} \cdot \%\ \mathrm{of\ body\ protein})}$$

$$\mathrm{MODR} = \frac{[\%\ \mathrm{of\ MO\ in\ feed} + (\%\ \mathrm{of\ MP\ in\ feed} \cdot \%\ \mathrm{of\ fat\ in\ MP})] \cdot (\mathrm{kg\ of\ feed\ eaten})}{(\mathrm{final\ bodyweight} \cdot \%\ \mathrm{body\ fat}) - (\mathrm{initial\ bodyweight} \cdot \%\ \mathrm{body\ fat})}$$

where MP is the marine protein source (e.g. fish meal) in the feed and MO is the marine oil source.

2.3. Nutrient retention efficiency

Nutrient-to-nutrient ratios are often used to evaluate the efficiency of food production systems. Such conversion efficiency ratios are a measure of the proportion of the dietary nutrients and energy that is retained in the animal product. These calculations are commonly given for a specific study or a single production batch. However, for the evaluation of the sustainability of an entire food production industry, all relevant data must be available. Norwegian aquaculture has a mandatory system for reporting detailed 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 producing companies, have been used to calculate the nutrient flow in Norwegian salmon production in 2012.

The amounts (%) of nutrients and energy from the feed that were retained in the animal (whole body or edible part) product were calculated from:

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

65% of the whole salmon was considered to be edible (The Norwegian Food Consumption table).

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

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

Corresponding parameters can be calculated for lipids, the lipid efficiency ratio (LER), and for energy, the energy efficiency ratio (EER). The lipid deposited may, however, originate from lipid, protein or carbohydrates in the feed.

3. Results and discussion

3.1. Overview of feed resources used and diet composition

Feed composition has changed considerably during the relatively short history of intensive salmon farming. In 1990 and earlier, around 90% of the feed was composed of ingredients of marine origin, whereas less than 30% of the diet was of marine origin in 2013 (Fig. 1). The limited supply of fish meal and fish oil makes this shift from marine to plant ingredients necessary to be able to produce increasing amounts of salmon. However, this shift may also affect how efficiently the raw materials in the feed are converted into edible product.

In 2012, the three major feed companies in Norway, BioMar, Ewos and Skretting, used around 1,630,000 tonnes of ingredients to produce salmon feed in Norway. Of these, 485,000 tonnes (31%) were of marine origin and 1,080,000 (66%) were derived from plants. Of the total diet, 37% came from plant protein sources, mainly soy protein concentrate, followed by sunflower expeller and wheat gluten (Table 1). Rapeseed oil was the only plant oil used in the salmon diet in 2012. The starch fraction was mainly wheat, with minor amounts of pea and tapioca.

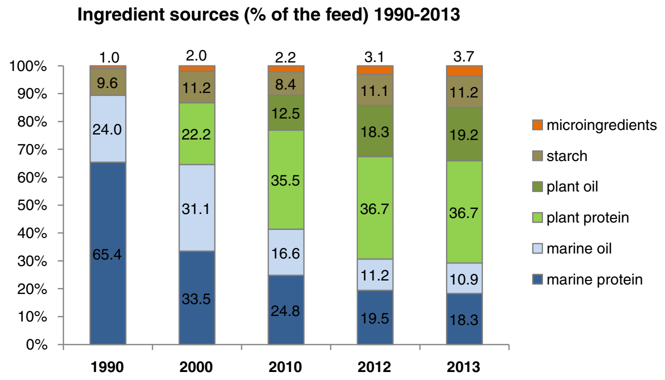

Fig. 1. Nutrient sources in Norwegian salmon farming from 1990 to 2013. Each ingredient type is shown as its percentage of the total diet.

Microingredients accounted for 3.1% of the total ingredients in 2012 and 3.7% in 2013.

The level of marine ingredients in Norwegian salmon feed was reduced from 41% to 31% of the diet between 2010 and 2012, while there was only a minor reduction in the use of marine ingredients between 2012 and 2013. In total, the Norwegian salmon feed industry used 317,000 tonnes of fish meal and 183,000 tonnes of fish oil in 2012 (Fig. 2), which amounted to 6% and 22%, respectively, of the global production of fish meal and fish oil in 2012. Around 30% of the fish meal and 22% of the fish oil used in 2012 came from fish silage and trimmings. Fish meal and fish oil from forage fisheries made up 19.5% and 12.5%, respectively, of the total ingredients in the salmon diet in 2010. These numbers were reduced to 13.5% and 7.9% of the diet in 2013. The origin of the marine ingredients in the salmon feed changes according to price and availability. In 2010, 52% of the fish oil and 47% of the fish meal from forage fish was of North Atlantic origin. Since then, the proportion of fish meal and fish oil from South America has increased, and in 2012 only 35% of the fish meal and 29% of the fish oil from forage fish came from the North Atlantic, whereas 44% of fish oil and 34% of fish meal came from South America. Practically all of the fish meal and fish oil from South America were produced from Peruvian anchoveta (*Engraulis ringens*). Peruvian anchoveta accounted for 37% of the marine ingredients used in Norwegian salmon feed in 2012. Capelin (*Mallotus villosus*) and sprat (*Sprattus sprattus*) were the dominating species from the North Atlantic, accounting for 15% and 10%, respectively, of the marine ingredients. All of the by-product fish meal and fish oil originated from the North Atlantic. The by-product fish meal and fish oil originated mainly from herring (*Clupea harengus*) trimmings (73%), with small amounts of trimmings from capelin, mackerel (*Scomber scombrus*) cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*).

Table 2 shows the nutrients used in Norwegian salmon production in 2012 and the average composition of Norwegian aquaculture feed in 2012. The average composition of Norwegian feed has been calculated from data provided by the three largest Norwegian feed companies (BioMar, EWOS and Skretting) and reflects their use of feed ingredients for aquaculture feed in 2012, as well as the chemical composition of each feed ingredient. Of the 1,585,000 tonnes of feed used in 2012 in Norwegian aquaculture, 1,452,000 tonnes, or 92%, was fed to Atlantic salmon (Akvafakta, 2014). The three feed companies that have provided the feed ingredient data have a market share of approximately 90% (Nordic Innovation). The total amounts of nutrients used for salmon production in Norway in 2012 (Table 2) can be estimated by multiplying the average feed composition by the total amount of salmon feed used in 2012 (Akvafakta, 2014). Microingredients, such as crystalline amino acids, pigments, vitamins and mineral mixes, are not included. The average dry matter content of feed ingredients was 94%, and the same dry matter content was assumed for the feeds, since no data were available. The dry matter content of feeds is normally close to this value. Furthermore, not all ingredients have been analysed, so the nutrient composition is partly based on estimated values. Thus, the precision of the data is not as high as in controlled studies. The data include all losses, discarded feed batches, and failed productions, and thus represent the total use of nutrients in Norwegian salmon farming industry in 2012. To our knowledge, such a detailed and complete dataset is not available for any other feed and meat production method. In order to assess the sustainability of food production, however, similar data should be provided by other food production industries in Norway and other countries.

3.2. Nutrient flow in Norwegian salmon production

In 2012, 1,232,094 tonnes of salmon was harvested in Norway (Statistics Norway, 2013). The weight of salmon produced that year has been calculated as the difference in biomass between 31 December 2012 and 31 December 2011 (29,000 tonnes). Thus, the total production in 2012 was estimated to be 1,261,000 tonnes. The 1,452,000 tonnes of

Table 1
Feed ingredients used in Norwegian salmon feed in 2012. Data are reported by EWOS, BioMar and Skretting.

		Feed ingredient	Total amount used (tonnes)	% inclusion (of total diet)
Plant ingredients	Protein sources	Soy protein concentrate	346,730	21.3
		Sunflower expeller	97,354	6.0
		Wheat gluten	97,137	5.8
		Fava beans	30,753	1.9
		Pea protein	12,936	0.8
		Maize gluten	12,509	0.8
		Horse beans	4442	0.3
	Oil sources	Rapeseed oil	298,991	18.3
	Starch sources	Wheat	161,432	9.9
		Pea	16,466	1.0
		Tapioca	3396	0.2
Marine ingredients	Protein sources	Fish meal	317,241	19.5
	Oil	Fish oil	182,579	11.2
Microingredients		Pigments, vitamins, minerals, amino acids	50,715	3.1

feed registered for production of this volume equals an estimated economic feed conversion factor of 1.15. Table 3 shows the composition of whole body and fillets of Atlantic salmon, and the total amount of nutrients in the whole body, edible part and trimmings of farmed salmon produced in Norway in 2012. The fillet yield depends on several factors, here 65% of the salmon is considered as edible product (The Norwegian Food Consumption Table). This represents a high fillet yield, and the actual amount of nutrients in fillets may be somewhat lower than the calculated figures. If this is the case, the amount of nutrients in trimmings will be higher. In total, 820,000 tonnes of salmon fillets, containing 9.45 million GJ, and 156,000 tonnes of protein for human consumption were produced in 2012. The 441,000 tonnes of trimmings contained an estimated amount of 6.4 million GJ, 118,000 tonnes of lipid and 8700 tonnes of EPA and DHA. Around 90% of the trimmings from the salmon industry is utilised for different purposes (only blood from the slaughter process is not utilised). Around 10% of the trimmings is exported for human consumption (heads, backs), around 8% is utilised for health products and pharmaceuticals such as omega-3 additives. The majority of the offal is used to produce feed ingredients such as oil and meal, protein concentrates (23%) and ensilage (40%). This is used in other animal productions, and for fur animal production (Olafsen et al., 2014).

Fig. 3 shows the contents of fat, protein, energy and phosphorous in the 2012 salmon. The nutrient content was comparable to that reported in a previous study in 2010 (Ytrestøyl et al., 2011), except for a reduction in EPA and DHA content in both whole body and fillets due to the reduction in marine ingredients in the diet between 2010 and 2012. Concern has been expressed that the decreasing level of EPA and DHA in farmed salmon may reduce the health benefits of consuming salmon. The European Food Safety Authority (EFSA) recommends a daily intake of 0.25 g EPA and DHA for healthy adults, to prevent cardiovascular disease. The Norwegian farmed salmon in 2012 contained 1.36 g EPA + DHA per 100 g of fillet. According to the EFSA recommendations, 130 g of Norwegian farmed salmon per week is sufficient to supply the recommended intake of EPA and DHA for healthy adults. The 11,000 tonnes of EPA and DHA in the salmon fillets produced in Norway in 2012 would cover the recommended intake for around 120 million people for one year.

3.3. Nutrient retention efficiency

The retention data given in Table 4 include all losses of feed and feed ingredients, all loss of fish (mortality and escapees), and poor and failed production runs of both feed and salmon. Thus, the data show the retention of the total amount of nutrients in the entire Norwegian salmon production in 2012. Consequently, these retention data cannot be compared to data from controlled, single production runs of salmon or other species, which are often reported in the literature. 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 a constant production of salmon over a few years, since the production cycle of salmon is more than one year. It should also be noted that the retention values given for lipid, EPA and DHA include the salmon's production of these nutrients. Since lipids can be produced from carbohydrates and amino acids, 'retention' of lipids is an approximate term. For simplicity, however, the term is used here, since it shows the net flow of these nutrients from feed to salmon fillets. The retentions of protein and lipid are sometimes referred to as the *protein productive value* (PPV) and the *lipid productive value* (LPV), respectively. Carbohydrates are not included in the overview of the nutrient flow, partly due to lack of data from analyses, and because the content of glycogen is very low in fish (~1%). Most of the carbohydrates from feed will end up either as part of the lipid fraction or as energy not retained. It should be noted, however, that the increased use of protein ingredients of plant origin, which contain indigestible carbohydrates, reduces the energy retention compared to the previously used fish meal-based feeds.

3.4. Retention of protein, lipid and energy

Table 4 shows that 24% of the energy and 27% of the protein (nitrogen) in the feed ingredients used in Norwegian salmon farming in 2012 was incorporated into the edible part of salmon. 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). However, the potential in salmon may be considerably higher (Grisdale-Helland et al., 2013). It is difficult to find comparable data for other animal production methods. Austreng (1994), Åsgård and Austreng (1995), Åsgård and Hillestad (1998) and Bjørkli (2002) have compared the retention of protein and energy in

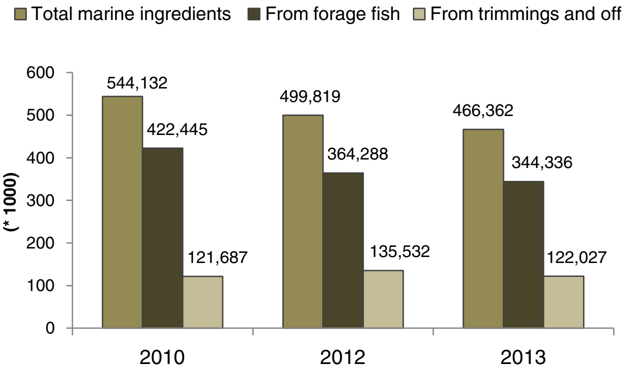

Fig. 2. Use of marine ingredients in Norwegian salmon feed from 2010 to 2013 (in tonnes).

Table 2
Estimated average feed composition and the total amount of nutrients and energy used in Norwegian salmon feed in 2012.

	Average composition of Norwegian salmon feed in 2012 (% or MJ/kg) [a]	Total amount of nutrients used in Norwegian salmon feed 2012 (tonnes or GJ) [b]	Nutrients from marine ingredients (tonnes or GJ) [c]	Nutrients from plant ingredients (tonnes or GJ) [d]
Dry matter	93.8	1,528,961	469,233	1,009,013
Energy	24.5	39,930,108	13,519,644	26,365,196
Protein (N × 6.25)	35.5	578,994	212,469	364,615
Lipid	32.5	529,904	212,940	316,964
EPA	1.5	24,903	24,903	0
DHA	1.1	18,106	18,106	0
Phosphorus	0.9	15,011	6747	4645

Average dry matter content in feed ingredients was 93.4%, and the same average dry matter content was assumed for feed.

[a] Calculated from all ingredients used in 2012 and their chemical composition, reported by the three largest Norwegian feed companies (BioMar, Ewos and Skretting).

[b] Calculated from average composition and the total of 1,451,908 tonnes of feeds used in 2012 (Akvafakta, http://akvafakta.fhl.no/fhl_statistikk/SRL/2013/Akvafakta%2013-01.pdf).

[c] Fraction of nutrient of marine origin in the feed ingredients multiplied by the total amount of nutrient used in feed in 2012.

[d] Fraction of nutrient of plant origin in the feed ingredients multiplied by the total amount of nutrient used in feed in 2012.

Atlantic salmon, chicken and pig. Bjørkli found similar energy retention (23%) in salmon fillets as we found in the present study, whereas the protein retention was slightly higher (31%). The data from Bjørkli were calculated by a slightly different method than what was used in the present study (the cost of production of fry, chicken and piglets are included in Bjørkli's calculations). However, Bjørkli's calculations are the same for all three species, and can be used to compare the different animal productions to each other. According to Bjørkli, the protein retention in the edible parts of chicken and pig were 21% and 18%, respectively, whereas the energy retention was 12% and 14%.

The concept of retention has been used above for nutrient ratios, but it is also used as a collective term for any calculation of efficiency ratio of energy or nutrient utilisation from feed into food product. Examples are protein and energy efficiency ratios. Producing 1,261,000 tonnes of salmon from 579,000 tonnes of protein (N × 6.25) results in a PER value of 2.2 for Norwegian farmed salmon in 2012 (Fig. 4). Using the same calculation for the 820,000 tonnes of the edible parts of salmon produced, the PER value for salmon in 2012 was 1.4. The energy efficiency ratio (EER) in whole salmon in 2012 was 3.2, while it was 2.1 in the edible parts. For whole salmon and salmon fillets, the lipid efficiency ratio (LER) was 2.4 and 1.5 in 2012. There were only minor differences between 2010 and 2012 for these ratios. These calculations of PER, LER and EER cannot, as the retention data, be compared to values obtained for single production units or in controlled experimental studies. The PER, LER and EER do not consider differences in body composition between species and are therefore not good measures of production efficiency. Besides, retention values, PER, LER and EER are expressions of total protein and lipid retention, and do not distinguish between feed ingredients of different origins, such as marine or vegetable ingredients, or offal. The origin of the feed ingredients and how they are produced are important aspects of sustainability that must be addressed using other indicators and methods, such as life cycle assessment (LCA) or indicators of marine ingredient use.

The high content of long-chain polyunsaturated fatty acids is often promoted as the most important health benefits of consuming Atlantic salmon, but the protein in the fish is also beneficial for human health (Bergeron and Jacques, 1989; It-Yahia et al., 2003; Liaset et al., 2009; Wergedahl et al., 2004). A general increase in fish consumption is recommended in Norway, although no specific recommendations on intake have been given (Anonymous, 2010). The 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% (salmon farmed, raw; FCT 2014) and of 18.6% in chicken (whole chicken with skin included; The Norwegian food consumption table 2014), 63 g of protein corresponds to 317 g of salmon fillet or 339 g of chicken. The edible fractions of both salmon and chicken with skin are 65% (FCT, 2006), resulting in 487 g salmon or 521 g chicken (live weight) produced to yield 63 g protein.

Sufficient protein production for the world's growing population is a global 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 methods is an important factor when assessing their 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 those fed feeds in which up to 80% of the fish meal and 70% of the fish oil had been replaced by plant 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 were 2.80, 3.03 and 2.81 (Torstensen et al., 2008). Bendiksen et al. (2011) found no significant differences in PER

Table 3
Composition of whole body and edible part of Atlantic salmon, and total amount of nutrients and energy in the whole body, edible part and trimmings of Atlantic salmon produced in Norway in 2012. Calculations of the three latter are based on a total amount of 1 260 841 tonnes of salmon produced in Norway in 2012 of which 65% is considered edible (FCT, 2006) resulting in 819 546 tonnes of salmon for human consumption.

	Whole body composition a) (% or MJ/kg)	Composition of salmon fillet b) (% or MJ/kg)	Total nutrients in whole body of salmon c) (tonnes or GJ)	Total nutrients in edible part of salmon d) (tonnes or GJ)	Amount of nutrients in trimmings e) (tonnes or GJ)
Dry matter	41.2	38.3	519,466	314,050	205,416
Energy	12.6	11.5	15,886,592	9,449,370	6,437,222
Protein (N × 6.25)	17.5	19.1	220,647	156,226	64,421
Lipid	21.3	18.4	268,559	150,797	117,763
EPA	0.60	0.52	7520	4222	3297
DHA	0.98	0.85	12,354	6937	5417
EPA + DHA	1.58	1.36	19,873	11,159	8714
Phosphorus	0.35	0.25	4357	2012	2345

a) Mean values of salmon (5 kg) fed 3 different commercial diets. Data from Lerøy, not published.

b) Mean values of NQC of salmon (5 kg) fed 3 different commercial diets. Data from Lerøy, not published.

c) Data for whole body composition multiplied by total salmon production in 2012 (1,260,841 tonnes).

d) Data for fillet composition multiplied by total salmon fillet production in 2012 (819,546 tonnes fillet).

e) Nutrients in total salmon produced minus nutrients in edible part produced in 2012.

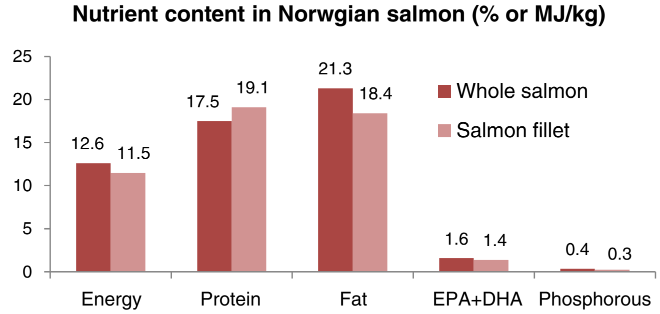

Fig. 3. Nutrient content in whole salmon and fillets produced in Norway in 2012. Energy content is given in MJ/kg, other nutrients as their percentage of total nutrient content.

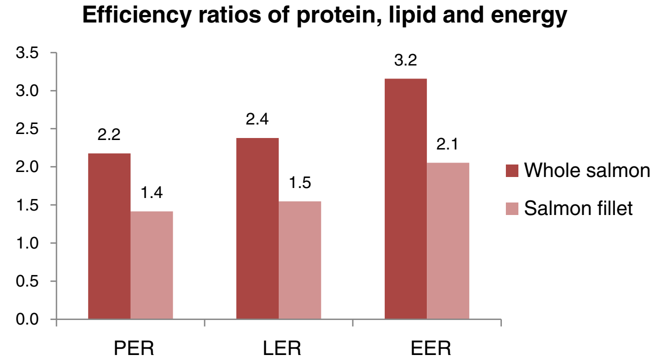

Fig. 4. Nutrient productive values in fillets and whole salmon produced in Norway in 2012. PER = protein efficiency ratio, LER = lipid efficiency ratio, and EER = energy efficiency ratio.

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. However, Leyton et al. (2009) found a small reduction in PER (8.5%) when the fish meal fraction was reduced from 36% to 5% of the diet. These studies show that Atlantic salmon can be produced with feeds containing high levels of ingredients of plant origin, and only low amounts of marine ingredients. However, the sustainability of replacing marine ingredients (fish meal and fish oil) by plant ingredients must be thoroughly assessed, since the production of plant ingredients requires water, fertilizers, phosphorus, pesticides, land area and transportation. It contributes also 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.

Fish generally convert feed energy to bodyweight more efficiently than warm-blooded animals. Homeotherms have a lower production efficiency than poikilotherms, due to their high maintenance and respiratory costs. On average, only 2% of the energy consumed is used for biomass production in homeotherms, whereas poikilotherms convert 17% of the energy consumed to biomass (Smith, 1992). However, the potential is much higher; in cultured Atlantic salmon more than 50% of the energy consumed was retained in the salmon (Grisdale-Helland et al., 2013). Aquatic animals have some advantages over land 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, which excrete urea or uric acid. The buoyancy of aquatic animals in water also saves energy and reduces the need for a heavy skeleton, thus increasing the edible portion of the aquatic animals compared to terrestrial animals. The cultured production of animals generally improves the energy conversion, since food is more readily available. This results in a higher feed intake and a reduction in activity, which increases growth and the 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 production methods. The total amounts of resources that are utilised in the production and the waste that is generated must also be considered. A nutrient-dense and energy-dense feed is more costly to produce in terms of the use of resources and the consumption of energy than a low-energy feed, and in industrial food production the production of feed has a major impact on the demands for energy and resources.

Table 4
The amount of nutrients and energy in the feed ingredients that was retained (% of in feed ingredients) in whole salmon, edible part (fillet) and in trimmings, in Norwegian salmon production in 2012.

	Retention in whole body of salmon	Retention in edible part of salmon	Retention in trimmings [a]	Not retained—loss [b]
Energy	40	24	16	60
Protein (N × 6.25)	38	27	11	62
Lipid [c]	51	28	22	49
EPA[c]	30	17	13	70
DHA[c]	68	38	30	32
EPA + DHA [c]	46	26	20	54
Phosphorus	29	13	16	71

[a] Retention in whole body (%)—retention in edible part (%).
[b] 100 (%)—retention in whole body (%).
[c] Includes lipids produced from non-lipid precursors.

3.5. Retention of omega-3 fatty acids and phosphorous

EPA and DHA are nutritionally important for humans, and salmon is an important source of these fatty acids in Norway. From a consumer perspective, the concentration of EPA and DHA in salmon is important. Marine ingredients were the only sources of EPA and DHA in Norwegian salmon feed in 2012, and since fish meal and fish oil are limited resources, both the retention of EPA and DHA and the utilisation of these from trimmings and by-products are important aspects. Table 2 shows that 25,000 and 18,000 tonnes of EPA and DHA, respectively, were used in Norwegian salmon feed in 2012. In whole salmon, 46% of these omega-3 fatty acids was retained, and in fillets 26%. Of the amount in the feed ingredients, 20% was retained in trimmings, whereas 54% of EPA and DHA was not retained (Table 4). These retention values include the salmon's production of EPA and DHA. The retention of DHA was higher than the retention of EPA both in whole salmon and in fillets, 70% of the EPA and 32% of the DHA in the feed ingredients were not retained in the salmon. The retention of DHA was also higher than the retention of EPA in all body compartments (Table 4), perhaps reflecting the elongation of EPA to DHA (Turchini et al., 2010). The retentions of EPA and DHA were lower in 2012 than in 2010, both in whole salmon and in fillets (Ytrestøyl et al., 2011). The sources of fish oil in the salmon feed changed between 2010 and 2012. In 2010, 75% of the fish oil in the diet came from the North Atlantic, whereas in 2012, fish oil from South America accounted for almost half of the total. Fish oils from the North Atlantic have a lower concentration of EPA than South American oils, so the ratio of EPA/DHA in the feed was higher in 2012 than in 2010 (1.4 and 1.2, respectively). This may have affected the retention of EPA and DHA. However, the retention values were calculated from the nutrient content of salmon fed commercial feeds in two separate benchmark trials in 2010 and 2012, where the salmon were harvested in July and September, respectively, and this may have affected the energy status of the fish. This probably also affected the deposition, and thus also the retention, of EPA and DHA in different body compartments. However, there are few available data on whole-body nutrient composition of harvest-size salmon. Access to accurate and standardised data is therefore a challenge in this kind of study, because retention values depend on representative data of nutrient contents in whole salmon. The shortage of fish oil and the resulting increase of plant oils with a high content of n-6 fatty acids in salmon diets have increased the n-6/

n-3 ratio in salmon fillets during the last decade (NIFES sjømatdata). This raises concerns both for fish health and for the beneficial health effects of salmon for the consumer, and it is therefore important to optimise the retention of EPA and DHA in commercial salmon farming.

Phosphorus (P) is an essential nutrient for both plants and animals, and is therefore added in both agricultural fertilizers and animal feeds. The world's currently available P sources are limited, and it is believed that P will become a limited resource for food production in the near future (Smit et al., 2009; Van Enk et al., 2011). The ingredients used by the three feed companies BioMar, EWOS and Skretting for aquaculture feed production in 2012 contained 15,000 tonnes of P (Table 2), of which 6747 tonnes (45%) originated from marine ingredients, 4645 tonnes (31%) originated from plant ingredients, and the remaining 3620 tonnes (24%) were added as crystalline mineral compounds. The 1,452,000 tonnes of feed that were used in 2012 contained 0.9% P, a total 13,070 tonnes of P. 29% of the dietary P was retained in the salmon (Table 4), meaning that 71% of the phosphorus in the feed was released into the sea. Of the 15,000 tonnes P in the feed, a loss of 71% amounts to 10,700 tonnes. This is more than the amount that originated from the marine ingredients in the salmon feed used in Norway in 2012. Consequently, much of the P used for growing crops for feed ingredients is transferred to the sea, and increased use of plant ingredients in fish feed thus increases the drain of P from land to sea. Furthermore, some plant ingredients contain components, such as phytic acid, that decrease P absorption in the salmon's intestine, thus increasing the need for added P. From the perspective of phosphorus sustainability, plant ingredients are not beneficial, unless the P discharged from aquaculture can be captured and reused. Improving the availability of P from the marine ingredients in particular, and all sources in general, would improve the resource balance of phosphorus.

3.6. Indicators of dependency of marine protein and oil resources

The amount of wild caught fish used in the production of salmon has so far received most of the attention when examining sustainability. The fish in/fish out (FIFO) ratio is often considered to be an estimate of the amount of wild caught fish needed to produce the amount of fish oil and fish meal required to produce 1 kg of salmon. However, the FIFO ratio is not an indicator of the sustainable use of marine resources, because sustainability must be based on a responsible harvest of the fish species that are used for fish oil and fish meal according to international fishery regulations.

Following the decrease in marine ingredients in salmon feed between 1990 and 2013 (Fig. 1), the FIFO ratios for fish oil and fish meal in Norwegian salmon farming have decreased from 7.2 to 1.7 and from 4.4 to 1.0, respectively (Fig. 5). The FIFO ratio is often used, both in scientific publications (Naylor et al., 2009; Tacon and Metian, 2008) and in the public debate, because it is apparently easy to relate to. However, published FIFO values for salmon production during the last decade range from less than 2 to 8.5 (Bendiksen et al., 2011; Jackson, 2009; Naylor et al., 2009; Tacon and Metian, 2008). The variation in reported FIFO values is a result of different inclusion levels of marine ingredients, different feed conversion ratios, and different conversion efficiencies of industrial fish into fish oil and fish meal. Some authors calculate FIFOs as separate values based on either fish meal or fish oil (Kaushik and Troell, 2010), while others subtract the fish oil yield from the fish meal production (Tacon and Metian, 2008). Naylor et al. (2009) calculated one reduction fish equivalent for fish meal and another for additional fish oil, and added these values to give a combined FIFO required to produce 1 kg of farmed fish. Jackson (2009) proposed another approach to this issue, in a more global perspective for several aquaculture productions with different demands for fish oil and fish meal. Thus, a FIFO ratio is calculated for a combination of several aquaculture production methods, with different dependencies on fish meal and fish 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 demand for fish meal than fish oil in the diet. In theory, this way of calculating a FIFO ratio for an aquaculture production method will reflect what is actually consumed of marine ingredients. When this calculation method is used for the total global aquaculture production, the estimated volume of wild fish consumed as fish meal and fish oil agrees with the estimate published by FAO (20.2 million tonnes of wild fish in 2006).

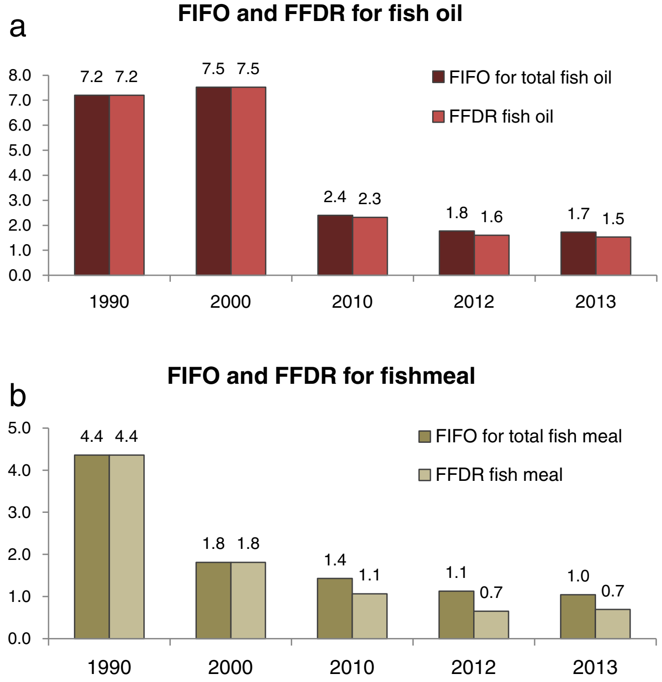

Fig. 5. Development of fish in/fish out (FIFO) ratios and forage fish dependency ratios (FFDR) for a) fish oil and b) fish meal in Norwegian salmon farming in the period 1990 to 2013.

It is also important to be aware that the FIFO ratio is very sensitive to fish oil yield. The fish oil yield depends on the fat content of the forage fish, which varies a great deal between species, and within one species with size and season. Irrespective of how the FIFO is calculated, it shows the relationship between forage and salmon product on a kilogram-to-kilogram basis, and does not consider the difference in nutrient content between the forage fish and the salmon product. Thus, it does not measure how effectively the marine resources are utilised. The forage fish dependency ratio is a somewhat more precise measure of the dependency of marine resources, since the fish meal and fish oil produced from trimmings and offal are excluded from the calculation. Between 1990 and 2013, the forage fish dependency ratios for fish meal and fish oil in Norwegian salmon farming fell from 7.2 to 1.5 for fish oil and from 4.4 to 0.7 for fish meal (Fig. 5), which is well below the ASC standards for FFDR of 1.35 and 2.95 for fish meal and fish oil, respectively.

Neither FIFO nor FFDR consider the edible yield or the nutrient content of the forage fish and of the salmon product, which is an important aspect in a resource efficiency perspective. The marine nutrient dependency ratios account for the differences in composition of the marine resources used in the salmon feed and in the salmon product (Crampton et al., 2010). Fig. 6 shows the marine protein dependency ratio for the Norwegian salmon production for marine protein from 1990 to 2013. In 1990, 3.8 kg of marine protein was used to produce 1 kg of salmon protein. In 2013, the amount of marine protein consumed in the production of 1 kg of Norwegian salmon had fallen to 0.7. Thus, from being a net consumer of marine protein, the Norwegian salmon has become a net producer. The corresponding marine oil dependency ratio was 2.8 in 1990, whereas in 2013 only 0.5 kg marine

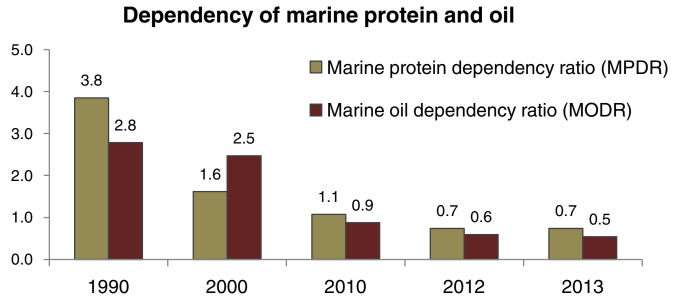

Fig. 6. Dependency of marine protein and oil from forage fish in Norwegian salmon farming from 1990 to 2013 calculated as marine protein dependency ratio (MPDR) and marine oil dependency ratio (MODR). Fish oil and fish meal from fishery by-products are not included when calculating the MODR and MPDR.

oil was used to produce 1 kg of fat in salmon. However, the fatty acid composition of the salmon reflects the fatty acid composition in the feed. Thus, reducing the amount of marine fat in salmon feed will reduce the amount of the typical long-chained unsaturated marine fatty acids EPA and DHA in the salmon, and increase the amounts of n-6 fatty acids (which are typically found in plant oils). Thus, nutrient dependency rations for EPA and DHA could perhaps be a better indicator for dependency of marine fat, as long as these fatty acids are supplied from the marine environment, although there is also some endogenous production in the salmon of omega-3.

4. Concluding remarks

Several aspects must be addressed when assessing the environmental performance of food production systems. The input of organic and inorganic resources and the output of both, in terms of nutrients for human consumption and in terms of waste and emissions to the environment, must be quantified. Life cycle assessment methodology (LCA) is often used to study the environmental efficiency of food production systems. Recycling of nutrients from agro-industrial by-products into animal production is a key factor in increasing the environmental efficiency of food production, and is positive for overall productivity and efficiency. Mass balance models are more suitable than LCA models for tracking nutrient flows and estimating nutrient retention efficiencies. However, it is essential to have access to accurate data to be able to track the major flows of nutrients in food production systems and estimate how efficiently they are utilised. The availability of representative data on nutrient composition of the feed, final product, and (in particular) of the parts of the animal that are not consumed by humans is necessary for tracking the nutrient flows when drawing up a resource budget for an entire food production system. An overview of the inputs and outputs of nutrients and energy such as the one presented in this study should be obtained for other food production systems.

The efficiency of a food production system depends also on how much of the final product is actually consumed by humans. The FAO has estimated that 30% of the food produced in the world is not consumed, for 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 the harvest and storage of food. Avoiding these losses will reduce the demand for land, water, and energy, and will reduce the emissions of greenhouse gases. Thus, more focus should be directed towards reducing food losses after the product leaves the farm gate.

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References

Akvafakta, 2014. http://akvafakta.fhl.no/category.php?categoryID=38 (Accessed October 2014).

Anonymous, 2010. Norske anbefalinger. Norwegian Directory of Health. http://www.helsedirektoratet.no/ernaering/matvarer_og_n_ringsstoffer/n_ringsstoffanbefalinger/norske_anbefalinger (Accessed June 20th 20114).

Åsgård, T., Austreng, E., 1995. Optimal utilization of marine proteins and lipids for human interests. In: Haaland, Reinertsen (Eds.), Sustainable Fish Farming. Balkema, pp. 79–87.

Åsgård, T., Hillestad, M., 1998. Eco-friendly aquafeeds need accurate design. Feed Tech. 2, 13–15.

Åsgård, T., Austreng, E., Holmefjord, I., Hillestad, M., Shearer, K., 1999. Resource efficiency in the production of various species. In: Svennevig, et al. (Eds.), Sustainable Aquaculture: Food for the Future. Balkema, pp. 171–183.

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

Bartley, D.M., Brugère, C., Soto, D., Gerber, P., Harvey, B. (Eds.), 2007. Comparative Assessment of the Environmental Costs of Aquaculture and Other Food Production Sectors: Methods for Meaningful ComparisonsFAO 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 http://dx.doi.org/10.1016/j.aquaculture.2011.01.040.

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, pp. 50–80.

Bjørkli, J., 2002. Protein og energiregnskap hos laks, kylling, gris og lam (Protein and energy account in chicken, pig and lamb). Agricultural University of Norway (Master thesis at. (In Norwegian), 41 pp.).

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

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. Glob. Environ. Chang. 17, 238–249.

Eagle, J., Naylor, R., Smith, W., 2004. Why farm salmon outcompete fishery salmon. Mar. Policy 28, 259–270. http://dx.doi.org/10.1016/j.marpol.2003.08.001.

Einen, O., Holmefjord, I., Talbot, C., Åsgård, T., 1995. Auditing nutrient discharges from fish farms. Theoretical and practical considerations. Aquac. Res. 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. Mar. Policy 33, 479–488. http://dx.doi.org/10.1016/j.marpol.2008.11.003.

FAO, 2011a. Energy-smart Food for People and Climate. Food and Agriculture Organization of the United Nations.

FAO, 2011b. World Livestock 2011—Livestock in Food Security. Food and Agriculture Organization of the United Nations, Rome.

FAO, 2012. The State of the World Fisheries and Aquaculture 2012. Food and Agriculture Organisation of the United, Rome.

Fréon, P., Cury, P., Shannon, L., Roy, C., 2005. Sustainable exploitation of small pelagic fish stocks challenged by environmental and ecosystem changes: a review. Bull. Mar. Sci. 76, 385–462.

Gjedrem, T., 2010. The first family-based breeding program in aquaculture. Rev. Aquacult. 2, 2–15. http://dx.doi.org/10.1111/j.1753-5131.2010.01011.x.

Grisdale-Helland, B., Lemme, A., Helland, S.J., 2013. Threonine requirement for maintenance and efficiency of utilization for threonine accretion in Atlantic salmon smolts determined using increasing ration levels. Aquaculture 372–375, 158–166. http://dx.doi.org/10.1016/j.aquaculture.2013.11.004.

IFFO, Internationaol Fishmeal and Fish Oil Organisation, 2010. http://www.iffo.net/ (Accessed October 2014).

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., 2009. Fish in–fish out, ratios explained. Aquacult. 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., Troell, M., 2010. Taking the fish-in fish-out ratio a step further. Aquacult. Europe 35, 15–17.

Leyton, P., Refstie, S., Árnason, J., Åsgård, T., 2009. Sustainable and cost-efficient replacement of fish meal by animal and plant protein in feeds for Atlantic salmon *Salmo salar*. Aquacult. Eur. Trondheim 515–516 (Aug 2009. Abstracts).

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. Biochim. Biophys. Acta Mol. Cell Biol. Lipids 1791, 254–262.

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

Naylor, R., Burke, M., 2005. Aquaculture and Ocean resources: raising tigers of the sea. Annu. Rev. Environ. Resour. 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.

Olafsen, T., Richardsen, R., Nystøyl, R., Strandheim, G., Kosmo, J.P., 2014. Analyse av marint restråstoff, 2013. Sintef report A26097. Norwegian. ISBN: 978-82-14-05721-8, p. 42.

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. Environ. Manag. 35, 161–174.

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. http://dx.doi.org/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. Mar. Policy http://dx.doi.org/10.1016/j.marpol.2010.01.027 (34815-820).

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. http://dx.doi.org/10.1016/j.aquaculture.2007.10.053.

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

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

Singh, R.K., Murty, H.R., Gupta, S.K., Dikshit, A.K., 2009. An overview of sustainability assessment methodologies. Ecol. Indic. 9, 189–212. http://dx.doi.org/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. 0-06-046328-7 (617 pp.).

Statistics Norway, 2013. http://www.ssb.no/aarbok/tab/tab-376.html (Accessed November 2014).

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.

The Norwegian Food Consumption Table (FCT), 2006. http://matportalen.no/matvaretabellen/index_html/tabell_view?nutrients=&searchmode=%20normal&grouping=0&togglerowcol=col (Accessed August 2014).

Thodesen, J., Grisdale-Helland, B., Helland, S.J., Gjerde, B., 1999. Feed intake, growth rate and feed utilization of offspring from wild and selected Atlantic salmon (*Salmo salar*). Aquaculture 180, 237–246.

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? Rev. Fish. Sci. 19, 257–278. http://dx.doi.org/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, M.H.G., 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: Cleveland, C. (Ed.), Encyclopedia of Energy vol. 1. Elsevier, San Diego, pp. 97–108.

Turchini, G.M., Francis, D.S., Keast, R.S.J., Sinclair, A.J., 2010. Transforming salmonid aquaculture from 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 Innovation Network. Ministry for Economic Affairs, Agriculture and Innovation. ISBN: 978-90-5059-414-1.

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. J. Nutr. 134, 1320–1327.

Ytrestøyl, T., Aas, T.s., Berge, G.M., Hatlen, B., Sørensen, M., Ruyter, B., Thomassen, M., Hognes, E.S., Ziegler, F., Sund, V., Åsgård, T., 2011. Resource utilisation and eco-efficiency of Norwegian salmon farming in 2010. Nofima Report 53 2011. ISBN: 978-82-7251-945-1 (65 pp.).