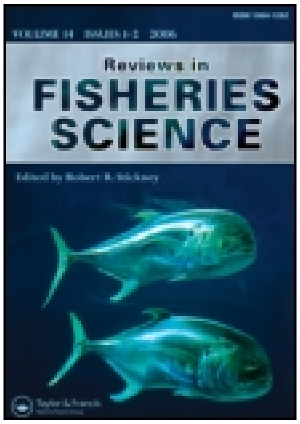

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Atlantic Salmon (*Salmo salar*): The “Super-Chicken” of the Sea?

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Atlantic Salmon (*Salmo salar*): The "Super-Chicken" of the Sea?

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In this article, the definition of sustainability is discussed, particularly in relation to the use of marine feed resources. The current review gives an overview of the development of Atlantic salmon (Salmo salar) aquaculture and how it has evolved due to changes in legal and management framework conditions. Atlantic salmon production is characterized with high utilization of nutrients, a high yield of production, and a large demand for rendered by-products. All of these factors compare favorably to production of most terrestrial farm animals. Historically, salmon feed has contained fishmeal and fish oil as the primary protein and fat source. Rising demand for feed ingredients has not increased pressure on forage fish resources. Rather, there has been an increased use of plant protein and fat sources. Increased utilization of plant ingredients may not be as sustainable as often claimed. Provided that marine harvest is carried out within legal frames, harvesting the marine ecosystem is a sustainable operation, and at present, the only significant source of long chain n-3 fatty acids. It is concluded that Atlantic salmon farming can be compared to raising a marine "super chicken" being among the most sustainable meat products in the world food market.

Keywords aquaculture, Atlantic salmon, feed resources, fisheries, sustainability

INTRODUCTION

Atlantic salmon (*Salmo salar*) has become a "super-commodity" during the last decade, a uniform product available on demand around the globe. Aquaculture production of Atlantic salmon reached approximately 1.5 million metric tons (tons) in 2009 (Table 1), with Norway being the largest producer followed by the United Kingdom, Chile, and Canada. A fundamental question for the future prospect of this industry is whether it is "raising the tiger of the sea" by consuming large amounts of valuable human food in the form of pelagic feed fish, creating huge amounts of waste and negatively impacting the marine ecosystems to produce a luxury product for the wealthy population (Naylor and Burke, 2005), or it is developing a "super-chicken" of the oceans for feeding the world's growing population a healthy seafood (Mozaffarian and Rimm, 2006) and relieving environmental pressure on marginal agricultural lands (Olsen, 2011).

It can be argued that Atlantic salmon is the most efficient domesticated farm animal, as 100 kg dry feed yields 65 kg Atlantic salmon fillets compared to only 20 kg of poultry fillets or 12 kg of pork fillets (Anonymous, 2010a). It can also be argued that using pelagic fish feed resources in salmon feeds yields up to five times the quantity of fillets compared to letting wild cod graze on these resources and then harvesting the cod (Åsgård et al., 2010).

In a number of review works, on the other hand, it is claimed that people believe aquaculture relieves pressure on ocean

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Table 1 World production of Atlantic salmon in 2010 by country (Lassen et al., 2011)

	Tons	%
Norway	944,600	65
United Kingdom	141,800	10
Chile	129,500	9
Canada	118,000	8
Faroe Island	42,100	3
Australia	33,000	2
United States	18,000	1
Ireland	17,800	1
Others	1,400	0
Total	1,446 200	

fisheries while the opposite is true for aquaculture production of Atlantic salmon (Naylor et al., 1998, 2000; Naylor and Burke, 2005), as farming carnivorous species requires large inputs of wild fish for feed (Naylor et al., 1998, 2000; Naylor et al., 2009; Folke and Kautsky, 1989, 1992; Folke et al., 1994). The underlying message given is that salmon farming is not a sustainable operation (Folke and Kautsky, 1989, 1992; Folke et al., 1994; Naylor and Burke, 2005), as it is an inefficient use of resources, generates large amounts of waste that are stored or exported, and may also represent a health risk for the consumer.

A different approach is that terrestrial feed resources are more sustainable than marine, as they reduce wild fish inputs in feed and, in that way, prevent over exploitation of marine fish stocks (Tacon and Forster, 2003; Tacon and Metian, 2008, 2009a,b). This approach does not take into account the environmental costs by producing the alternative plant ingredients. They apparently assume that plant products are produced sustainably and that the resulting increased demand by substituting fishmeal and fish oil in aquafeeds can be delivered within the capacity of the words agriculture today.

There is no doubt that intensive meat production has high environmental costs connected to feed resource consumption. The fundamental question with respect to salmon aquaculture is how farmed salmon compares to other food items, whether the indicators used for this comparison are valid, and if the development in the salmon industry will lead to improved sustainability and food security in the food production system for our planet in the future (Diana, 2009). However, as salmon, in most respects, is the globally leading aquaculture species in terms of biological knowledge, production technology, and market development (Asche, 2008), the questions and their answers have relevance for all successful aquaculture species.

Salmon Aquaculture Background

Farming of Atlantic salmon in sea cages was developed in Norway during the early 1970s (Figure 1) and was soon after established in countries around the north Atlantic, Pacific Canada, Chile, and Australia. In its early years, the industry supplied high-end markets a luxury product out of season and received farm-gate prices of approximately €25 per kg (inflation adjusted) (1 € = 1.4 US$). The production techniques of juveniles (smolts) were already well established for cultivation and restocking purposes (Skavhaug, 2005). Initially, smolts were obtained from established hatcheries (Osland, 1990), but in 1971, the Norwegian government also established two research stations dedicated to applied aquaculture research, Matre (Institute of Marine Research) and Sunndalsøra (Norwegian University of Life Sciences), with a research focus on selective breeding, nutrition, general production techniques, and delivery of smolts to commercial farms. Grow-out operations were carried out in relatively small cages of a circumference of 35–40 m and a depth of 5–6 m located in sheltered waters, and the salmon were fed diets based on ground pelagic fish, supplemented vitamins, carbohydrates, and binders (20–35% fat and 40–55% protein of dry weight). During those early days, feed efficiency was generally poor, and it could take up to 7 kg of moist feed to produce 1 kg of salmon weight gain. In 1972, Atlantic salmon used 1.9 kg animal protein to produce 1 kg of salmon that contained 0.18 kg protein (Åsgård et al., 1999). The combination of sheltered sites with shallow water and low water exchange and large amounts of feed waste created incidents with anaerobic sediments beneath the cages and out-gassing of carbon dioxide and hydrogen sulphide.

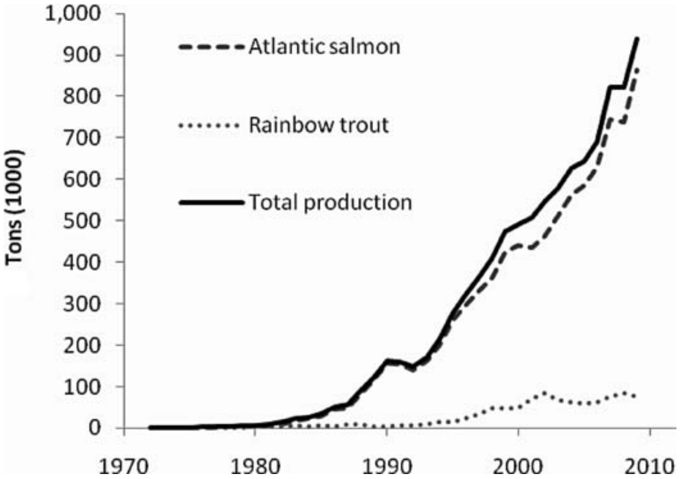

Figure 1 Production of Atlantic salmon and rainbow trout in Norway from 1972 to 2009 in 1,000 tons.

Dry pelleted diets for juvenile Atlantic salmon were developed by Eva Bergström (Swedish Salmon Research Institute, Älvkarleby, Sweden) in cooperation with EWOS Ltd. (Bergen, Norway) in 1956 and dry pelleted diets for salmon in sea water were introduced in the 1970s. During the 1980s moist diets based on the use of ground pelagic fish were gradually phased out. The early pelleted diets contained low lipid levels (8–22%) and high protein levels (55–45%).

Before the salmon industry developed, fishmeal was used mainly in feeds for domestic homoeothermic animals (meat, fur production, and pets), and fish oil was used for industrial purposes, such as for paints, lubricants, tanning, soap, printing ink, and hydrogenated purposes like margarine and shortening. With the development of intensive aquaculture production over the past 40 years, there has been a dramatic redistribution of available fishmeal and fish oil. Today, around 63% of annual global fishmeal production and 81% of fish oil is utilized for aquafeeds (Chamberlain, 2011).

The introduction of extrusion technology to pelletize feeds in the 1990s allowed higher inclusion levels of fat and, as a consequence, higher dietary energy. This led to a rapid increase in the lipid level in the salmon feed to about 30%. To restrict production growth, the Norwegian government implemented quotas on the amount of feed used on salmon and trout farms from March 1996 through December 2005 (FOR-1996-02-29-223; FOR-2005-12-28-1709). This made it beneficial to further increase dietary energy in order to reduce the feed conversion ratios (FCRs; equal to (weight unit feed fed)/(weight unit wet fish gain)). By implementing vacuum-coating techniques, the lipid level (fish oil) was increased to 35–37% (Figure 2). FCRs of around 0.8 are not uncommon using these modern diets (Einen et al., 1999).

In Norway today, extruded diets, vacuum coated with fish or rapeseed oil, are fed exclusively to salmon in approximately 4,000 sea cages of a total volume of 67 million m^3. There is a large variation in the size of the cages used. At present (Anonymous, 2010b), the size distribution is approximately 900 small ($< 9{,}000$ m^3), 1,950 medium ($> 9{,}000$ m^3 and $< 19{,}499$ m^3), 959 large cages (19,500 m^3 $<$ cage $<$ 38,999 m^3), and 212 very large (cage $>$ 39,000 m^3) of a circumference of up to 160 m and a depth of 30–50 m.

While the main driving force for the technological development of the salmon industry is innovations at the farms and among the industry's suppliers, Norwegian legislation has also influenced the structure and contributed to the development of the industry (Asche, 2008; Aarset et al., 2004). The focus and objectives of the regulations have changed over time. In the 1970s, the great interest for establishing salmon farms led to a temporary act requiring a governmental permit to build aquaculture operations and also limited the size of the individual sea cage operation to 8,000 m^3 (OT-PRP, 1973). These restrictions in Norway encouraged Norwegian companies to invest in salmon farming in other countries (Asche et al., 2003). This promoted the rapid transfer of technology and breeding material to other countries and continents. In 1981, the first permanent aquaculture act was implemented, aimed at balancing the development of the industry in relation to the market for farmed salmon, regional considerations, and ownership structure. In particular, ownership regulations ensured that the owner, in person, should operate the farm (Aarset et al., 2004). This act was revised in 1985, and the objectives got a stronger focus on profitability and balanced regional development, but with liberalization with respect to ownership (LOV-2005-06-17-79). Regional considerations, or issuing licenses for specific areas, were intended to create economic development also in the northern regions. Distributing the farms along the whole Norwegian coastline from south to northeast has probably been the most important factor in combating viral diseases and parasites (Krkosek, 2011). By a revision in 1991, the term "balanced development" was changed to "sustainable development," indicating a stronger focus on environmental issues, and the regulations regarding ownership were further liberalized.

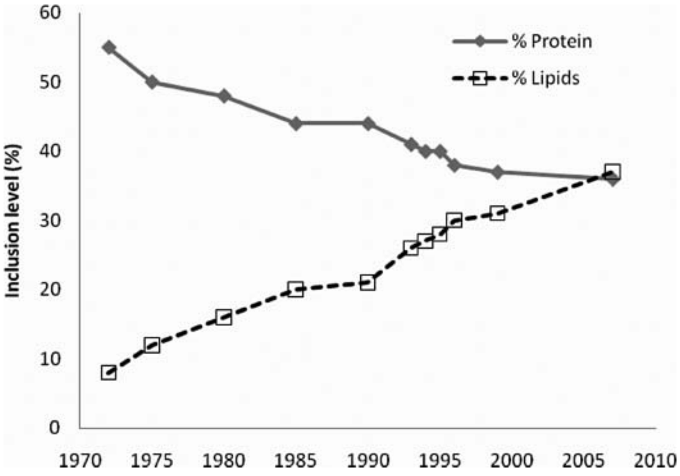

Figure 2 Protein and lipid percent in Norwegian dry feeds for Atlantic salmon. Feeds prior to 1990 were pelleted. Diets after 1990 are extruded, and after 1993, the lipid level was increased by vacuum coating.

The focus on sustainability is formulated in a "strategy for environmentally sustainable aquaculture industry" issued by the Norwegian Ministry for Fisheries and Coastal Affairs (FKD, 2009) with defined targets for impacts of:

- diseases,
- genetic interaction with wild counterparts and escapees,
- pollution and effluents,
- use of area, and
- feed and feed ingredients.

Today, the limitations in ownership have been further relaxed. Permission from the Ministry of Fisheries and Coastal Affairs is required for companies to take possession of more than 15% of the country's total aquaculture production, and no company can control more than 25% of Norway's salmon production (FOR-2004-12-22-1800). The liberalization of ownership has led to a substantial merging and acquisition of producers and had a tremendous impact on the owner structure and size of the salmon aquaculture industry. While the ten largest companies in 1990 produced 8% of total Norwegian quantity, this production had increased to 46% by 2001 (Jakobsen et al., 2003). In 2009, the five largest companies produced 56% of the Norwegian production and 46% of total world production of Atlantic salmon (Table 2).

Table 2 Five largest salmon producers and their share of Norwegian and world Atlantic salmon production (2009) (Lassen et al., 2011)

Ranking	Group	Head-office	Total (tons)	Norway (tons)
1	Marine Harvest Group	Norway	340,000	215,000
2	Lerøy Seafood Group	Norway	112,000	112,000
3	Cermaq	Norway	95,000	34,100
4	Salmar	Norway	71,500	71,500
5	Grieg Seafood	Norway	50,000	50,000
	Total five largest		668,500	482,600
	Worldwide production quantity		1,468,400	855,700
	Share of total		46%	56%

SUSTAINABILITY

The Food and Agriculture Organization (FAO, 1996) recognizes food as one of the primary needs of humans and defines food security to exist "… when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (n.p.). It is important to note that not only is sufficient and safe food a human right, but the preferences of the individuals are also important in this aspect. The main task of agriculture, fisheries, and aquaculture is to feed the growing world population, which is estimated to rise to approximately 9 billion by 2050 (UN, 2004). This will be a serious challenge, since in 2009, 1 billion people were already suffering from hunger and malnutrition (Tirado et al., 2010). The use of both terrestrial and aquatic resources for the development of sustainable food production in various regions of the world will be required to meet the future demand for food as well as to formulate strategies to enhance food security, improve nutrition, and alleviate poverty.

All food and feed production systems are associated with an environmental cost that varies from product to product and between countries, regions, and various continents. It is claimed that no food production system now in use is truly sustainable from an energy or biodiversity perspective as they generate waste, require fossil energy, use water, and change land cover (Diana, 2009). Establishing some general indicators for comparing sustainability of products from the capture and culture of wild and farmed animals originating from different ecosystems (i.e., agricultural or marine products) and regions is an enormous task (Rebitzer et al., 2004). The application of an indicator or a measure developed for one system to another system may give different results leading to inaccurate or false conclusions.

The most commonly accepted definition of sustainable development was given by the Brundtland Commission of United Nations (Brundtland, 1987), namely "sustainable development is the development that meets the needs of today without compromising the ability of future generations to meet their own needs." By nature, sustainability is therefore a community rather than a personal concern (Pelletier et al., 2009). Based on the Brundtland Commission's definition of sustainable development, at least three criteria should be considered: (1) Will the operation cause impact on the ecosystem (aquatic or terrestrial) lasting for centuries? (2) Will the operation consume non-renewable resources, or is the resource use unacceptably high? (3) Is the impact of effluents on the ecosystem unacceptable?

Humans need food daily; the alternative is replacement, not absence. The major question for the sustainability of Atlantic salmon as a food is if it should be replaced with other food items that are more sustainable and have better impacts on human health, or should the recommendation be to consume more salmon? Should fishmeal and fish oil in salmon diets be replaced with plant products, and what are the benefits and shortcomings of these replacements? Sustainability also has another dimension—the development over time. It is easier to accept animal production when the development over time shows reduced environmental impacts compared to a production system with increased impacts. Life cycle assessment (LCA) is a methodological framework for estimating the environmental impacts attributed to the life cycle of a product (Rebitzer et al., 2004), such as global warming, acidification, eutrophication, ecotoxicity (terrestrial and aquatic), biotic resource use, and others (Pelletier et al., 2007). LCA in the agricultural system is relatively well established (Pelletier et al., 2007), and during recent years, it has also been applied to seafood production systems (Ellingsen et al., 2009; Papatryphon et al., 2004; Mungkung et al., 2006). The major challenge here is to develop categories appropriate to quantify the environmental interactions characteristics for seafood production and to articulate the limitations of the information generated (Pelletier et al., 2007).

One of the most controversial issues in LCA is the co-product allocation (Weidema and Schmidt, 2010; Weidema, 2001). This is not surprising because, for some products, it will have a substantial impact on the results achieved, as well as the environmental reputation of food items. For instance, are feathers, entrails, and bones in chicken production an equal co-product to the dressed chicken, or is it waste? It is reported that emission from Canadian Atlantic salmon farms "increased largely due to greater use of poultry products" (Pelletier et al., 2009), and it is also suggested that a marked improvement in environmental performance could be achieved through replacing "mixed whitefish trimmings meal/oils in the UK" with plant proteins. These conclusions raise two fundamental questions. Is it more environmental friendly to send "waste" from animal production and fisheries to landfills, or is there more "sustainable" use of these "resources" than in aquafeeds? There is no doubt that poultry or fish fillets are the primary product, and, in the opinion of the authors, the environmental cost should be placed on the product in relation to its commercial value. Using by-products from both terrestrial and aquatic animals as ingredients in fish feeds saves edible grain and forage fishes and should be encouraged through the sustainability indicators.

Emission of greenhouse gasses (GHG em) and cumulative energy use (CEU) are commonly used indicators for LCA of seafood. It is clear that a tonne of GHG em will contribute to

Table 3 Mean trophic level and estimated PPR (kg C/kg fish wet weight) (Pauly and Christensen, 1995)

Species	Trophic level	PPR
Cod, hakes, haddock	3.8	76
Jacks, mullets, sauries	3.8	72
Herring, sardines, anchovies	3.0	10
Mackerels	3.4	28

climate change regardless of where emission occurs. This is also true for ozone-depleting substances and consumption of non-renewable resources (Pelletier et al., 2007). These indicators are considered to be suitable for cross-sector comparisons of sustainability of food items.

Biotic resource use estimates the amount of primary production required (PPR) for producing the product, and is intended as an indicator for depletion of biological resources. Calculating PPR in an aquatic system is based on an estimate of 10% mean transfer efficiency between trophic levels (Pauly and Christensen, 1995). The calculated PPR and estimated trophic level for some fishes are shown in Table 3, showing large differences among forage fish species. Table 4 shows LCA values calculated for aquaculture production in different countries. The reported values for PPR ranges from 137 kg C per kg salmon live weight to 18.4 kg C per kg salmon, depending on the amount of marine ingredients used in the feed. Since it is estimated that the forage fish species range in trophic level between 2.6 to 3.4, the trophic level will thus be of considerable impact on the PPR values (Table 3). For rainbow trout, it is concluded that the use of fishmeal and fish oil is by far the most important contributor to PPR use, and therefore, their substitution with plant ingredients leads to significant sustainability improvements (Papatryphon et al., 2004). Based on similar calculations, it is claimed that the European salmon farming industry requires a marine support area for feed estimated at 40,000 to 50,000 times the area of cultivation and is equivalent to about 90% of the primary production of the fishing area of the North Sea (Naylor et al., 1998). Do these numbers mean anything in relation to depletion of marine resources, and is it really more sustainable to harvest at lower trophic levels for forage organisms? There are strong warnings that fishing down the food web may lead to collapses in fisheries and that harvest should be balanced and targeted for a stable average trophic level over time (Pauly and Palomares, 2005).

Table 4 LCA of salmon produced in Norway, United Kingdom, Canada, and Chile (Pelletier et al., 2009); values are given for production of 1 kg life weight

	CEU (MJ)	PPR (kg C)	GHG em (kg CO_2 eq)
Norway	26.2	111.1	1.8
United Kingdom	47.9	137.2	3.3
Canada	31.1	18.4	2.4
Chile	33.2	56.6	2.3

PPR = biotic resource use, kg C = cumulative C consumption in kg, CO_2 eq = CO_2 equivalents.

In agricultural production systems, the use of the PPR indicator seems reasonable, as all trophic levels are available and marketable and the production quantity at each trophic level can be considered independent except for influence by market mechanisms. In harvesting wild marine resources, the lower trophic levels are not accessible or requested by the market and in addition tied up by strong biological dependencies. PPR applied on harvests of natural resources does not seems equally applicable, and used in comparison between agriculture production and wild harvest of marine resources, the results will be meaningless and the conclusion wrong. The number “50,000 times area of cultivation” (Naylor et al., 1998) seems alarmingly high, but it equals only harvesting feed from approximately 4,500 m^2 uncultivated land per kg chicken produced. However, in the subarctic region, 4,500 m^2 would not produce sufficient food for growing 1 kg chicken, and it would be impossible to justify the economical costs of harvesting wild terrestrial food for commercial chicken production.

PPR used on waste or by-products will work against the intention of this indicator and encourage rather than preserve depletion of biotic resources. Based on the assumption that it is legitimate to use the oceans for human food production, the management principle should be based on a regulated and balanced harvest of the ecosystems under an eternity perspective and with a primary focus on fishes for direct human consumption and a secondary focus on forage fishes. The integrity of the ecosystem and the total yield of food are then the important factors.

Feed Resources

Feed provision is the single most important contributor to resource use and emissions associated with the farm-gate production of salmon cultured in net-pen systems (Pelletier et al., 2009), as it is for terrestrial farmed animals. Cattle and other ruminant livestock, such as sheep and goats, graze one half of the planet’s land area. Ruminants, along with pigs and poultry, also eat feed and fodder raised on one-fourth of the cropland (Durning and Brough, 1991). The global livestock sector is estimated to contribute to 18% of anthropogenic greenhouse emission and 63% of reactive nitrogen mobilization and consume 58% of human-appropriated biomass (Pelletier and Tyedmers, 2010). This cropland and these resources could alternatively be used for producing grains for direct human consumption.

For “global” salmon, feed accounts for 93% of the farm-gate CEU, 100% of the biotic resource use, and 94% of global warming and acidifying emissions (Pelletier et al., 2009). Feed also represent approximately 50% of the operational costs in salmon farming (FDIR, 2010a). Salmon farmers, therefore, have a strong focus on feed cost, i.e., the cost of feed per unit salmon produced. There are still many options for improving the overall environmental performance of salmon production through the development of least-environmental cost formulations. These are not necessarily the same as least-economic cost formulations (Pelletier et al., 2009).

Many discussions on the ecological impacts of feed and feeding of salmon have a partial focus on the use of marine resources used in feeds (Folke and Kautsky, 1989, 1992; Naylor and Burke, 2005; Naylor et al., 2000). Although not always intentionally, these studies often give the impression that using agricultural feedstuffs in fish feeds would reduce the environmental impacts compared to using marine feed resources. There is no doubt that overexploitation of marine resources will have negative impacts on marine ecosystems and that some may be long-lasting effects. However, the impacts on the terrestrial ecosystems of today's industrial agricultural operations are clearly visible, and these impacts are, to a large extent, irreversible or would take centuries to revert to the natural state.

There are fundamental differences between growing, harvesting and processing grains, and fishing and processing wild-living marine animals for feed. However, both systems utilize niches in the ecosystems that alternatively would be utilized by other plants or animals. Both systems have advantages and disadvantages as raw material for feeds.

- Growing grains causes long-term changes to the landscape, while pelagic fisheries by purse seine do not influence the sea bed.
- Growing grains requires inputs of non-renewable resources, such as fertilizers, and causes atmospheric emission, while pelagic fish, harvested sustainably, is a potentially renewable resource. Fisheries require a relatively high energy input in locating, harvesting, transporting, and processing of the fishes for feed, while agricultural production requires less fossil energy.
- Agricultural operations require use of herbicides and pesticides and also have a severe impact on terrestrial biodiversity, while well-managed fisheries for pelagic fishes have relatively low impacts on marine biodiversity and do not require pesticides or herbicides.
- Fisheries are utilizing a limited natural resource, while agricultural operations are limited by land but leave larger possibilities to intensifying and increasing production.

There is, at present, significant pressure from several directions to increase the level of terrestrial plant and animal feed ingredients in aquafeeds. On one hand, this may lower the usage of fish-based raw materials or, on the other hand, lead to a potential increased aquaculture production. The latter is the most likely scenario as the world's population continues to grow and increased purchasing power will require larger quantities of food, including seafood.

From an industrial point of view, the desire for alternative feed resources is understandable. There is no doubt that the agricultural industry sees salmon diets as attractive high-priced targets for their protein and fat sources. Heavy reliance on fishmeal and fish oil makes the aquaculture industry vulnerable to shortages in feedstuffs and to increased feed costs in periods of low supply. As such, the aquaculture industries would greatly benefit from other protein and lipid supplies. Relatively cheap alternative animal and plant feed ingredients sources would open the door for increased salmon production and to more predictable feed costs in relation to other competing agricultural meat products. This would benefit both the aquaculture as well as the agricultural industries. However, this is mainly a question of industrial development rather than an effort to move toward higher sustainability. So far, there are no objective metrics to show that terrestrial agricultural animal and plant feed resources are any more sustainable than feed ingredients derived from wild-caught marine fishery resources.

Fishmeal and Fish Oil

The fishmeal and fish oil industry plays an important role in the world's fisheries. It utilizes primarily fish stocks with generally low acceptance as human food within developed countries, and it is a cornerstone in rendering bycatches and by-products from fisheries and aquaculture, such as viscera, body frames, and trimmings.

Fish oil was used as fuel in lamps as early as 800 AD, while fishmeal was a by-product used as fertilizer or animal feed. Fish oil was also the major product after industrialization of the fish oil process (circa 1850) and was used in paints, lubricants, tanning, soap, printing ink, and for other industrial uses (International Fishmeal and Fish Oil Organisation, 2011). During and after World War II, fishmeal became an important protein source for poultry and swine production and later also for fur animal production. The prime Norwegian fishmeal (NorSeaMink®, Nordsildmel LTD, Norway), made from fresh raw material, was originally developed for feeding mink for fur production. As aquaculture production of salmon developed, it became used as the main ingredient in formulated salmon diets.

The landings of fish for fishmeal and fish oil production has been relatively constant from 1970 up until today, 23.2 ± 3.7 million tons (Tacon and Metian, 2009a); however, in recent years, there is a declining trend (Chamberlain, 2011). In addition, approximately 6.5 million tons of by-products and trimmings from fish processing for human consumption is processed into fishmeal and fish oil (Chamberlain, 2011). Overall, this yields approximately 5–7 million tons fishmeal, of which 1.2 million tons comes from by-products and trimmings (Chamberlain, 2011) and approximately 1 million tons of fish oil. The main producers and species used for this fish oil and meal production are shown in Table 5, and the origin of fishmeal and oil used in Norwegian salmon production is shown in Table 6.

The potential for further increase in total landings of small pelagic fishes for reduction to fishmeal and fish oil purposes seems limited. World fisheries do, however, produce large amounts of discards, defined as the proportion of catch that is returned to sea for whatever reason (FAO, 1995), the majority of finfish probably as dead fish (Ulleweit et al., 2010; Harrington et al., 2005; Catchpole et al., 2007; Suuronen, 2005). The estimates of these quantities varies between 18 and 40 million tons (Kelleher, 2005) to the most recent of

Table 5 Sources and average production (1,000 tons) of fishmeal (2005–2009)

	By-products (%)[a]	Production[b]	Major species[a]
Peru		1, 509	Peruvian anchovy (*Engraulis ringens*), Chilean jack mackerel (*Trachurus murphyi*), Chub mackerel (*Scomber japonicus*)
Chile	14	776	Peruvian anchovy (*Engraulis ringens*), Chilean jack mackerel (*Trachurus murphyi*), Chub mackerel (*Scomber japonicus*)
Thailand	60	442	Sardinellas (*Sardinella* spp.), Indian mackerel (*Rastrelliger kanagurta*), Indian mackerel nei (*Rastrelliger* spp.), Anchovies nei (*Engraulidae*)
United States	25	243	Gulf menhaden (*Brevoortia patronus*), Atlantic Menhaden (*Brevoortia tyrannus*), Atlantic herring (*Clupea harengus*), Pacific herring (*Clupea pallasii*), California sardine (*Sardinops sagaxcaerulea*)
Japan	90	207	Chub mackerel (*Scomber japonicus*), Japanese anchovy (*Engraulis japonicus*), Japanese jack mackerel (*Trachurus japonicus*), Japanese sardine (*Sardinops melanostictus*), Pacific herring (*Clupea pallasii*)
Denmark	20	186	Atlantic herring (*Clupea harengus*), Norway pout (*Trisopterus esmarkii*), Blue whiting (*Micromesistius poutassou*), Sand eels (*Ammodytes* spp), European sprat (*Sprattus sprattus*)
China		239	Chilean jack mackerel (*Trachurus murphyi*), Chub mackerel (*Scomber japonicus*), Japanese anchovy (*Engraulis japonicus*), Japanese jack mackerel (*Trachurus japonicus*), Japanese sardine (*Sardinops melanostictus*), Pacific herring (*Clupea pallasii*)
Norway	22	152	Capelin (*Mallotus villosus*), Norway pout (*Trisopterus esmarkii*), Blue whiting (*Micromesistius poutassou*), Sand eels (*Ammodytes* spp), European sprat (*Sprattus sprattus*)
Mexico	50	84	California sardine (*Sardinops sagaxcaerulea*), Chub mackerel (*Scomber Japonicus*)
Iceland	32	146	Capelin (*Mallotus villosus*), Blue whiting (*Micromesistius poutassou*), Atlantic herring (*Clupea harengus*)
Morocco		61	European anchovy (*Engraulis encrasicolus*), European sardine (*Sardina pilchardus*)
Ecuador		93	
Russian Federation	50	68	
South Africa		85	S. African anchovy (*Engraulis encrasicolus*), Cape horse mackerel (*Trachurus capensis*), S. African sardine (*Sardinops sagax*)
Pakistan		53	
India		48	
Malaysia		47	
Spain		55	
Canada	100	30	Atlantic herring (*Clupea harengus*), Pacific herring (*Clupea pallasii*), Capelin (*Mallotus villosus*)
Other countries		684	
Total production	1,228	5,211	
Average	25		

[a] By-products obtained from Chamberlain (2011), and major species from (Peron et al., 2010).
[b] Production quantity data obtained from International Fishmeal and Fish Oil Organisation (2011).

Table 6 Sources of fishmeal and fish oil used in Norwegian feeds for Atlantic salmon and rainbow trout in 2008 (Winther et al., 2009)

Species	Percent of fishmeal	Percent of fish oil
Blue whiting (*Micromesistius poutassou*)	27	8
Anchovy[a]	23	22
Herring (*Clupea harengus*)	17	23
Sand eel (*Ammodytes marinus*)	14	7
Jack mackerel[a] (*Trachurus symmetricus*)	6	1
Herring cuttings	4	12
Sprat (*Sprattus sprattus*)	4	9
Capelin (*Mallotus villosus*)	1	1
Mackerel (*Scomber scombrus*)	1	
Cuttings, undefined	1	
Menhaden[a]		7
Pilchard[a] (*Sardina* spp)		5
Horse mackerel (*Trachurus trachurus*)		1
Other species	2	3
Sum	100	99

[a] Not landed in the northeast Atlantic.

approximately 38.5 million tons (Davies et al., 2009). Post-harvest waste and discards from recreational fisheries are not included.

Total landings of fish from fisheries and aquaculture, crustacean, and shellfish in 2009 were about 145 million tons (FAO, 2010) of which 118 million tons were for human consumption. However, 118 million tons round weight fish for human consumption produce in the range of 50–60 million tons by-products as skin, bone, blood, and guts. Approximately 10% of this is used for fishmeal and fish oil production (Chamberlain, 2011), the largest quantity probably is dumped back to sea or in landfills. There is a large potential for recovering and utilizing by-products and discards as fishmeal and fish oil.

Harvesting Raw Material from Lower Trophic Levels

Over the past decade, there has been considerable interest in the potential harvest from lower trophic levels. The main driving force is that these species are mostly non-utilized stocks with large standing biomasses. Furthermore, for many species, like krill and copepods, annual production often exceeds the standing biomass and can thus support a high annual harvest. For example, a total catch of only 1% of annual production of *Calanus* in the Norwegian Sea will yield 2–3.5 million tons for production of marine oils and protein. It is also well established that the supporting biomass at lower trophic levels is generally an order of magnitude higher than the next trophic level (Pauly and Christensen, 1995). Following this, it is possible to argue for either a catch of, e.g., 100,000 tons of herring or 1 million tons of its natural food *Calanus*.

Although there are several principal candidates for such harvests, such as mesopelagic fish, krill, amphipods, and copepod species (Olsen et al., 2010), only a few can be regarded as economically and practically feasible at the present time. This is due to limitations instituted by local governments, lack of schooling behavior that increases the cost of fishing, and high rates of autolysis after they are landed (Olsen et al., 2010). The species that has received the most attention is Antarctic krill (*Euphausia superba*). The total biomass in the Antarctic has been estimated at 50–500 million tons with variations due to methods used for abundance estimation and uncertainty of estimate (Nicol et al., 2000; Siegel, 2005; Atkinson et al., 2008).

These fisheries are regulated by the Conservation of Antarctic Marine Living Resources (CCAMLR). For sub-area 48, the Scientific Committee of the CCAMLR has agreed to a precautionary catch limit of 3.47 million tons (Anonymous, 2007). However, total catch (area 48) reported for the 2007/2008 season was small (around 150,000 tons), so there is a significant potential for increased harvest. Other krill and planktonic species are likely to attract interest in the coming years.

Another promising group is mesopelagic fish. This is a group of fish that live in the intermediate pelagic water between the euphotic zone at 100 m depth and the deep bathypelagic zone at 1000 m. Fisheries were explored during the 1980s but never developed. However, global biomass has been estimated to around 1,000 million tons (Gjøsæter and Kawaguchi, 1980) with particular high densities in the Arabian Sea with stocks of several hundred million tons (Gjøsæter and Kawaguchi, 1980; Gjøsæter, 1984). The major group of mesopelagic fish, myctophtids, has an estimated biomass in a range of 600 million tons. In the Antarctic region, myctophids amount to around 70–396 million tons (Sabourenkov, 1991; Kozlov, 1995). Although being relatively small in size, most species can still be caught in high densities with commercial trawls and may thus be attractive as targets for commercial fisheries. Many are also relatively rich in lipids and constitute a significant lipid source. Mesopelagic fisheries have a huge potential for catch based on their population biomass alone. Even with moderate estimates, a harvest of 4 million tons in the Antarctic is realistic.

However, fishing at lower trophic levels does need to proceed with caution, as these organisms are feed for fish and mammals farther up the food web. Future harvest may thus affect the ecosystem nutrient flow and fisheries farther up the food web. On the other hand, the current pattern of harvest, where higher trophic levels are heavily overexploited, is not the most sustainable and quantitatively most efficient. It is therefore possible, or likely, that properly regulated future fisheries exploiting the full range of trophic levels of marine ecosystems can be more sustainable with higher biomass harvest than present-day fisheries.

Criteria for Sustainable Harvest of Forage Fish

Harvesting of well-managed resources should not result in lasting footprints on the marine ecosystems, especially because these species of fish have short life histories. Fishing methodology applied for harvesting small pelagic fish, such as purse seining, has also been verified as energy efficient in relation to harvested biomass (Schau et al., 2009).

The quality of management of fish resources varies substantially throughout the world. In the most developed regions, resources are well managed, while in other areas, such systems are only partly in place or absent. According to the FAO, four main elements should be in place for a successful management of living resources (FAO, 1995):

1. Scientific knowledge about the resources and a system for transferring this knowledge to advice for management.
2. A management system consisting of (a) legislation and (b) political will to govern internationally through negotiations with other states and to govern human activities (the fishery) nationally.
3. An active control of the fishery.
4. A system for accounting fish catch (fishery statistics).

The management of fisheries is strongly dependent on the degree of the success of these four factors, and each factor is important for successful management of fish resources (FAO, 1996).

In the northeast Atlantic region, The International Council for the Exploration of the Seas (ICES, www.ICES.dk) has the main task of providing knowledge and scientific advice for the management of living marine resources in the region. The status of the stocks is determined by assessments made by the scientific expert groups within ICES. The most important clients are the European Union (EU), Russia, Norway, United States, Canada, and Iceland. The advice given is standardized to meet the requirements of managers to assess the status and development of the resources. The information is centered on a set of reference points for sustainable fisheries. These include spawning stock biomass monitoring and the degree of harvest (fishing mortality) (ICES, 2010a). Managers respond to changes in these parameters in order to achieve a long-term optimal yield and to avoid collapse of the stocks.

Fish stocks are interactive due to predation and food competition among other factors. By harvesting one stock, other stocks are affected. Bycatches also complicate management because it is often incorporated as an unaccounted fishing mortality. It is, therefore, a challenge to manage ecosystems in a way that gives the highest economical long-term yield of the system. Fish stocks migrate between different economic zones and international waters. This complicates the management and leads to conflicts between counties, often resulting in overexploitation.

Northeast Atlantic stocks that are used as feed for the aquaculture industry (Table 6) include blue whiting, herring, sand eel, and sprat. They are all subject to harvest control rules and are managed according to precautionary principles. However, the status of these stocks varies. Sand eel stocks in the North Sea are managed by the EU and Norway and are suffering from recruitment failure, which has led to a decrease in stock size (ICES, 2010c). Further reductions of fishing mortality are necessary for the stocks to recover, especially in the northern parts of the North Sea.

In addition, blue whiting stocks have experienced impaired recruitment, and the stocks have decreased in recent years (ICES, 2010d). This stock is managed by the EU, Norway, Russia, Iceland, and the Faroe Islands. A management plan has been implemented, which means that the harvests are adjusted in relation to the rebuild or depletion of the stock. The fishery, therefore, must be classified as being managed according to precautionary principles. The fish stocks used for aquafeed in Europe (Table 6) are considered by ICES to be harvested sustainably. The stocks are managed by management plans, and these plans are evaluated by ICES to be in accordance with a sustainable harvesting of the stocks (ICES, 2010b,c,d).

Other sources of raw material for the production of aquafeeds are sardine, which dwell off northwest Africa, and anchovy off Chile and Peru. There is little information of the abundance of sardines. Morocco, Mauritania, and Senegal perform acoustic abundance estimates of the stock, and an assessment is done by an FAO expert group dealing with small pelagic stocks in the area (FAO Working Group on the Assessment of Small Pelagic Fish off Northwest Africa, 2008). The estimated stock of these fish seems to be good for allowable catch (G. Bianchi and J. Csirke, FAO, Rome, personal communication). However, the management system is not well developed, and quota systems are not in place. This stock, therefore, has the potential to be vulnerable to overfishing.

Anchovy stocks off the coast of Peru and Chile are surveyed and regularly monitored by the scientists who perform assessments in these countries (FAO, 2010). According to FAO officials, the management system is also functioning well (G. Bianchi and J. Csirke, FAO, Rome, personal communication). In 2010, the stock was in good condition. However, it is a challenge from the stock-management perspective to predict the stock status because of the wide fluctuations in stock size due to changes in the climatic conditions (El Niño) and to adjust harvest quota accordingly.

In general, the marine recourses used by the salmon industry are managed in a way that prevents the stocks from overfishing and collapses. However, based on a long-term maximum sustainable harvest yield, there is potential for more efficient management of most fisheries. The potential seems even larger if a proper ecosystem approach is used for stock management in the future.

Plant Feed Ingredients

Increasing the use of plant feedstuff into salmon diets is often marketed as a sustainable alternative to marine products. However, this may not be as obvious as claimed. The main challenges in using plant protein sources in diets for carnivorous fish lie in their lower levels of protein and higher levels of starch, unfavorable amino acid and mineral profiles, and high levels of fiber (Hemre et al., 2009). They also contain many unwanted components, such as indigestible carbohydrates (Hemre et al., 2003; Opstvedt et al., 2003) or antinutritive factors (ANFs) (Krogdahl et al., 1994, 2010; Francis et al., 2001), that will affect both growth rates and fish welfare. There is also a challenge with levels of some limiting essential amino acids that reduce production efficiency. Well-formulated mixtures of plant proteins and improved processing conditions show potential to increase the nutritional values. Today moderate inclusions of plant protein will result in fish growth rates that are comparable to fishmeal (Hemre et al., 2009). But challenges remain to incorporate higher levels of plant protein and their concentrates in fish feeds.

Production and processing of many plant feedstuffs is highly dependent on such non-renewable resources as fossil fuels, electricity, chemical fertilizers, pesticides, herbicides, and hybrid seeds. Furthermore, increase in grains and oilseeds production requires the use of large land areas and fresh water for irrigation purposes. For example, expansion of soybean agriculture in Brazil has caused the destruction of most of the Cerrano ecosystem, and this expansion is threatening the southern Amazon forest. Therefore, the soybean trade between Brazil and Europe is creating environmental, social, and economical concerns that have not yet been fully resolved (Cavalett and Ortega, 2009).

Some markets have a general skepticism toward genetically modified organisms (GMOs) in food and feed. This is mainly due to potential ecological impacts and health risks for humans and the production animals. EU regulations require labeling of feeds containing protein or DNA from GMOs with "This product contains genetically modified organisms" (EU-Regulation, 2003). The European feed manufacturers have therefore avoided use of GMO ingredients in fish feeds.

The inclusion levels of plant proteins and lipids are shown in Figure 3. Since introduction of pelleted diets to salmon during the early 1970s, plant proteins (e.g., corn, wheat, soybean, canola or rapeseed, lupin,) and their concentrates have been added in low levels ($\approx 10\%$), partly as a component of carbohydrate sources (e.g., wheat) as a source for improving pellet quality and as partial replacement of fishmeal with cheaper protein sources. The inclusion level has steadily increased since 1990, and by 2010, the level had increased to approximately 40%.

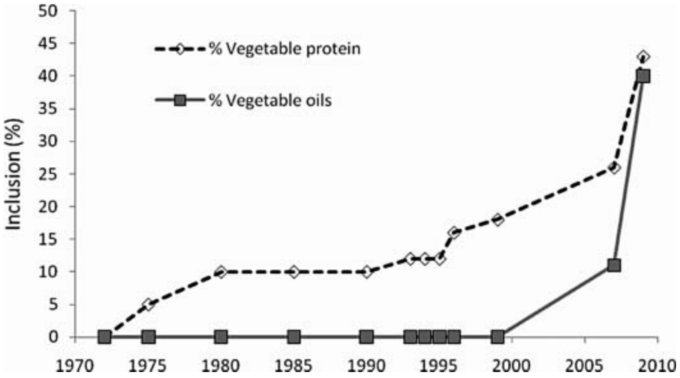

Figure 3 Inclusion levels of vegetable proteins and oils in Norwegian salmon diets; information provided by the major feed producers in Norway and calculated on the basis of information from Norwegian Seafood Federation (FHL), Norway (www.fhl.no).

The production of Atlantic salmon in 2009 was approximately 1.5 million tons (Table 1). Based on 38% protein, 37% lipids, and 10% digestible carbohydrates in the diets and an FCR of 1.25, the quantity required for the respective nutrients will be 690,000 tons protein, 660,000 tons lipids, and 180,000 tons carbohydrates.

Assuming a salmon feed based on 100% plant sources, the total agricultural area needed to cultivate various crops will be approximately 1.1 million ha based on the following estimates:

carbohydrates ≈ 270,000 tons of wheat (United States) ≈ 75,000 ha;
proteins (–contribution from wheat) ≈ 1,560,000 tons soy (Brazil) ≈ 675,000 ha;
lipids (–contribution from soybean) ≈ 950,000 tons rapeseed (Europe) ≈ 320,000 ha.

The hypothetical area required for supplying 100% of the macro nutrients (protein, fat, and carbohydrates) from plant sources (wheat, soybeans, and rapeseed) is in the scale of 45% of the total agricultural land in Denmark.

Dependency on Fishmeal and Oils

It has been claimed that salmon farming is heavily dependent upon fishmeal and oil for its production (Naylor et al., 1998; Tacon and Metian, 2008). Fishmeal is generally included in feeds as an excellent source for essential amino acids and related components that promote feed palatability. Fishmeal has always been a relatively expensive feed ingredient compared to soybean meal, with its cost remaining relatively constant in the past at 2 to 2.5 times higher (Asche and Tveteras, 2004). However, during the late 1990s, there was an increase in the price of fishmeal, most likely driven by increased demand, not only for aquafeeds, but also for swine and poultry feeds (Kristofersson and Anderson, 2006).

Increased demand for marine resources was predicted due to the growing need of fishmeal and oil caused by the expanding aquaculture industry (Naylor et al., 2000). History has proven this to be wrong. Rather, increased use of fishmeal and fish oil has resulted in higher prices for marine feed ingredients and increased use of plant proteins and oil (Figure 3). There have not been increased landings of fish for reduction purposes, rather a slight decline the last years (Chamberlain, 2011). This shows that innovation in the aquaculture feed industry has been able to develop alternative protein and fat sources and that regulations of fisheries have worked by preventing increased landings of forage fishes.

The recent findings of an EU project show that it is feasible to reduce both fishmeal and fish oil in feeds substantially, 12–16% and 8–12% respectively, with the use of alternative feed ingredients from plant origins without significantly affecting the growth performance of the fish or their nutrient utilization (Aquamax, 2010). In some studies, however, salmon fed feeds based on 80% of dietary protein and 70% lipids from plant protein and vegetable oil sources have shown reduced feed intake and lower growth performance compared to fishmeal-based diets. Reductions in fishmeal level at the expense of fish and plant protein concentrates do not show reduced growth rates (Torstensen et al., 2008; Storebakken et al., 1998; Espe et al., 2006, 2007), however, the use of these products at higher levels may not be economically feasible for commercial aquaculture at present. Higher level fishmeal reductions have been achieved in rainbow trout than Atlantic salmon (Kaushik et al., 1995; Vielma et al., 2000).

Advances in processing conditions have resulted in high-quality soybean and rapeseed (canola) protein concentrates, but so far, their cost has been prohibitive for use in commercial feeds. Moreover, the concentrations of amino acids and balance of digestible (available) amino acids from various protein sources in feeds should conform to the essential amino acids requirements of fish, but these requirements are largely unknown. Depending on the protein source and the method used in processing, antinutrients may also exert a significant effect on amino acid utilization, gut functions, and immune response. Plant proteins lack some of the compounds that promote food intake and enhance palatability; thus, additional research is required to identify these compounds and develop suitable feed additives to improve the nutritional value of feeds based on plant proteins. Ongoing collaborative research efforts between plant geneticists, product processors, and fish nutritionists will resolve the major technical problems associated with ANFs and plant protein quality.

Dietary lipids are important sources of energy and essential fatty acids (EFA) in salmon diets. Energy requirements of Atlantic salmon can be met by protein and, to a lesser extent, by carbohydrates, while long-chain (C_{20} and C_{22}) polyunsaturated fatty acids (PUFA) of the n-6 and n-3 series are required for optimum growth, health, gonad development, cellular integrity, and eicosanoid production. (Sargent et al., 1999a,b, 2002; Henderson and Tocher, 1987; Tocher et al., 1998, 2003). The requirement for PUFA in salmon is estimated to be about 1% of the diet and can be supplied by including approximately 4% fish oil in feeds (Olsen et al., 1991; Yang and Dick, 1994). The early commercial dry pelleted feed of the 1970s contained between 10 and 20% lipids. Since that time, fat levels have increased to about 35% today (Froyland et al., 1998) (Figure 2). The reasons for the increase were higher availability of good quality fish oils, increased stability of fish oil in the feed, technological achievements making it possible to produce feeds containing high fat levels, governmental regulation stimulating high-energy diets, consumer preferences for high fat levels in the salmon, feed costs, and increased growth rate and protein-sparing effects (Bell et al., 2001, 2004; Froyland et al., 1998; Stubhaug et al., 2005; Torstensen et al., 2000).

The industry does not seem to favor reducing the dietary fish oil levels significantly. One reason is that a major marketing argument for Atlantic salmon is its high n-3 highly unsaturated fatty acids (HUFA), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA) content, which have many health benefits for consumers including reduced risk of coronary heart disease (Mozaffarian and Rimm, 2006). The industry, however, is looking for alternatives to fish oil. Driven both by a limited global supply and also for economical benefits by replacing high-priced fish oils with less expensive alternatives, the strategy used by industry is to blend marine oils with vegetable oils.

Replacing fish oil with plant oils, which are deficient in n-3 HUFA, however, reduces the content of EPA and DHA in fillets and, thus, the health benefits for consumers (Anonymous, 2010c). Several strategies have been developed to maintain high levels of EPA and DHA in fillets by finishing diets prior to harvest (Torstensen et al., 2005). Still, increasing vegetable oil addition will inevitably reduce the content of these fatty acids, thus requiring consumers to eat larger portions of farmed salmon to obtain the desired health benefits. Fortunately, the portion required to achieve health benefits is lower than common portion sizes. Minimum levels of fish oil inclusions will probably be set by the lowest portions recommended for eating (European Food Safety Authority [EFSA], 2010). Although new sources for n-3 HUFA are being sought, at present, there are no real alternatives to fish oils as sources of EPA and DHA.

INDICATORS FOR ASSESSMENT OF SUSTAINABLE USE OF FISHMEAL AND FISH OIL IN SALMON FEEDS

The Organisation for Economic Co-operation and Development (OECD) defines indicators for sustainable development as a "statistical measure that gives an indication on the sustainability of social, environmental and economic development. Sustainable development indicators are indicators that measure progress made in sustainable growth and development" (OECD, 2005, n.p.). Suitable indicators should be simple and directionally clear (Valentin and Spangenberg, 2000), where simple means that their calculation should be transparent, and directionally clear means that they should indicate trends relevant in terms of sustainability and that they are able to signal progress. A number of indicators have been used to assess the sustainability of aquaculture production, but all of them suffer from flaws and are subject to misinterpretation.

The ratio or indicator "fish in to fish out" (FIFO—the unit of fish consumed per unit fish produced) is commonly used to highlight the high inclusion rate of fishmeal and fish oil in diets for carnivorous fish and shrimp and, as such, is often used to argue that salmon farming is not sustainable. Although the FIFO calculations may be useful to measure raw material usage in salmon diets, it is argued here that the index is not an appropriate indicator for environmental or ecological sustainability of salmon farming. Furthermore, the FIFO index has many flaws and should be improved even with current usage. Although there are several methods for calculating FIFO (Tacon and Metian, 2008; Kaushik and Troell, 2010), the most common use FCR and feed composition data to calculate the amount of fishmeal and fish oil used per unit fish produced. The amount of fish oil is the net added quantity and not the fat content of the diets, as fishmeal also contain approximately 10% fat. Based on global average wet-fish-to-fishmeal yield (22.5%) and wet-fish-to-fish-oil yield (5%), the amount of fish needed for providing fishmeal and the extra fish oil are calculated, and the largest number is presented as the total FIFO number (Tacon and Metian, 2008). There are, however, several limitations by using this calculation:

- The intention of calculating FIFO is to get an indicator for long-term sustainability of fish resource use (Tacon and Metian, 2008), but it does not specify whether this is an ecological dimension of danger for overexploitation or ethical where fish suited for human consumption is used as feed. It does say something about total use of marine resources but nothing about the sustainability of harvest or the relative efficiency of use.
- Twenty-five percent of world fishmeal production comes from fishery by-products (Chamberlain, 2011), and the FIFO does not take this into account. The FIFO will therefore give an overestimation of the fish input.
- A substantial amount of additional "fish" is needed for supplying the high oil levels used within salmon diet. The surplus fishmeal fraction is used in feeds for other animals. This additional meat output is not included in the calculation (Kristofersson and Anderson, 2006).
- By-products of Atlantic salmon are, to a large extent, utilized as feeds for other animals as salmon oil, fishmeal, or hydrolysates. These products go back into the fishmeal and fish oil pool and should be subtracted from the amount of fishmeal and oil used in salmon production.
- The retention of nutrients is not considered. The protein level in salmon and the fishes used in fishmeal production are at a comparable level, but lipid is not. Salmon contain 20% lipids based on round weight (Berge et al., 2005; Hemre and Sandnes, 2008) compared to approximately 7% in the case of the "average" forage fish (Crampton et al., 2010). Not

compensating for this difference in content results in a three times overestimate of fat used.

- Considering the ethical issue of feeding edible fish to salmon, the FIFO does not take into account processing yields of small pelagic fishes, which is relatively low compared to the high edible yield of salmon (Bjørkli, 2002).
- The FIFO does not give any indication of the alternative uses of the fish. As landings of fish used for reduction has been relatively constant during the last decades, this quantity is independent of demand from aquaculture (Kristofersson and Anderson, 2006).

Because of these shortcomings, it has been suggested that FIFO should be replaced by the marine nutrient dependency ratio (MNDR) (Crampton et al., 2010) or, more specifically, one for protein (MPDR) and one for oil (MODR). The dependency ratio is calculated as (protein (or oil) fed) : (protein (or fat) produced). This ratio has several advantages over the FIFO index, although the word "dependency" seems inaccurate and should be replaced. Dependency could be both economic or nutritional, and what is economically feasible does not reflect what is nutritionally required. At present, Atlantic salmon can be produced with an MPDR of 0.66 and an MODR of 0.8 (Crampton et al., 2010). MODR assumes comparable fatty acid profiles in the dietary marine lipids as the salmon fillet. By inclusion of plant fat sources, this will not be true. It can thus be questioned if a ratio between "fed" and "produced" in this case will be correct.

A refinement was suggested by the Salmon Aquaculture Dialogue (World Wide Fund for Nature [WWF], 2010). The prerequisite for sustainable feed production is presence and evidence for traceability of all feed ingredients and that no feed ingredients originate from species on the IUNC Red List of Threatened Species (International Union for Conservation of Nature [IUCN], 2010). The Salmon Aquaculture Dialogue (WWF, 2010) suggested the use of two indicators for assessing sustainability of salmon feeds—forage fish dependency ratio (FFDR) and fish protein index (FPI)—and also suggests acceptable values for these indicators.

The FFDR is calculated for fishmeal (*m*) and oil (*o*), respectively, as

$$\begin{aligned}\mathrm{FFDR}_m &= ((\%\text{fishmeal in feed from forage fisheries})\\ &\quad \times (\text{eFCR}))/22.5,\\ \mathrm{FFDR}_o &= ((\%\text{fish oil in feed from forage fisheries})\\ &\quad \times (\text{eFCR}))/5.0,\end{aligned}$$

where eFCR (economical FCR) is calculated as: eFCR = (feed (kg)/(net aquaculture production, kg (wet weight), and the number 22.5 and 5 take into account the conversion (yield) into fishmeal and fish oil, respectively.

The percentage of fishmeal and fish oil excludes meals and oils from fishery by-products and whole fish rejected for human consumption by official regulations. The suggested acceptable levels for sustainability are $\mathrm{FFDR}_m < 1.31$ and $\mathrm{FFDR}_o < 2.85$.

The FPI is the ratio of protein in the salmon and the amount of protein from forage fisheries fed:

$$\begin{aligned}&\mathrm{FPI} = (\text{protein in salmon(kg)})/\\ &((\text{kg fishmeal from forage fisheries in feed}) \times 0.68 \times (\text{eFCR})),\end{aligned}$$

where 0.68 is the average protein content of fishmeal (68%/100).

The suggested acceptable limit is 0.8, and it is suggested that it be implemented no later than 1 January 2014.The rationale for developing the $\mathrm{FFDR}_{m/o}$ and the FPI is to ensure that increasing demand for feed ingredients from a growing aquaculture industry do not result in overfishing and collapse of small forage fish stocks. It is doubtful that this will have any significant effect on fishing intensity, as there are other markets for fishmeal. However, forcing the industry to develop alternative protein and lipid sources will enhance further increases in production of salmon. The limitation of these indicators is similar to the MPDR/MODR in that the word "dependency" could be misleading. It is not a nutritional dependency, it is a use of input factors with the objective of low production costs and high productivity, the main drivers for the development of the industry (Asche, 2008). For example, Atlantic salmon does not require 35% fat in the diet. This could easily be reduced by up to 75% without creating nutritional deficiency problems in the salmon. However, it would reduce growth rates and increase production costs.

REGIONAL DIFFERENCES IN PRODUCTION

There are marked regional differences in both material and energy usage and its associated emissions per unit of Atlantic salmon produced. Overall, the impacts are lowest for Norwegian production in most impact categories and highest for United Kingdom-farmed salmon (Pelletier et al., 2009). FCRs are reported to average 1.103 in Norway, 1.331 in the United Kingdom, 1.313 in Canada, and 1.493 in Chile. This is a remarkable difference (35%), as farming technology is comparable and the production is more or less run by the same companies in all four countries (Table 2), although it can partly be explained by differences in the national regulatory framework on feed composition.

There are, however, also significant differences within each country. In Norway, for example, eFCR ranges from 1.18 to 1.39 with both annual and regional differences (FDIR, 2010a). It is also noticeable that the regional difference appears to be similar from year to year. The reported eFCR values are, in all cases, high compared to reported biological FCR values that range between 0.8–1.0 (Einen et al., 1999; Bell et al., 2010; Oxley et al., 2009; Noble et al., 2008; Krogdahl et al., 2004; Nordgarden et al., 2003). There are several reasons for this. Feed composition and feeding regimes (monitoring, overfeeding) will certainly influence the eFCR, although diseases, unexplained mortalities, escapes, and other losses during the production cycle have a major impact on the eFCR. For example, the fish losses in Norwegian salmon farming in 2009 were approximately 20% and included mortality (35 million), discarded at processing

(1.9 million), escapees (0.2 million), and unidentified losses (8.7 million) of a stock of 233–239 million Atlantic salmon (FDIR, 2010b). Linear regression of the regional eFCR values versus the corresponding percentage of fishes lost during the years 2008 and 2009 gave the equation eFCR = 70,894 × (% losses) – 71,903. This equation explains (R^2) 24% of the variation, demonstrating that reductions in diseases and fish losses are important factors in improving the sustainability of salmon production.

ATLANTIC SALMON—OUR MOST EFFICIENT LIVESTOCK?

The large reduction in unit price of Atlantic salmon over the past years indicates that the market is not strongly linked to markets for other products except other salmonids (Eagle et al., 2004). There is little price correlation to poultry, swine, or other agricultural products. Most likely, farmed Atlantic salmon wins share from a large variety of products and that the effect on each of them is too small to detect (Asche et al., 2001).

Producing food by intensive aquaculture of carnivorous fish, like Atlantic salmon, is in many respects comparable to agricultural meat production (Folke and Kautsky, 1989). With respect to sustainability, the Atlantic salmon industry should be compared to intensive agricultural production of meat, and primarily to the agricultural meat production based on grain and oilseeds as feedstuffs like poultry and pig (Forster and Hardy, 2001).

Compared to terrestrial animals, Atlantic salmon are very efficient in retaining protein and energy. The reproductive capacity is huge, and the resources used to produce seeds are insignificant compared to poultry and swine. They are poikilotherms and do not require energy for maintaining a constant body temperature. They are living in the aquatic environment, where excretion of ammonia, in addition to urea, lowers the cost of metabolizing amino acids. Furthermore, fish are practically weightless in the water and do not need to expend energy for carrying their body weight or opposing gravity, and a weightless animal does not need a strong and heavy skeleton.

The processing yield of Atlantic salmon is relatively high compared to domestic animals (Åsgård and Austreng, 1995; Bjørkli, 2002). Bleeding results in a weight loss of approximately 2% (Erikson et al., 2010). Atlantic salmon also deposit most of the fat in the muscle, giving a higher slaughter yield compared to fish that deposit lipid in the liver. Reported slaughter yields (bled and gutted) vary between 86 and 92% (Bjørkli, 2002; Einen et al., 1999) and are influenced by gonad size and visceral fat deposition. The relative low weight of the skeleton give fillet yields of 75–77% (Skjervold et al., 2001; Rora et al., 1998) or edible yields in the range of 60–68% (Bjørkli, 2002; Einen et al., 1999). Bjørkli (2002) compared edible yields of Atlantic salmon to pig, poultry, and lamb, and Atlantic salmon yields were substantially higher (Table 7). The values presented in Table 7 are comparable to an earlier study (Åsgård et al., 1999), with only minor differences in the numerical values. These calculations take into account differences in FCR, differences in edible yields, and the cost of progeny. Atlantic salmon has a higher protein and energy retention in the edible part of the animal compared to other domestic animals. Pig, the most efficient terrestrial domestic animal, has an FCR of more than twice that of Atlantic salmon. The energy retention in edible part of the pig is 14% compared to 23% in salmon, and protein retention is 18% and 31%, respectively (Table 7).

Table 7 Product yield, energy, and protein retention in edible parts of Atlantic salmon, pig, chicken, and lamb (Bjørkli, 2002)

	Atlantic salmon (*Salmo salar*)	Pig (*Sus scrofa*)	Chicken (*Gallus gallus*)	Lamb (*Ovis aries*)
Harvest yield (%)[a]	86.0	72.5	65.6	46.9
Edible yield (%)[b]	68.3	52.1	46.1	38.2
FCR[c]	1.15	2.63	1.79	6.3
Energy retention (%)[d]	23	14	10	5
Protein retention (%)[e]	31	18	21	5

[a] Harvest yield is yield of gutted and bled animal.

[b] Edible yield is ratio of total body weight that is normally eaten, muscle, body adipose tissue and liver, lung, and heart for pig. Skin is excluded for all animals.

[c] FCR = (kg feed fed)/(kg body weight gain).

[d] Energy retention = (energy in edible parts)/(gross energy fed).

[e] Protein retention = (kg protein in edible parts)/(kg protein fed).

Lipids are the main dietary source of energy for Atlantic salmon. Based on an edible yield of Atlantic salmon of 68% (Bjørkli, 2002), a fillet fat content of 20% (Skjervold et al., 2001), an FCR of 1.2, and a dietary fat content of 35%, the apparent yield of fat is around 30%. In this respect, salmon is the most efficient farmed animal to convert feed-grade fish oil into food for humans. It probably also compares well with the industrial production of ω3 concentrates sold as food supplements.

The GHG em (CO_2 equivalents) gives a slightly different picture. In terms of calculations based in relation to edible product, Atlantic salmon shows an emission comparable to wild-caught Atlantic cod and chicken (Table 8) while substantially less than beef and pork. The reported value of 2.9 kg CO_2 equivalents per kg edible fish (Winther et al., 2009) is in the range of those reported elsewhere, 2.2–3.0 (Ellingsen et al., 2009; Pelletier et al., 2009). There are, however, large regional differences ranging from 1.78 kg CO_2 eq/kg (whole weight) for Norwegian-produced salmon to 3.27 CO_2 eq/kg (whole weight) for fish produced in the United Kingdom (Pelletier et al., 2009), but this has been explained by higher use of marine resources for fish produced in the United Kingdom.

A salmon fed a diet based on lower levels of marine byproducts is more energy efficient than a salmon fed a diet containing a higher amount of ingredients used from marine sources because, in general, land-based crops can be produced more efficiently with respect to GHG em than fish caught commercially

Table 8 Carbon footprint for fish (kg CO_2 eq/kg edible part) and meat

Product	kg CO_2 eq/kg edible part	Reference
Beef (Swedish)	30	Cederberg et al. (2009)
Pork (Swedish)	5.9	Cederberg et al. (2009)
Chicken (Swedish)	2.7	Cederberg et al. (2009)
Atlantic salmon (farmed)	2.9	Winther et al. (2009)
Atlantic cod (*Gadus morhua*)	2.9	Winther et al. (2009)
Herring (*Clupea harengus*)	0.52	Winther et al. (2009)

(Ellingsen et al., 2009). Another reason for the higher gas emissions from marine feed ingredients is the cost of drying process to produce fishmeal (Cappell et al., 2007).

IMPACTS OF FEEDING IN OPEN-CAGE SYSTEMS

Substantial quantities of solid and dissolved waste are discarded from salmon farms into the environment, the majority from grow-out stages in marine cages. The principal sources of waste in farm effluents are surplus diet, fecal excretion, and metabolic end-products.

The amount of wasted feed by surplus feeding or pellet fines depends highly on husbandry practices on the farm and processing quality of the feed. Surplus feed are usually consumed by wild fish around the cages (Husa et al., 2010) and represents as such not a solid and dissolved waste problem.

Feces contain about 6% of the feed organic matter and 70% of the ash (Denstadli et al., 2006; Refstie et al., 2004), resulting in an excretion of about 110–130 kg dry feces per tonne of feed fed. The quantity excreted is, however, strongly influenced by the feed composition. Feed ingredients containing high levels of ash and fiber will increase excretion, whereas it is reduced with higher inclusions of dietary energy (lipids) and highly digestible fishmeal. Further reduction in fecal waste can be achieved by using processed products like plant protein concentrates and refining feed formulations and with advances in extrusion technology.

The holding capacity of a fish farm site is defined as the maximum fish production that allows a viable macrofauna to be maintained in the sediment beneath the cage (Hansen et al., 2001). Exceeding the holding capacity will shift decomposition processes from aerobic to anaerobic, and sulphate reduction may predominate (Holmer and Kristensen, 1996). An increase in the activity of sulphate-reducing and methanogenic bacteria within the sediment has resulted in out-gassing of carbon dioxide and/or hydrogen sulphide at some marine cage farms (Samuelsen et al., 1988). This has been attributed to loss of appetite, gill damage, and increased mortalities of fish. In addition, stress induced by exposure to hydrogen sulphide and poor water quality may be responsible for the increase in and persistence of disease at some fish farms. In areas away from the sea cages, as organic material flux and oxygen demand decrease, animal communities return to background conditions typified by increased species diversity and functionality (Kutti et al., 2007b).

The largest environmental impacts of marine cage farming are restricted to the immediate vicinity of the aquaculture operation (Kutti et al., 2007a). Large-scale effects on the benthos in close proximity are generally limited within 250 m of the farm (Kutti et al., 2007b). Many factors can influence the extent of environmental impacts—geographical location of the site, type of cultivation practice, conditions of natural habitats, natural systems capacity, type of feed and feed additives used, therapeutants, and geological and hydrological conditions. For example, when farms are located in shallow waters or those having low tidal currents, the buildup of organic matter may be significant (Brown et al., 1987; Tsutsumi et al., 1991), while relocation of cages to deeper (50–300 m) sites with stronger water currents will reduce the problems (Kutti et al., 2007a).

Significant progress in research activities has enabled a better understanding of digestion, absorption, and excretion of feeds by fish, and the new knowledge of in vivo metabolism in fish has resulted in higher nutrient and energy retention as well as lower excretion of metabolic end-products. This has resulted in higher nutrient and energy retention as well as lower excretion of metabolic end-products via the gills and in dissolved waste in urine. As a consequence of these efforts, metabolic excretion from Norwegian salmon farms has increased by only 20% between 1994 to 2008, despite the fact that production increased four-fold in the same period (Husa et al., 2010).

Mass balance models have been developed for nitrogen and phosphorus, indicating that 50% of the nitrogen and 28% of the phosphorus supplied with the food is lost in the dissolved form (Pearson and Black, 2001). The main effect influencing the nitrogenous waste outputs are those that influence the catabolism and retention of amino acids. Amino acid composition of the diet is therefore a factor with a determinant effect on dissolved nitrogen waste (Cho and Bureau, 2001). A significant amount of research has also been directed toward improving the bioavailability of bound phosphorus in plant protein and fishmeal to reduce undigested phosphorus that settles in sediments (Hua and Bureau, 2010).

OTHER ENVIRONMENTAL CONCERNS

Interaction with Wild Salmon

A major concern for Atlantic salmon farming is interactions with wild stocks. The Norwegian Ministry of Fisheries and Coastal Affairs declared a vision in their strategy for a sustainable aquaculture that diseases associated with fish farming should not result in decline in wild stocks. Furthermore, fish farm escapees should not lead to permanent impacts on the genetic structure of wild stocks (FKD, 2009). A risk assessment in Norway (Taranger et al., 2010), however, indicated that this will be a challenge with respect to the effect of salmon lice on migrating Atlantic salmon smolt and sea trout (*Salmo trutta*)

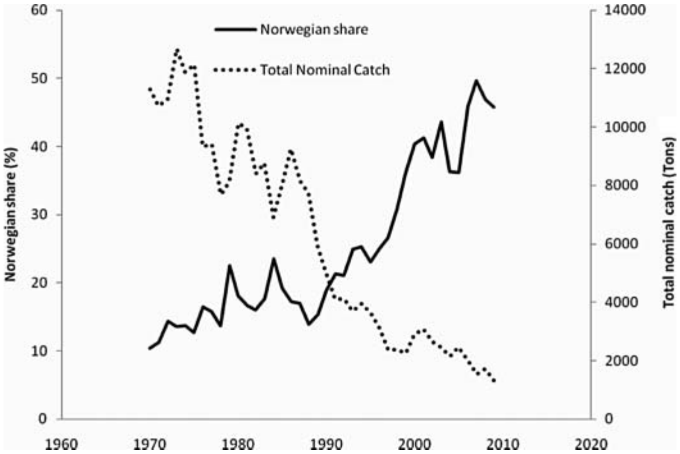

Figure 4 Nominal catch of Atlantic salmon in the North Atlantic and the Norwegian share of this catch (NASCO, 2010).

as well as with respect to the genetic structure in wild salmon stocks.

The situation for Atlantic salmon in the north Atlantic is of concern (North Atlantic Salmon Conservation Organisation [NASCO], 2010), and there has been a dramatic decline in nominal catch during the last 40 years (Figure 4). The nominal catch in the north Atlantic in 2009 (1,300 t) was the lowest in the ICES time series (ICES, 2010e). However, over the same period, the Norwegian share of this catch has increased from about 10% to between 40 and 50%. It can thus be concluded that the general conditions for Atlantic salmon in Norway is relatively better than in the rest of the north Atlantic region, even though 80% of the salmon farming in the Atlantic is done in Norway. There is no apparent relationship between the expansions of catch over time of wild salmon in Norwegian rivers with the quantity of farmed salmon. So far, there seems to be no measurable impact at the national level of Norwegian salmon farming on the wild salmon stocks in Norwegian rivers.

The widely observed downward trends among the geographically distributed stocks indicate that large-scale factors play a key role in controlling the Atlantic salmon abundance. Despite management measures aimed at reducing exploitation in recent years, there has been little improvement in the status of stocks over time. ICES conclude that this is mainly because of continuing poor survival in the marine environment attributed to climate effects (ICES, 2010e). Cultured salmon have brought down the price and largely replaced captured salmon in the market and probably contributed to rebound of some salmon stocks (Diana, 2009), for both Atlantic as well as Pacific salmon (*Oncorhynchus* spp.).

Diseases and Parasites

Diseases represent challenges in relation to impact on wild populations, welfare of the farmed fish, and impacts of therapeutants on the ecosystem. In all forms of intensive culture where species are reared at high densities, infectious disease agents are transferred between individuals. Salmon in cage culture are particularly susceptible to disease transmission, since pathogens are readily transported in sea water and since there are no barriers between fish in cages or between cages and between wild fish and farmed fish. The salmon aquaculture industry, during its development over the last 40 years, has experienced numerous serious disease outbreaks. The quantity of antibiotics used by the salmon industry in Norway peaked in 1987 at approximately 48 tons for treating a production of 55,000 tons primarily against cold water vibriosis (*Vibrio salmonicida*). A commercial vaccine was introduced the same year and resulted in a substantial decrease the following two years before furunculosis (*Aeromonas salmonicida*) caused a second peak in the use of antibacterial agents in 1989 and 1990. The introduction of oil-adjunvanted vaccines during 1992 and 1993 reduced the amount of antibiotics sold to approximately 1 tonne (Markestad and Grave, 1997). For comparison, the sales in 2009 were 1,313 kg for a production of 940,000 tons, or a reduction per unit of fish produced of 99.8% compared to 1987. Meat production from livestock in Norway require 20 times the amount of antibiotics per unit of meat produced, and in an European dimension, the use of antibiotics in Norway is low. Bacterial diseases in salmon farming are presently under control due to efficient vaccines (Bravo and Midtlyng, 2007; Sommerset et al., 2005; Markestad and Grave, 1997).

The viral infections infectious salmon anemia (ISA) and pancreatic disease (PD) together with salmon lice are currently the main health management issues in Atlantic salmon farming. The losses due to ISA in Chile are the most serious losses the salmon farming industry has experienced. The losses started with development of sea lice resistance to emamectin benzoate in 2005 and a subsequent severe sea lice situation. This was followed by extensive outbreak of ISA, which caused a decline in Atlantic salmon production in Chile from almost 400,000 tons in 2005 to an estimated production of 100,000 tons in 2010 (Asche et al., 2009).

ISA was first diagnosed in Norway in 1984 and was since reported in Atlantic Canada (1996), Scotland (1998), the Faroe Islands (1999), and the United States (2000) (Lyngstad et al., 2008). It was probably transmitted to Chile by import of salmon eggs from Norway, and the first disease outbreak in Chile was observed in 2007 (Vike et al., 2009). Mortality from this disease typically increases slowly, and may reach significant levels (0.5–1%/day). The major pathway of infection is probably horizontal (Lyngstad et al., 2008), but there are also indications of vertical transmission (Vike et al., 2009). ISA is listed as a "non-exotic disease" (List 2) in the European Economical Zone (EC-88, 2006). Norway only exceptionally permits vaccination against "non-exotic diseases"(FOR-1996-02-29-223) but uses eradication of confirmed populations and fallowing of the farm site. However, Chile permits vaccination against ISA (PHARMAQ, 2011).

The first diagnosis of PD was in 1976, and it has become a major problem in Ireland and on the west coast of Norway. Symptoms include anorexia, lethargy, and increased fecal cast.

Mortality can be high, but substantial costs are also associated with poor growth rate (Kristoffersen et al., 2009). A vaccine against PD is available (www.aqua.intervet.com), but general approval is not yet issued in Norway to allow its use.

Sea lice, marine ectoparasitic copepods, are distributed worldwide on farmed and wild finfish and have been a problem for farmed salmon from the early days (Brandal and Egidius, 1979). It is estimated that the sea lice control costs in the range of € 0.1–0.2 kg^{-1} or approximately 6% of production costs (Costello, 2009). The most troublesome species is the common salmon lice (*Lepeophtheirus salmonis*) in the northern hemisphere, while Caligus (*Caligus rogercresseyi*) dominate in salmon farms in Chile (Costello, 2006).

Even though the lice problem is long-standing, the development of sustainable methods of controlling has not been able to keep up with resistance development and production intensification, leading to a heavy reliance on very few chemotherapeutants (Denholm et al., 2002). Resistance toward organophospates (1991) and pyretorids (around 2000) have been reported in Norway, Scotland, and Ireland. The first reports on resistance against emamectin benzoate was first reported in Chile in 2005 (Bravo et al., 2008), in the United Kingdom and Ireland in 2006, and Norway and Canada in 2007. Salmon lice is a threat to wild salmon stocks (Skilbrei and Wennevik, 2006), particularly the seaward-migrating wild smolts. Threshold values for treatments against salmon lice are set low in order to limit the negative impacts on wild salmon stocks.

Escapees and Genetic Interaction

Escapees represent problems in relation to genetic interactions with wild populations and as a reservoir for pathogens and parasites. Experimental studies have shown a strong potential impact of escaped farmed salmon on the wild population. Farmed salmon are reproductively inferior to wild fish, and their offspring show reduced survival. Offspring from farmed fish grew faster and seem also to displace wild parr (Fleming et al., 2000; McGinnity et al., 2003). Simulations based on these data suggest a substantial change over ten generations with a fixed intrusion rate of 20% (Hindar et al., 2006). A significant change in genetic profiles was observed over time in the three Norwegian rivers (Opo, Vosso, and Eio Rivers), but no changes in genetic profiles were observed in four others (Namsen, Etne, Granvin, and Hå Rivers). A small reduction in F_{ST} (fixation index) values and genetic distances among populations was observed in the contemporary samples compared with the historical samples, indicating a reduction in population differentiation over time (Skaala et al., 2006).

Area

Use of sea area is mainly a concern in relation to other users, including recreational, fishery, transport, or other aquaculture activities. The net cage area of Norwegian salmon farming is approximately 3–4 km^2 of coastal areas, assuming an average cage depth of 20 m. However, traffic closer to aquaculture operations than 20 m and fishing closer than 100 m is prohibited (LOV-2005-06-17-79). If this is included, the Norwegian salmon farms tie up approximately 60 km^2 and 350 km^2, respectively, or up to 0.4% of a total coastal area of 89,100 km^2 inside the base line.

CONCLUSIONS AND FUTURE PERSPECTIVES

Atlantic salmon is an accepted and appreciated seafood product in the international food market. In view of increasing demand for seafood and the limited ability for further increases in supply of wild fishes, the future market potential for Atlantic salmon seems good. From a 20–30-year perspective, it seems possible to increase the sales by a factor of three to five times the production today. The most obvious limiting factor for future growth in salmon production seems to be availability of sustainable sources of n-3 HUFA.

Presently, there are no cost-effective substitutes for fish oil with respect to supply of n-3 HUFA. Replacement of fish oil with plant oil results in changes in the fatty acid profile of the final product and may influence consumer acceptability. However, dietary fat levels in feeds are far above requirements for the fish, and lowering the inclusion rate combined with increased use of plant oil sources will temporarily solve the shortage. In the long term, new sources for n-3 HUFA may be obtained through the production of lipid-rich single-cell proteins (including algae) by the genetic modification of oilseeds or other sources of oil or by harvesting farther down the marine food web. There is also research with respect to genetic modification of the salmon as an alternative to improve efficiency (Smith et al., 2010).

The claimed dependency of salmon farming on feeds containing fishmeal has been overestimated. Increased demand for fishmeal has resulted in increased prices without apparent increased fishing effort for forage fishes but with increased inclusion rates of terrestrial plant and animal protein sources in diets for salmon. With the size of the salmon farming industry and the research capacity of institutions serving this industry, it is likely that alternate protein sources will be developed to supply the needs of the salmon feed industry.

Marine feed resources used in salmon diets are generally well managed. There are no objective measures showing that plant feedstuffs are more environmentally sustainable that fishmeal and oil. Fishmeal produced from seafood processing byproducts and from well-managed small pelagic fishes has low impacts on the environment, and Atlantic salmon utilize this feed source efficiently compared to other animals. Objectively, there are no reasons for not utilizing these resources for producing salmon. In fact, producing salmon is probably their most efficient use.

Open-cage systems release nutrients into the sea, and fecal material and surplus feed settle beneath the cages. This may create problems locally, but problems connected to eutrophication in a regional dimension connected to salmon farming have not been reported. A focus on low-effluent feed formulations is necessary in order to limit problems with local eutrophication and to permit further growth.

The challenge for the salmon farming industry in the future will be to exploit the possibilities in the market, at the same time keeping the environmental impacts within societies' acceptable limits. The major environmental challenges are interactions with wild salmon through genetic interactions and transmissions of diseases and parasites

Farming of salmon is a young industry; in 1971, the annual production of Atlantic salmon in Norway was 175 tons. This is equal to approximately one day's production of a modern farm. The industry has developed rapidly and made significant important improvements in many areas. However, there is still need for a continued and strong focus on improving the sustainability of the industry. The most obvious task is to reduce the losses of fish during the production. Today, one out of five smolts stocked in a cage will not reach the market due to diseases, escapes, and production disorders. Reducing these losses would improve animal welfare and also reduce the resources used in production.

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