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Summary
Salmon farming is the most highly developed form of large scale intensive aquaculture owing to its productivity growth and technological change.

The fundamental questions are how farmed salmon compares to other food production systems and prospects for its improved sustainability.

This paper reviews the criticisms of Atlantic salmon farming, in particular those relating to its ecological and environmental record.

Compared with terrestrial livestock, fish are better suited for farming, being cold-blooded (ectothermic) with neutral buoyancy in water, which enhances production efficiency, and farmed fish are more productive than wild fish as they use less energy and lack predators.

Some of the criticisms of salmon farming are entirely erroneous (e.g. that hormones or growth promoters are used).

Others are unfounded today due to the rapid advances made since the industry started in the 1970s (e.g. that antibiotics are overused; that health risks exist from eating salmon due to the presence of contaminants; that using fishmeal and fish oil

is unsustainable and threatens wild fisheries; that salmon farm effluent threatens the coastal ecosystem).

It is concededthat infestation of salmon (Lepeophtheirus salmonis) by sealice and the risk of salmon escaping from farms remain valid concerns. Sealice numbers can readily build up in salmon farms and, even if satisfactorily controlled in the cages, infectious stages of the parasite may leave the cage and potentially infect adjacent wild salmon populations.

Escaping farmed salmon may contribute to this, but can also potentially breed with wild salmon and affect the native salmon gene pool.

However, there is no convincing evidence that the salmon farming industry is responsible for the widespread decline in wild salmon and sea trout populations, which began to decline before salmon farming was established.

Life cycle analysis suggests salmon farming and cod fishing are comparable. However, catching cod prey species (e.g. capelin) to use as salmon feed ingredients is a far more efficient way of supplying nutrients for human consumption than leaving such prey in the sea and harvesting the resulting cod.

Recent detailed studies of the salmon farming industry in Norway have shown that it is a more efficient way of producing nutrients for human consumption than either pig or chicken farming, as demonstrated by its climate impact, area of land occupation, and use of non-renewable phosporus resources.

Farmed salmon retain nutrients more efficiently and are better converters of feed nutrients to nutrients for human consumption than the most efficient land animal production.

There is no evidence that the progressive replacement of marine protein and oil by plant protein and oil is more sustainable than salmon farming based on wild-caught fish (or their by-products).

At the same time it causes the farmed salmon content of long-chain polyunsaturated fatty acids (PUFAs) (especially Eicosapentaenoic acid or EPA and Docosahexaenoic acid or DHA) to fall with negative implications for consumers (pending availability and consumer acceptance of cost-effective alternative PUFAs), unless they compensate by consuming more oil-rich fish or take PUFA supplements.

The salmon farming industry continues to innovate and prioritise to improve its sustainability, to improve seawater survival and to find cost-effective alternatives to the limited supply of fish oil, which is currently the only practical source of EPA and DHA.

A subsequent paper will consider the extent to which the improved environmental track record and resource efficiency of Atlantic salmon farming is duplicated by other aquaculture species.

Although it has been shown that much of the criticism of salmon farming is false or exaggerated, the industry is small in a global aquaculture context. Do these (or other criticisms) hold true, for example, with the farming of warmwater shrimp or carp?

Such questions are relevant when considering aquaculture's global role in food security and how best to guide its sustainable development.

Keywords
aquaculture; eco-efficiency; environmental impact; life cycle analysis; productivity; salmon farming; supply chain; sustainability.

Abbreviations
FAO Food and Agriculture Organisation; FCR Food conversion rate; FIFO Fish-in, Fish-out ratio; GM Genetic modification;
PCB Polychlorinated Biphenyls; PPR Primary Productivity Requirement; EPA Eicosapentaenoic acid; DHA Docosahexaenoic acid; DNA Deoxyribonucleic Acid; PUFA Polyunsaturated Fatty Acid; HACCP Hazard Analysis Critical Control Point; EFSA European Food Safety Authority; HCH Hexachlorocyclohexane; LCA Life Cycle Analysis.

Glossary
A coproduct is a product produced jointly with another product; an epizootic is a disease that appears as new cases in animals at a substantially elevated incidence rate and is an analogous term to 'epidemic' applied to human populations; eutrophication is the ecosystem response to the addition of artificial or natural substances (e.g. nitrates and phosphates through fertilizers or sewage) to an aquatic system; To fallow an aquaculture site means leaving it empty of fish for a period without restocking in order to allow the seabed to return to normal condition and to restore the site's productivity; feed conversion rate = (kg feed fed)/(kg bodyweight gain); fish-in fish-out ratio (when used about aquaculture) refers to the input of fish materials (usually fishmeal and fish oil) as feed ingredients compared to the resulting output of farmed fish; fishmeal trap is a term denoting the concern that increased demand for feed by aquaculture will increase fishing pressure on wild stocks and hence threaten the sustainability of the associated capture fisheries; a gadoid is a soft-finned marine fish which is a member of the family Gadidae including cod; a genome is the complete set of DNA within a single cell of an organism and genomics is the genetic discipline that sequences, assembles, and analyzes the function and structure of genomes; genetic modification (GM) (e.g. of a fish or a plant) results in a genetically modified organism (GMO), which possesses a novel combination of genetic material obtained through the use of modern biotechnology; life cycle analysis (LCA) is a technique to assess environmental impacts associated with all the stages of a product's life from start to finish; an oil adjuvant is an immunological vehicle for enhancing the potency of a vaccine, eg by emulsification in mineral oil; Organoleptic properties are the aspects of food or other substances as experienced by the senses, including taste, sight, smell, and

touch; a poikilotherm is an organism with an internal temperature which varies, usually in response to changing environmental temperature and is sometimes known as an 'ectotherm' or 'cold-blooded'; a reduction fishery is a fishery that 'reduces' its catch to fishmeal and fish oil and is also known as a 'feed' fishery or a 'forage' fishery; salmonids are fish which are members of the Salmonidae, or salmon and trout family, which belong to the order Salmoniformes; a smolt is a juvenile salmon in freshwater or estuarine conditions which has become silvery in colour and is ready to go to sea; triploid fish have three sets of chromosomes instead of the normal two ('diploid'), usually because the egg is physically shocked shortly after fertilisation occurs, resulting in sterile fish.

1. Introduction

Aquaculture is a more varied activity than land animal farming, encompassing a range of systems for rearing finfish, molluscs, crustaceans, and aquatic plants, in freshwater or seawater.

From 1980 to 2010 world food fish production by aquaculture has expanded almost 12-fold at an average annual rate of 8.8%, although slowing to an average annual rate of only 6.3% over the last decade to reach 63.6 million tonnes in 2011 (excluding aquatic plants).1

The contribution of global aquaculture to world seafood production for human consumption has risen from 9% in 1980 to 47% in 2010.

The hunting of fish and the problem of static or declining fish stocks represent an uncertain and erratic way to meet demand consistently on a long-term basis.

The high price and seasonal supply of wild salmon helped to encourage pioneering investment in farming of Atlantic salmon (Salmo salar) in the late 1960s and the industry took off in Norway and the UK in the 1980s, followed by North America and then Chile, as retailers and food service companies found they were able to place contracts for year-round supply of consistent product.

The development of salmon farming has been characterised by progressive industrialisation and commoditisation. However, aquaculture, especially the farming of carnivorous fish like salmon, has attracted intense and often misinformed criticism.

This has been linked mainly to the use of diets containing fishmeal and fish oil or minced wet fish, – the subject of a previous paper2 in World Agriculture.

At the same time improvements in diet formulation and feeding systems have resulted in feed conversion rates (FCR) improving from almost 3.0 in 1980 to just over 1.17 in 2012,3,4 meaning that the quantity of feed needed per unit liveweight gain has reduced by approximately 60% over the period.

Global production of farmed Atlantic salmon reached 2.0 million t (whole round, bled weight) in 20125 which is small (ca. 3%) in relation to estimated total global aquaculture production.1 Fig. 1 shows global production of Atlantic salmon has increased from 2002 to 2013 (estimated) by main production regions, whereas Fig. 2 shows a stagnating wild fish catch compared with aquaculture supply since 2000, with a forecast to 2020.

Atlantic salmon farming is recognised as the most highly developed form of intensive fish cultivation.

Accurate information is also available enabling detailed analysis of its efficiency, especially for the Norwegian salmon farming industry, which dominates global salmon production and is the technical model for intensive cage-based aquaculture.

This paper surveys the main criticisms of aquaculture, with special reference to Atlantic salmon. When assessing the validity of such criticisms, the fundamental question with respect to salmon aquaculture is how farmed salmon compares to other food items and production systems and if developments in the salmon industry will lead to improved sustainability.

The answers to such questions have implications for other forms of aquaculture and may help assess the potential role for global aquaculture in future food production and food security.6,7

2. Suitability of fish for farming

Compared with warm-blooded animals, cold-blooded 'poikilotherms,' such as fish, are more efficient converters of feed energy to bodyweight, especially under farming conditions. Firstly they have lower maintenance and respiratory costs.8

Their protein metabolism uses less energy since they excrete ammonia directly into the environment instead of excreting urea or uric acid.

Also their neutral buoyancy in water saves energy by avoiding the need for a heavy skeleton to counteract gravity. In general this means a greater proportion of the fish carcase is edible compared with land animals; this is especially the case for carnivorous fish which have a shorter digestive tract compared with fish species more adapted for a vegetarian diet.

Compared with fish in natural environments, farmed fish show improved growth and nutrient retention because they are protected from predators and utilise less energy in accessing food.9

Compared with intensively housed land animals, it is difficult to maintain a controlled environment within a fish farm and maintain biosecurity.

This is especially the case in seawater cages and will be considered further, together with the prospects for mitigation. Most aquatic animals have far greater reproductive capacity than terrestrial livestock, but also allocate less resource to reproduction.

Although many fish have microscopic larval stages, the cost of producing salmon fry is low as they produce relatively large eggs (with attached yolk sacs), which in turn develop into larvae capable of feeding readily on inert hatchery diets once the yolk sac contents are fully consumed.

3. Salmon productivity growth and technological change
Fig 3 shows the development of Norwegian farmed salmon production over the period from 1985 to 2011, the average cost of production and the average export price.

Production has increased from 31 177 to 1 005 600 t while the production costs and sales prices have fallen steeply.

Thus in 1986 the average production cost was 76.1 NOK/kg but it had fallen to 15.5 NOK/kg in 2005 (1 NOK or Norwegian krone equals 0.16 US dollar as of Dec. 2013), since when costs have slightly risen and prices have fluctuated but the industry has remained profitable.

The price reduction has enabled the industry to continue expanding into new markets. This could not have taken place without lower costs due to increased productivity and technological change.10

This is because farmers have become more efficient (i.e. growing larger salmon more quickly with fewer losses) while at the same time they have benefited from improved inputs (including improved stock, better feed and rearing systems) and have gained economies of scale from establishing larger farms.

Thus improvements in diet and feeding systems, as well as better fish health, have improved FCRs for Norwegian salmon from almost 3.0 kg feed/kg salmon body weight gain in 1980 to just over 1.17 kg/kg in 2012.

This is partly due to a marked change in the ratio of protein to oil used in feeds related to the development of vacuum coating of lipids.

Crude protein levels of 45% and fat of 18% in the 1980s have changed to 36% and 38% respectively in the 2000s.11

The salmon farming industry has been criticised for its supposed reliance on dietary marine ingredients. However, the quantity of wild fish used to produce the fish meal and oil needed to rear 1 kg of farmed salmon (i.e. the Fish-in, Fish-out ratio or FIFO) has decreased from 4.4 and 7.2 in 1990 to 1.4 and 2.3 respectively in 2010; when corrected to take account of the use of processing by-products of capture fishing, the values in 2010 were 1.1 and 1.8 respectively.12

The limited and fluctuating supply and cost of marine ingredients have encouraged the Norwegian salmon farming industry progressively to substitute plant ingredients for marine ingredients, and there has been a further change since 2010, so current FIFO ratios are probably below 1.0 for fishmeal and close to 1.0 for fish oil.

These developments have progressively challenged the criticism that aquaculture of ‘carnivorous species’ (e.g. salmonids) is unsustainable (see 4(i)).

For increasing use of plant ingredients and other challenges, see section 8(viii).

4. The criticisms related to ecological impact and environmental pollution
(i) Introduction
Any production process interacting with the natural environment can potentially compromise the environment.

For instance it has been claimed that the use of dietary marine ingredients in fish farming causes unsustainable damage to wild fish stocks being harvested for fishmeal and fish oil, and that reduction fisheries will therefore inevitably become overfished.13

This so-called 'fishmeal trap' has not occurred, however, due to dietary innovation, increased use of fish process trimmings, and to the increasingly responsible management of reduction fisheries.10,14 Therefore the criticism is no longer valid except in the case of 'trash fish' feeding in South East Asia.2

However, there is a range of local environmental issues which is claimed to have detrimental effects on the local and regional environment.

Salmon is normally farmed in floating cages, hence by definition takes place in 'open' systems in which water exchange occurs continuously with the wider environment and economic performance of the fish in such systems demands that water quality remains at an optimum.

The implications for salmon farming are considered below, together with the allied risks of disease transmission to the wild, farmed salmon escapement, contamination from treatment chemicals, and effluent discharge/organic waste.

(ii) Effluent discharge/Organic waste
Organic waste beneath salmon farms comprises fish faeces and unconsumed feed, which can accumulate on the seabed.

This may impact on local seabed fauna and increase the risk of eutrophication with consequent negative effects on productivity.10

During the 1980s many salmon farms were located in sheltered sites close to shore to reduce potential storm damage. As a consequence, so called 'dead areas' developed on the seabed under the cages.

Since then salmon farming systems have evolved to use more exposed locations with stronger currents and deeper water beneath more robust cage groups (which are regularly rotated between farm sites to enable fallowing), ensuring waste materials are flushed to sea and salmon have optimal water quality.

Additionally improvements in FCR have reduced the feed requirement per tonne of salmon produced by around 60% since the 1980s.

The regulatory framework has also become more sophisticated, e.g. in Scotland regulation of benthic impact is exercised through rigorously applied discharge controls, the use of particle tracking models, which predict the seabed footprint, and the ‘steady state’ and ‘limiting factor’ principles.15

A recent detailed NOAA report concludes that marine cage culture has ‘minimal’ impacts to the environment where farms are appropriately sited and properly managed.16

(iii) Antibiotics, chemicals, and hormones, etc.
Although the use of antimicrobial growth promoters is widespread in intensive production of poultry and pigs, it should be noted that they are not used in salmon farming at all. Nor are hormones used in salmon farming despite frequent media comments suggesting otherwise.

Fig 4 illustrates the rise and fall of antibiotic use in Norwegian salmon farming over the period 1980 – 2011.

It can be seen that, after reaching a peak in the 1980s, use of antibiotics fell quickly to very low levels despite a rapid and continuing increase in salmon production.

This was almost entirely due to the successful introduction of oil-adjuvantedvaccines in controlling bacterial diseases. Antibiotics are only allowed on veterinary prescription and the amount used per kilo of meat from terrestrial livestock in Norway is 20 times the amount used for farmed salmon.7

There has been a similar reduction in the use of medicines to control sealice (Lepeophtheirus salmonis) infestation (e.g. azamethiphos; cypermethrin), and in the use of antifoulants to reduce build-up of algae on cages (e.g. using copper-based paints).

In the case of sealice, an integrated pest management approach has increasingly become the norm, resulting in much diminished severity of infection in recent years despite the declining effectiveness of individual drugs.

Treatment of affected fish has been by means of either in-feed antiparasitic drugs (emamectin benzoate; teflubenzuron) or by adding medicinal products applied as baths (e.g. peroxide) to the water in the cage.

Treatment of affected fish by means of in-feed or bath treatments in some instances is only partially successful due to the emergence of resistance.

There is also increasing use of biological control by the introduction to salmon cages of wrasse of various species (e.g. Labrus bergylta) or lumpsucker fish (e.g. Cyclopterus spp.), which feed directly on the lice attached to salmon skin; this approach has obvious environmental attractions and is now stimulating an interest in cultivation of these so-called ‘cleaner’ fish to supply to the salmon farming industry.

A key issue is the cost-effective production of disease-free juvenile cleaner fish and their management in commercial systems based on fish being stocked and harvested on 'all-in, all-out' principles.

Use of antibiotics can never be eliminated entirely for reasons of animal welfare and the possibility of emerging bacterial diseases.

However, there are continuing problems in controlling sealice infestation and it is estimated that during 2012 around 45% of Norwegian salmon farming sites were treated for sealice, with each being treated on average 2.5 times over the production cycle.

There is increased recognition of the importance of husbandry measures, such as zonal management among neighbouring salmon farm units (taking account of industry codes of good practice), and selective breeding for increased resistance.

The more recently established Chilean salmon farming industry continues to struggle with disease problems and lags behind the effective control achieved in Norway, Scotland and North America without large scale use of medicinal products.

(iv) Transmission of disease agents to and from wild stocks
The early growth of salmon farming was severely challenged by epizootics of infectious disease, in particular bacterial septicaemias, such as furunculosis (due to Aeromonas spp.) and vibriosis (due to Vibrio spp.).

Routine vaccination of smolts by injection prior to seawater transfer was found to be highly effective. An exception is Salmon Rickettsial Syndrome in Chile due to Piscirickettsia salmonis for which a satisfactory control method is so far lacking, although vaccines are under trial.

An increasing range of viral diseases has been found to affect farmed salmon and can cause severe losses, although viral vaccines against Infectious Pancreatic Necrosis and Pancreas Disease are now in routine use.

The sources of such infections are not always clear but there is increasing evidence that most if not all the causative organisms have been present in wild fish populations since before the start of salmon farming.

The presumption is that they rarely cause disease in wild populations, but can be transmitted to adjacent farmed stocks in hatcheries or cage farms where clinical disease can spread quickly in unprotected salmon under conditions of high stocking density.

Whereas bacterial and viral disease epizootics in farmed salmon may cause shedding of pathogens into the environment, there is little evidence that this causes clinical disease in adjacent wild fish, apart from occasional mortalities seen in wild gadoid fish, e.g. saithe (Pollachius virens), which have gained access to the salmon cage.

However, parasitic infestations of wild Baltic strains of Atlantic salmon with the skin fluke Gyrodactylus salaris caused severe losses in susceptible Atlantic salmon populations when infected fish were transplanted to Norway and released into the wild.

In the same way there is concern that sealice infestation in farmed salmon (in Europe due mainly to L. salmonis and in Chile due mainly to Caligus rogercresseyi) potentially threatens wild salmon populations.

Sealice occur naturally in the wild and, long before salmon farming started, sealice epizootics caused mortalities of wild Atlantic salmon in Canada17 while the presence of a few sealice on wild salmon has traditionally been accepted as a positive indication of freshly sea-run fish.

However, under farming conditions these crustacean skin parasites can multiply rapidly and infectious stages swim actively to find a suitable host elsewhere within the cage, or potentially leave the cage and may infest migrating wild salmon in the vicinity.

For this reason, treatment aims to prevent the development of sexually mature breeding lice, in order to reduce infection pressure for both farmed and wild salmonid populations, rather than just for farmed fish welfare.

Salmon farming does not appear to prejudice wild salmon populations with the possible exception of the effects of sealice. However, new problems will emerge and continuing vigilance is needed to control fish movements and hence limit the spread of fish disease organisms.

(v) The effect of salmon farming on wild stocks
The number of Norwegian farmed salmon reported as escaping each year is relatively low and fairly stable (Fig. 5) when compared with the increasing production, although it remains a continuing problem.

Escaped fish are likely to compete with wild salmon and may breed with them, hence affecting the gene pool (so-called 'genetic pollution').

Although the outcome of escapee-wild fish interactions varies with environmental and genetic factors, modelling suggests they may be negative for wild salmon18 and that gene flow from escaped farm fish to native wild fish may lead to genetic and behavioural changes in wild populations in the direction of domesticated salmon.

It is also possible that wild populations may suffer depressed productivity caused by ecological interactions with escaped farm salmon and their offspring.19 At the same time a concern is that escaping farmed salmon could transmit disease organisms to wild populations, especially sealice (see 4(iv) above).

Compulsory tagging of smolts prior to their being stocked in salmon cages is being considered by the Norwegian authorities for greater traceability of farmed salmon should they subsequently escape, in order to aid policing and the ability to penalise offending farms.

Other than adopting genetically modified (GM) technology (should approval be granted), the use of triploid salmon is the only way to rear sterile salmon in order to avoid any risk of genetic pollution from escaped fish (see 8(iv)), whereas the cost of on-shore tank production is likely to remain prohibitive in most cases.

Notwithstanding the above concerns, there is little scientific evidence to support the claim that salmon farming has caused the widespread decline in wild salmon fisheries in Europe and North America.

Mismanaged capture fisheries, habitat destruction, and excessive mortality from fishing have resulted in wide-scale extirpations, depletions and loss of biodiversity in both Atlantic and Pacific salmon (Oncorhynchus spp.); this occurred long before commercial salmon farming started in the 1970s.20,21

For Norway there seems to be no measurable impact at the national level of salmon farming on the wild salmon stocks in Norwegian rivers7. In Scotland anglers continue to blame salmon farming for the collapse of the west coast populations of Atlantic salmon and sea trout (Salmo trutta) in the 1980s.

Thus sea trout anglers blame salmon farming for the demise of the Loch Maree sea trout fishery22 and claim that by 1980 the fishery was in decline, although the scientific evidence for this stock status in 1980 is not clear cut.23

There seems no doubt that the fishery was collapsing in the late 1980s by which time salmon farming was established in the area. It therefore remains a possibility that the effect of neighbouring salmon farms (e.g. due to sealice) exacerbated the decline of a fishery that was already under stress due to environmental factors, such as the effect of freshwater acidification.

A more likely explanation for this timetable of events at Loch Maree22 is the introduction of legislation in 1984 (Inshore Fisheries Act), which opened up the zero to 3 mile coastal area to all mobile fishing gear.

The fact that farmed salmon has brought down the price and largely replaced wild capture salmon in the market, is probably contributing to the rebound of some salmon stocks for both Atlantic and Pacific salmon.6

(vi) Contaminants from marine feed ingredients entering the food chain
The use of fishmeal and fish oil will tend to concentrate contaminants present at low levels in forage fish and hence result in potentially elevated levels in farmed fish.

This has raised concern about the human health risks from consumption of farmed salmon and particular prominence was given to a report24 highlighting the presence of low levels of dioxins and PCBs in farmed salmon.

However, subsequent studies have shown the risks were greatly exaggerated (if they existed at all) and that any possible risks are in any event greatly outweighed by the resulting health benefits.25

More recent data showed that farmed salmon and trout contained on average lower levels of dioxins and PCBs than wild caught salmon and trout, at least for Europe.26

This may reflect the requirement since 2005/2006 for fishmeal and fish oil in the EU to be routinely tested for contaminants prior to manufacture.27

It is of interest that fish oil manufactured within the EU from forage fish caught in the Baltic is normally above the required maximum levels for certain contaminants and can only be sold after further purification steps under EU control; whereas wild-caught Baltic salmon may be legally offered for sale without any such control.

The permitted maximum levels of contaminants set by the EU for those contaminants perceived as undesirable in feeds and foodstuffs are laid out in Directive 2002/32/EC (undesirable substances in animal feed) and in Regulation EC No 466/2001 (maximum levels for certain contaminants in foodstuffs); these regulations cover dioxins, PCBs and heavy metals (e.g. mercury, cadmium, lead, arsenic), as well as pesticides (e.g. toxaphene, HCH isomers, endrin, endosulfan, aldrin and dieldrin).

In any event it seems clear that the progressive reduction in levels of dietary marine ingredients due to substitution by vegetable ingredients has also served to reduce the content of certain contaminants in raw marine feed materials, and hence trace levels of any such substances that may be present in the salmon product.

5. Comparison with conventional fishing

In 2011 global capture fish volume was 93.5 million tonnes of which 67.2 million tonnes was of food fish, as compared with 63.6 million tonnes of world aquaculture production of food fish.28

It seems probable that by 2015, or earlier, world food fish production for human consumption by aquaculture will for the first time exceed food fish production for human consumption from capture fisheries.29

Capture fishing shows an overall global pattern of static or declining catch with increasing marginal costs. The problems of overfishing, by-catch, discards and habitat destruction are well known.

The World Bank estimated that global fisheries currently run a net economic loss of about US$5 billion per year30 and they take in as much as US$32 billion per year in subsidies;31 the resulting artificial inflation of profits encourages increased effort regardless of the condition of the fishery and discourages conservation.32

In addition to the use of fish process trimmings, the marine ingredients used in salmon diets rely on capture of small pelagic species usually occurring in tight shoals which are caught using purse seines without impacting the seabed and with very low by-catch levels.

Also it is recognised that most of the assessed forage fisheries operate within the limits that would be considered consistent with current good industry practice in the context of single species management regimes.14

Comparisons of aquaculture with capture fishing are not straightforward as the energy transfer between different trophic levels is not well documented, but farmed fish are inherently more efficient due to their being protected from predators and not needing to forage for food (section 2).

Accepted theories on energy and matter flow between trophic levels indicate that farmed salmon (and carnivorous marine finfish culture generally) appropriate less ocean primary production than commercial capture fishing.33

Assuming a 10% energy flow between trophic levels, producing 1 unit of predatory fish (such as wild salmon) requires 10 units of food (largely small pelagic fish), or more if by-catch values are taken into account.34

Even when compared with the 2 – 5 units of pelagic fish formerly needed to produce one unit of farmed fish,35 there was a clear ecological advantage in favour of farmed salmon. Today, the comparison is even more in favour of farming due to the dominance of plant ingredients in salmon feed.

The evidence clearly indicates that aquaculture can be a more efficient use of living marine resources than commercial fishing33 if sustainably produced marine ingredients are used.

This has been well documented in the case of farmed Norwegian salmon as compared with capture fishing of wild cod (Gadus morhua).

It was shown that harvesting fish higher in the marine food chain, such as cod, is far less efficient in providing marine nutrients for human consumption compared to harvesting capelin (Mallotus villosus) to manufacture fishmeal and oil used in salmon production.

Capelin is an important food source for cod, but using the capelin resource to produce salmon gave nearly 10 times more marine protein, 15 times more energy and 6 times more EPA and DHA for human consumption (including the cod liver oil), when compared with harvesting the cod resource.12

Whereas farmed salmon and wild-caught cod are comparable when subjected to life cycle analysis (LCA) in order to compare their environmental impacts, it is of interest that the nutritional output of marine protein and essential fatty acids for human consumption from these two alternative ways of using the capelin resource is very different.36,37

6. Comparing salmon farming with land animal farming
Estimated 2011 global production of beef, pork, chicken, and fish (capture fisheries and aquaculture) is given in Fig. 6 (note FAO production data for land animal meat and for fish are not readily comparable being expressed in two different product forms: meat in carcass weight and aquaculture/ capture in live weight equivalent; FAOSTAT data38 on production of land animals is given in tonnes as carcass weight, but there is no comparable figure for live weight equivalent).

It is likely that by 2012 annual global aquaculture production will have exceeded global beef production.

Table 1 compares harvest yield, edible yield, energy retention, protein retention and energy retention in the edible parts of Atlantic salmon, pig, chicken, and lamb, as well as FCR.39

It can be seen that the processing yield of Atlantic salmon is high compared with domesticated land animals, reflecting a relatively low skeletal weight.40

Comparing the amount of protein in edible parts to the amount of protein fed to the animal, salmon retain the most protein (31%) relative to pig, chicken and lamb; salmon also retain the most energy (23%) in the edible parts39. The FCR data show that the most efficient converter is farmed salmon compared with land animals.

Although not included in the table, among the least efficient is wild salmon with an FCR of ca.10.4

The willingness of the Norwegian salmon industry to divulge accurate and comprehensive data has enabled rigorous analysis by the Norwegian Institute of Food, Fisheries and Aquaculture Research (NOFIMA) and SINTEF of its resource utilisation and eco-efficiency for the year 2010.

Thus Fig. 7 charts the carbon footprint and land occupation by Norwegian farmed salmon and how it compares with Swedish pig and chicken production (when comparing the surface area of the net pen and land use of the salmon feed inputs with the surface area of the land use for the land animal feeds, but excluding the sea primary production area associated with the origin of the marine ingredients).41

Fig. 8 is an overview of nutrient flows and energy use for Norwegian salmon in 2010.12

Key findings were as follows:
* The carbon footprint of Norwegian salmon was 2.6 CO2e/kg edible product compared with values of 3.4 and 3.9 for Swedish chicken and pig respectively.

* The land occupation per kg of edible product for Norwegian salmon was 3.32 m2/kg compared with values of 6.95 and 8.35 for Swedish chicken and pig respectively.

* Changing the diet composition from 85% plant ingredients to 88% marine ingredients resulted in almost the same carbon footprint, while excluding marine ingredients from South America and the Mexican Gulf from the 2010 diet increased the carbon footprint by 7%.

* Cumulative energy demand for the Norwegian 2010 salmon was 25.3 MJe/kg , edible product; the ratio of industrial energy input/energy output in salmon product was 3.6/kg live-weight and 6.2/kg edible product respectively. It should be noted that 'edible product' here excludes salmon heads, frames etc., which can be used to produce other forms of edible product or eaten directly by some Asian communities.

* Producing 1kg of edible chicken and pork requires 2-3 times more phosphorus (as fertilizer) compared with salmon, which retain around twice as much dietary phosphorus.

* Retention of EPA and DHA was 58% in the whole salmon and 26% in fillet, whereas overall retention of protein and energy was 26% and 21% respectively in the edible part of Norwegian salmon in 2010 (net of losses in feed and salmon production).

* The NOFIMA study shows clearly that salmon farming in Norway is a more efficient way of producing nutrients for human consumption than chicken and pork production. Farmed salmon retain nutrients more efficiently and are more efficient converters of feed nutrients to human food than pigs and chicken.

At the same time it should be noted that LCA of global salmon farming systems showed impacts in most categories were lowest for Norwegian production and that the most critical factor was least-environmental cost feed sourcing.42

In this connection it appears that the origin of feed ingredients affects the LCA results and environmental impacts are highly dependent on the reduction fish species used and the energy needed to catch them.43

Of particular interest was NOFIMA's finding that substitution of marine ingredients by plant ingredients had virtually no effect on carbon footprint.

The strong trend towards substitution in salmon feeds is occurring in other aquaculture feeds and has more to do with spreading the supply risk and being less reliant on limited supplies of marine ingredients showing marked volatility in costs.

There is no evidence that terrestrial agricultural animal and plant feed resources are more sustainable than those from wild- caught marine resources.

However, the environmental movement is dominated by marine conservation organisations which pressure fish supply chains to lower the use of marine ingredients for aquaculture diets without considering sustainability issues in regard to alternative ingredients (e.g. rain forest impacts of increased soya cultivation).

In addition to the factors considered in the NOFIMA study, plant production requires freshwater, unlike salmon farming (apart from hatchery smolt production), and contributes to depletion of the soil.

Most plant ingredients can also be used for human consumption, and the benefit of substituting marine ingredients produced from well managed fisheries supplying fish species for which there is little or no demand for human consumption is not obvious.44

These results are reinforced by the conclusion of Welch *et al.*33 that farming salmon increased production of animal protein at generally lower land, water, nitrogen and agricultural chemical costs than terrestrial livestock.

7. Farmed and wild salmon: supply chain issues, human nutritional issues, and coproducts In 2012 global supply of farmed salmon (dominated by Atlantic salmon) was 2.1 million tonnes (head-on; gutted) compared with approx. 824 000 tonnes of wild salmon, mainly comprising different species of Pacific salmon.5

Salmon consumption worldwide is over three times higher than it was in 1980 and what was once a luxury food is now among the most popular fish species in the U.S., Europe and Japan.

Salmon aquaculture is the fastest growing food production system in the world. To commercial supply chains salmon is a highly versatile raw material in terms of value adding options and product forms (e.g. smoked), as well as having a healthy image in common with other oily fish species linked to its long chain omega- 3 fatty acid content.

When compared with the quality aspects of meat products from land animals, salmon was rated as being superior in healthiness by European consumers.45

These attributes are common to both farmed and wild salmon, but does the farmed product have advantages or disadvantages in the market place compared with wild salmon?

Farmed Atlantic salmon products have proved highly attractive to both food service and retail distribution channels. For example in the UK, farmed salmon currently represents the most commonly stocked fish species on supermarket shelves, although smaller volumes of wild Pacific salmon are now becoming available in the UK, albeit at a price premium to the consumer.

This reflects the comparative advantage of aquaculture’s control over production compared with wild fish. In particular, wild fish suppliers are unable to match the year-round availability of fresh, frozen and processed salmon with consistent quality from supply chains willing and able to enter into forward contracts for agreed price and quantities.

Subjective evidence from blind taste panels suggests that farmed salmon is often preferred to wild salmon; this may, of course, be linked to farmed salmon containing over 30% more fat than wild counterparts and the likelihood that panellists are more acquainted with, and possibly conditioned to, the organoleptic properties of farmed salmon, which is more commonly consumed worldwide.

Commercially successful salmon farming (like broiler chicken farming) is all about management of the supply chain to provide continuity of supply.

The key steps include raw material procurement, farm management, processing and distribution, while at the same time other supply chain issues include quality assurance and verification that procedures are being followed, including audited verification of Good Manufacturing Practice and HACCP.

However, due to consumer concerns about overfishing, a supply chain requirement of growing importance for both farmed and wild salmon is independent third party certification of sustainable sourcing.

In the case of wild salmon, certain retailers and food service channels insist the source fishery demonstrates it is being sustainably managed, either by assessment and certification with the Marine Stewardship Council,46 or with the FAO-based Responsible Fisheries Management scheme, which has been adopted by Alaska Fisheries.47

In the case of farmed salmon, various organisations offer independent verification of responsible practice, e.g. Best Aquaculture Practice,48 and more recently the Aquaculture Stewardship Council.49 In addition the supply of fishmeal and fish oil is addressed by the Responsible Supply standard of the International Fishmeal and Fish Oil Organisation.50

The salmon farming industry in each of the major producer countries has established representative organisations, not only as a political voice, but also in an effort to improve the quality and sustainability of the industry.

This has close parallels with the various organisations representing terrestrial livestock industries. Thus in Scotland the Salmon Producers' Organisation51 is committed to maintaining standards in the industry via the independently audited Code of Good Practice for Scottish finfish aquaculture (covering food safety and consumer assurance; fish health and biosecurity; managing and protecting the environment; fish welfare and care; and feed and feeding).52

Retailers focusing on welfare may also demand other certifications and it is of interest that approx. 70% of Scottish farmed salmon is now certified by Freedom Food53 as achieving high fish welfare standards; this has in turn resulted in higher overall standards of farm practice, while aligning closely with consumer demands for farming systems which strive to care for the animals' well-being for both terrestrial and aquatic farming systems.

Unlike broiler chicken farming, for example, it should be noted that salmon cage systems are open to the environment, hence inherently less bio-secure. This in turn aligns with the perception of 'working with nature' to resolve problems like sealice control, while at the same time supply chains can claim to be responding to consumer demand for more 'natural' food.

The emphasis on environmental certifications must not obscure the fundamental objective of producing wholesome and nutritious food in a cost-efficient and safe manner. Salmon is an important source of the nutritionally important PUFAs, for which there is strong demand from the human nutritional sector as well as aquaculture.

Man has a limited ability to elongate and desaturate alpha-linolenic acid (e.g. from oil seeds) and it is generally recognised that the lack of long chain omega-3 fats in the meat of land animals and the presence instead of more saturated fats, especially of the omega-6 series, can predispose to human health problems (e.g. obesity and cardiovascular disease) if there is inadequate balance of omega-3 and omega-6 fats54.

Traditional poultry and eggs were one of the few land-based sources of long-chain n-3 fatty acids, especially DHA, which is synthesized from its parent precursor, but the evidence is that this has now changed with chickens in the UK market providing several times the fat energy compared with protein and much reduced PUFA levels, hence potentially negative consequences for animal welfare and human nutrition.71

This nutritional health benefit of salmon is shared by other high oil fish, hence adding further value to salmon as a product and a competitive advantage as against land animals.

The trend towards high energy salmon diets and the sole use of fish oil as a dietary fat source meant that formerly farmed Atlantic salmon, having a higher fat content than wild salmon, also had a higher content of PUFA than wild salmon, especially when oil-rich fish such as anchovy (Engraulis spp.), herring (Clupea harengus), or sandeel (Ammodytes spp.) were used.

Since the progressive introduction of vegetable oils as a partial dietary substitute for fish oil from around the year 2000, and influenced by the growing competition for PUFA-rich fish oils by the human nutrition industry, the content of PUFA in farmed salmon has reduced to only a third of what it was before the year 2000.55

This may undermine the basis of dietary recommendations for human consumption of oily fish; for example, EFSA56 recommends a minimum of 250 mg/day of combined EPA + DHA, whereas the UK (Scientific Advisory Committee on Nutrition)57 recommends a minimum of 450 mg/day of combined EPA + DHA and consuming fish twice a week, including one meal of oily fish.

Although different farmed salmon are being reared on different combinations of fish and vegetable oil, it is possible that some wild salmon will now contain more PUFA per gram than some farmed salmon.

However, it is clear that product differentiation is now occurring with some supply chains demanding their salmon is supplied with a greater concentration of EPA and DHA than other supply chains.

For example, certain UK retailers have focused on maintaining higher PUFA levels in salmon fillets and Scottish producers have contracted to supply this market segment; it is likely that segmentation will become increasingly apparent to consumers in terms of product labelling and premium pricing.55

Given the worldwide scarcity of PUFA-rich fish oil, this situation is likely to pertain until such time as new cost-effective PUFA sources emerge from current research and development using algal production and genetic modification of oilseeds (see 8 (vi)).

Not all salmon is eaten directly and salmon coproducts typically represent around 40% of total ungutted carcase weight; such coproducts include aquaculture meals and oils for livestock feeds (which cannot be recycled back into salmon feed to avoid potential health problems), but also a variety of value-added products for use in the human nutritional and pharmaceutical sectors.58

In general the protein quality of fish meat is higher than land animal meat, for example it is higher in lysine and methionine as a proportion of total amino acids. Table 2 compares the amino acid content in salmon meal and hydrolysate with the requirements of chickens and humans (adults and schoolchildren).59

Tryptophan seems to be the only limiting amino acid for all diets although this may be linked to analytical problems. Arginine for poultry seems to be the only true limiting amino acid in salmon meal, but not in the hydrolysate where threonine appears marginally limiting.

Farmed and wild salmon contain calcium, copper, iron, magnesium, manganese, phosphorus, potassium, selenium, sodium and zinc. Other micronutrients present include Vitamins A and D and a range of B vitamins, with farmed salmon being much higher than wild salmon in thiamine and folic acid.

Clearly the nutritional composition of wild and farmed salmon reflects their feed intake, which reflects the source of their feed. In the case of Norwegian farmed salmon, the marine feed ingredients may include fishmeal and oil from locally available fish (e.g. capelin) and process trimmings from fish for human consumption, as well as imported fishmeal and oil derived from species such as Peruvian anchovy (Engraulis ringens).

The majority of salmon dietary ingredients are now of vegetable origin, such as soya protein concentrate and rapeseed oil, and likely to be imported into the main salmon producing countries.

The efficiency with which salmon convert these feed nutrients to nutrients for human consumption and the superior quality of the output relative to terrestrial livestock have implications for future food security, especially given the static nature of capture fishing.

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8. Overcoming technical constraints

(i) Off-shore production

A possible alternative to the problems of siting salmon cage farms at inshore locations is moving the production units offshore to deeper and less sheltered waters, where ocean currents are stronger.

This avoids the risk that heavily used inshore sites can become progressively unusable despite adopting site rotation and fallowing. At the same time off-shore locations avoid many of the conflicts that occur with other marine resource users in the more crowded inshore waters, although user conflicts exist offshore too.

This requires sophisticated, capital-intensive cage rearing and feeding systems capable of withstanding open ocean gales; such offshore systems are now being introduced for marine fish and shellfish farming, but are at an early testing phase for commercial salmon farming.

(ii) Recirculation and land-based systems

Recirculation technology is showing potential for intensive aquaculture with minimal water consumption60 and is enabling salmon smolt production to take place under environmentally controlled conditions at optimal water temperatures with minimal bleed-in of freshwater.

Marine finfish species are also now being reared intensively in closed circuit, land-based, recirculation units away from the coast, hence potentially avoiding the problems of escapement and biosecurity described in relation to salmon cages, but the key issue is the cost of energy for such systems which may therefore be difficult to scale up commercially.

(iii) Genetic improvement

The relatively long generation time of salmon compared with warmwater farmed fish (e.g. Tilapia spp.) means that selective breeding takes longer.

However, during the last 40 years genetic progress with Atlantic salmon has markedly improved key production traits.

For instance, a near doubling in growth rate has resulted in a reduction in the length of the production cycle to 1.5 – 2 years;10 the onset of sexual maturation has been delayed; FCR has dramatically reduced; higher survival rates have been achieved (including increased resistance to specific pathogens); and fillet quality has been enhanced in terms of fat and colour.

The application to salmon aquaculture of molecular biology techniques (looking at single genes), as well as genomics (looking at DNA sequencing), is set to offer a fundamental approach to solving specific problems.

The first Atlantic salmon genome is about to be fully sequenced due to international collaboration61 and early project objectives are to identify the genes for sexual maturation, those that code for sealice resistance, and for preferred meat texture.

(iv) Triploids

The use of sterile salmon by farmers would overcome the risk of escaped fish affecting wild populations and two possible routes are being considered: triploidy and genetic modification.

Triploid induction (by shocking the egg shortly after fertilisation) was tested in the 1990s to prevent salmon maturation prior to harvest, but also resulted in poor performance, reduced disease resistance, and deformities and was therefore abandoned in favour of photoperiod control of maturation. It is now recognised that growth and survival of triploid salmon is strongly affected by family.

By means of correct selection, triploids were found to outperform their diploid siblings with minimal deformity rates62 and the feasibility of using triploid salmon is again being studied in Norway and Scotland.

(

v) GM salmon

The use of GM salmon is promoted as a sustainable alternative to conventional salmon farming. Thus trademarked ‘AquAdvantage’ salmon are Atlantic salmon with a gene from chinook salmon (Oncorhynchus tshawytscha) reducing the time to market by 50%. The owners, AquaBounty,63intend to grow the fish as sterile, all-female fish in land-based facilities.

The US Food and Drug Administration is currently considering their application to approve GM salmon for human consumption. If granted this would be the first genetically modified animal allowed to be sold to consumers.

Consumers in Europe are unlikely to accept the product. The largest global salmon farming company (Marine Harvest) has recently issued a statement saying that it does not support the introduction of GM salmon and asking for it to be specifically labelled as such in the event that it is approved for consumption.

The European salmon farming industry even avoids the use of (authorised) GM ingredients in the feed.

(vi) GM feed ingredients

The increased scarcity and cost of fish oil has spurred research into manufacture of long chain PUFAs, especially EPA and DHA, by means of algal production (e.g. by fermentation) and by genetic modification of oilseeds, such as soyabean, rapeseed, and Camelina sativa Limited quantities of these fatty acids are already commercially available from algal production, while GM material has only been produced experimentally and is some way from commercialisation assuming consumer concerns and regulatory hurdles are overcome.

As regards GM soya, canola, and other vegetable protein feed ingredients, these are now being used widely by the aquaculture industry.

However, so far, salmon feeds in Europe have not contained GM ingredients due to continuing consumer concerns.

(vii) Stock losses

Currently in Norway 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 use of resources.7

The situation in second-placed Chile is substantially worse, due mainly to health problems, and the authorities are now taking steps to reduce the density of farms in a given area and to open up new 'clean' sites.

Therefore disease prevention and control continues to be of major importance in salmon farming and the intense research focus on priorities, such as sealice, helped by new techniques becoming available, is likely to bring forward solutions.

(viii) Feeds

The main challenges to extending substitution of marine ingredients by further dietary inclusion of plant protein and oils is linked to their lower protein and unsaturated omega-3 fatty acid contents and higher starch and fibre contents, unfavourable amino acid profiles, and the presence of anti-nutritional factors.64

Plant protein and lipid inclusions had reached 40% by 20107 and are now exceeding 50% especially in the case of lipid sources.55

Given the level of research focus by nutritionists and feed formulators, there is little doubt that inclusion levels of plant materials will increase and that marine ingredients will be used more strategically, especially at critical parts of the life cycle, such as in first feeding and smolt transfer diets.65,66

The limiting marine-based nutrients of most concern for salmon performance are certain amino acids (e.g. lysine and methionine) and long-chain omega-3 fatty acids; the latter reflecting the increasing scarcity of suitable fish oil until alternative sources become available (see 8 (vi) above).

Although the long-chain omega-3 requirement of salmon is low and likely to be covered in practice by the dietary fishmeal, even in the absence of added fish oil,67the concern is more about the consumer impact of low levels of EPA and DHA in the resulting end-product.

Consumer concerns are also linked to the continued resistance within Europe to using land animal by-products in salmon diets despite the European Commission recently authorising the reintroduction of processed animal proteins from non-ruminant farm animals as feed ingredients (c.f. also resistance to GM materials).

However, increased use of plant materials raises its own sustainability issues, since calculations of the hypothetical area required for supplying 100% of all the macro-nutrients from plant sources indicate that Norwegian salmon production would need around 1.1 million hectares (45% of the total agricultural area of Denmark) in order to produce 270 000 tonnes of wheat, 1.56 million tonnes of soya, and 950 000 tonnes of rapeseed7.

Much of the soya would presumably come from Brazil and further expansion threatens the southern Amazon basin. Already the soybean trade between Brazil and Europe is creating environmental, social, and economical concerns that have yet to be fully resolved.68

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9. Conclusions

Whereas fishing and land animal production have developed over millennia, large scale intensive aquaculture has only developed over the past 30 – 40 years.

Over this same period, issues such as the use of antibiotics, biodiversity, pollution, and animal welfare, have come to the fore in regard to land animal production, especially in developed economies. Salmon farming is the most developed form of intensive aquaculture but from the start it has been subjected to constant critical scrutiny on these issues.

That it has not only survived, but grown to be a highly efficient global industry, is mainly due to innovation and rapid technological change enabling increased productivity, cost reduction, and close control of the production process.

These factors have enabled the industry to resolve most of its problems, improve its productivity, and succeed commercially on a global scale, while becoming increasingly sustainable.

The criticism that salmon farming relies on the unsustainable use of dietary ingredients of marine origin was reviewed in an earlier paper, which explained why the continuing substitution of marine ingredients by vegetable proteins and oils in salmon feed, together with the evidence that reduction fisheries are not being over-exploited to produce more and more fishmeal and fish oil, make this criticism increasingly untenable.

This review has covered other environmental criticisms of salmon farming, including the impact of its effluent discharge, the use of antibiotics and chemicals, the transmission of disease agents into the marine ecosystem, and the threat to wild salmon populations arising from escaped farmed fish (due either to interbreeding or to disease transmission).

During its rapid industrialisation, the industry has had to learn how to address these environmental effects and to evolve codes of good practice in order to avoid reduced productivity, hence reduced profitability, and to comply with government regulations.

Improved husbandry knowledge and operating practices, as well as tighter regulatory frameworks, have largely helped the industry to internalise and mitigate these problems in Europe and North America,69,70 with the Chilean industry somewhat lagging behind.

Sealice infections and salmon escapes are probably the most serious environmental challenges in salmon farming, at least for the dominant Norwegian industry. Intensive research continues to achieve more effective sealice control, including vaccination and the use of live cleaner fish to browse on lice attached to salmon skin.

The long term prevention of salmon escapees breeding with wild salmon depends on consumers accepting a switch to farming sterile salmon. Fears that farmed salmon may concentrate environmental contaminants in the flesh and hence pose a human health risk are false.

Nor is there evidence to support the view that salmon farming has been responsible for the widespread decline in wild salmon populations in Europe or North America.

When compared with wild-caught fish, farmed salmon has a clear ecological advantage. Norwegian studies by NOFIMA have shown that, if the objective is to provide marine nutrients for human consumption, it is far more efficient to harvest pelagic fish for fishmeal and fish oil to rear salmon than to leave them in the sea as prey for cod and instead harvest the cod resource.

Using capelin to produce salmon gave nearly 10 times more marine protein and 6 times more long-chain omega-3 fatty acids compared with harvesting the cod, despite farmed salmon and wild cod having comparable LCAs.

Overall salmon farming is a more efficient use of resources than commercial fishing, especially when taking account of fishing externalities.

In fact the oceans provide an under-utilised source of nutrients for human consumption and salmon farming offers an efficient mechanism for transforming these resources into high quality food that can be distributed worldwide and available all the year round.

The NOFIMA study shows that salmon farming in Norway is a more efficient way of producing nutrients for human consumption than chicken and pork production, as indicated by its climatic impact, area of land occupation, and use of non-renewable phosphorus resources.

Farmed salmon also retain nutrients more efficiently compared with pigs and chicken, but there is no evidence that terrestrial agricultural animal and plant feed resources are more sustainable for farming salmon than using feed ingredients based on wild-caught marine resources.

Although still young, the salmon farming industry has greatly increased the availability and reduced the cost of supplying salmon to world seafood markets.

It has also brought sustainable employment to many remote rural locations. The main challenge going forward will be to continue to grow sustainably in step with market and environmental considerations.

A major priority is the reduction in losses over the production cycle of around 20% of fish stocked into a cage. Also sealice infestation and escaped salmon must be better controlled. A potential limiting factor is the availability of PUFAs due to growing competition for fish oil from the human nutrition industry.

It will be necessary to increase further the proportion of plant oil (mainly rapeseed oil) in salmon feed, hence reducing the EPA and DHA levels in the fillet, which might adversely impact consumer demand; but in due course this will be solved when cost-effective material becomes available either from algal manufactured oils or from genetically-modified plants.

It will be of interest to consider whether valid comparisons can be made between salmon farming and other types of aquaculture, including less intensive systems, especially as regards environmental impact and resource use. The answers to such questions may help us to draw conclusions on the potential role of global aquaculture for future food production and food security.

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Figures

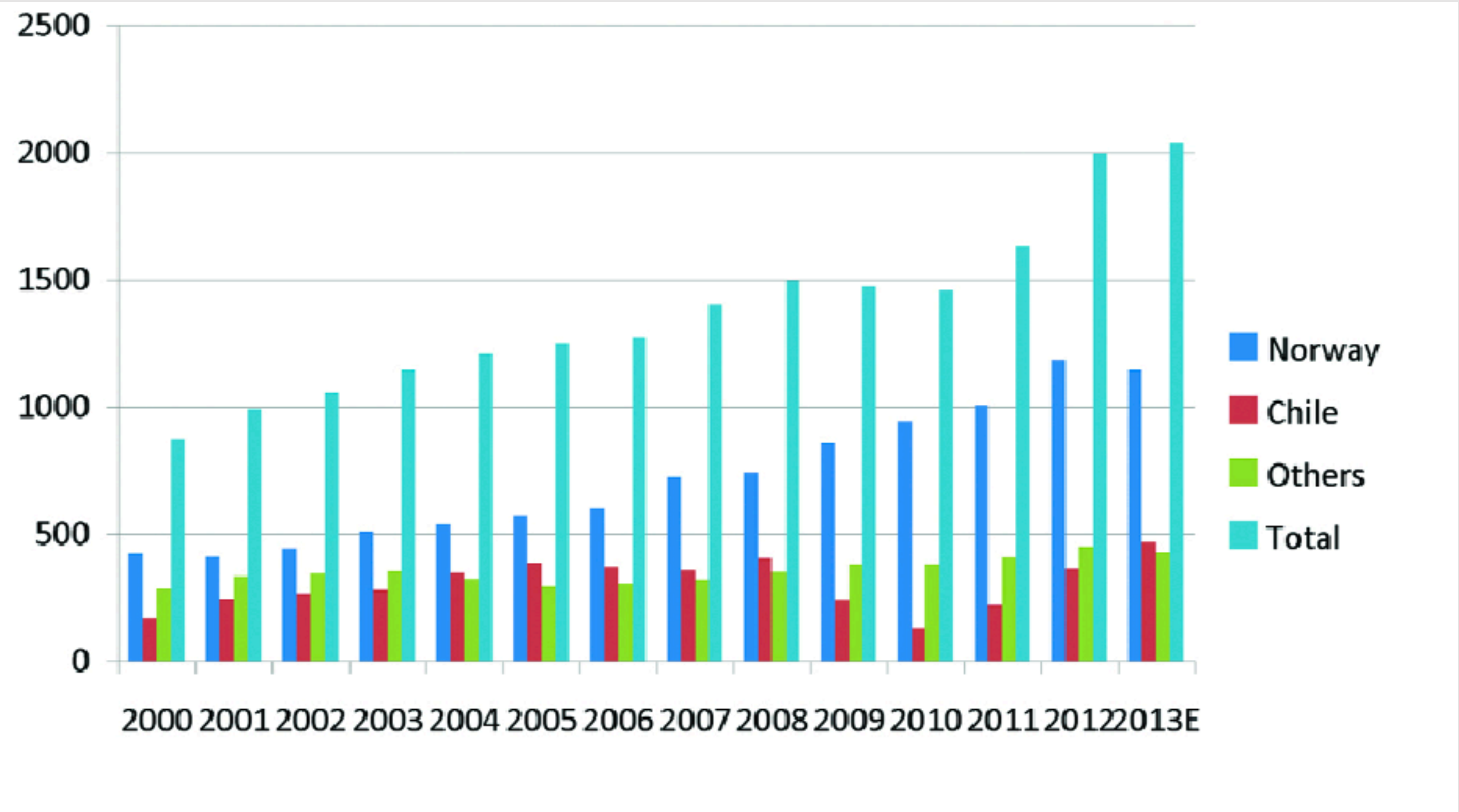

Figure 1.

Figure 1. Global production of farmed Atlantic salmon 2000-2013 (tonnes x 1000)

Source: Kontali Analyse (2013)

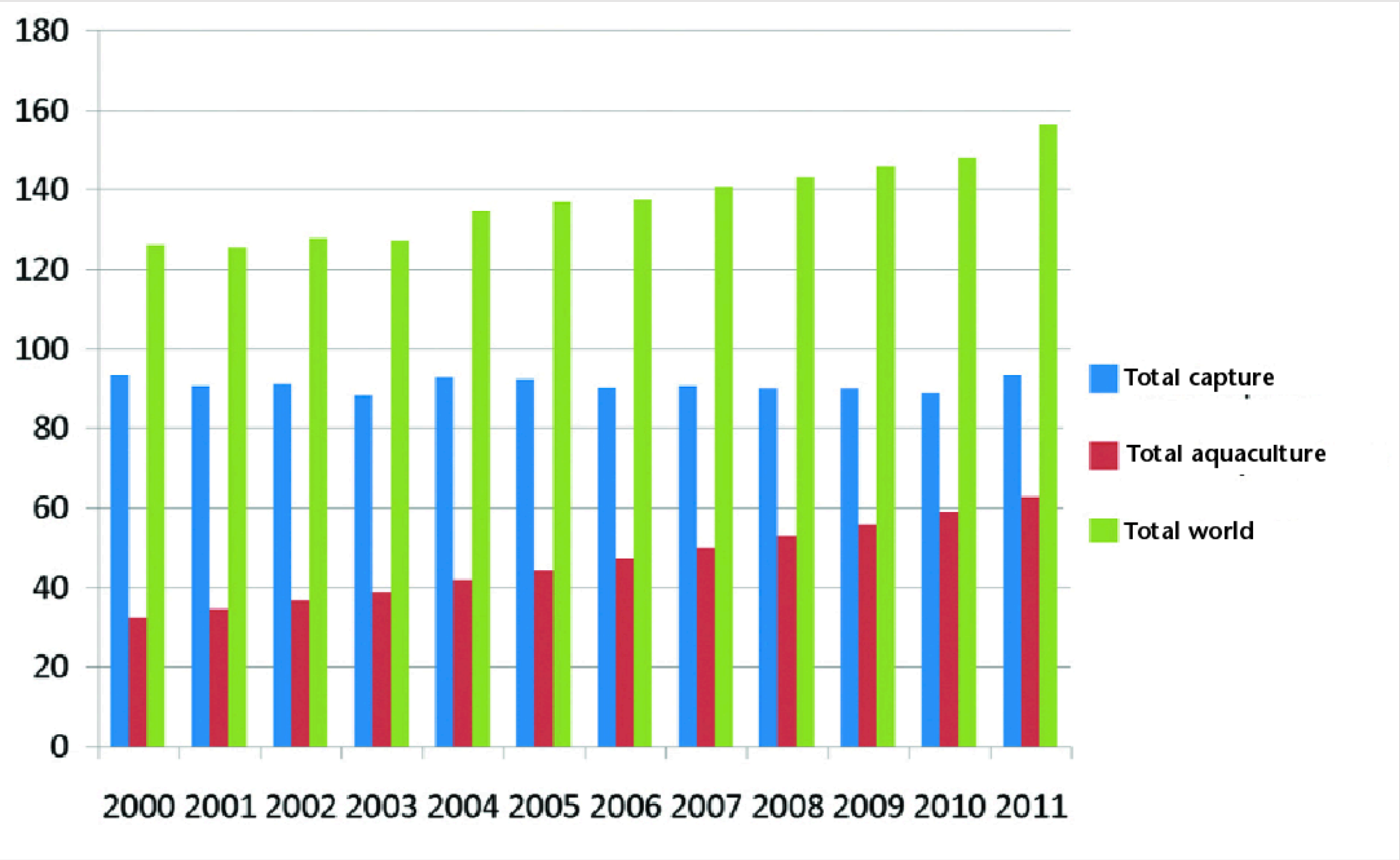

Figure 2.

Figure 2. Global fishery and aquaculture production, 2000-2011 (tonnes x million)
Source:
FAO Fisheries and Aquaculture Statistics and Information Branch 2013. Capture production 1950-2011. Aquaculture production 1950-2011.
Available at http://www.fao.org/fishery/statistics/en

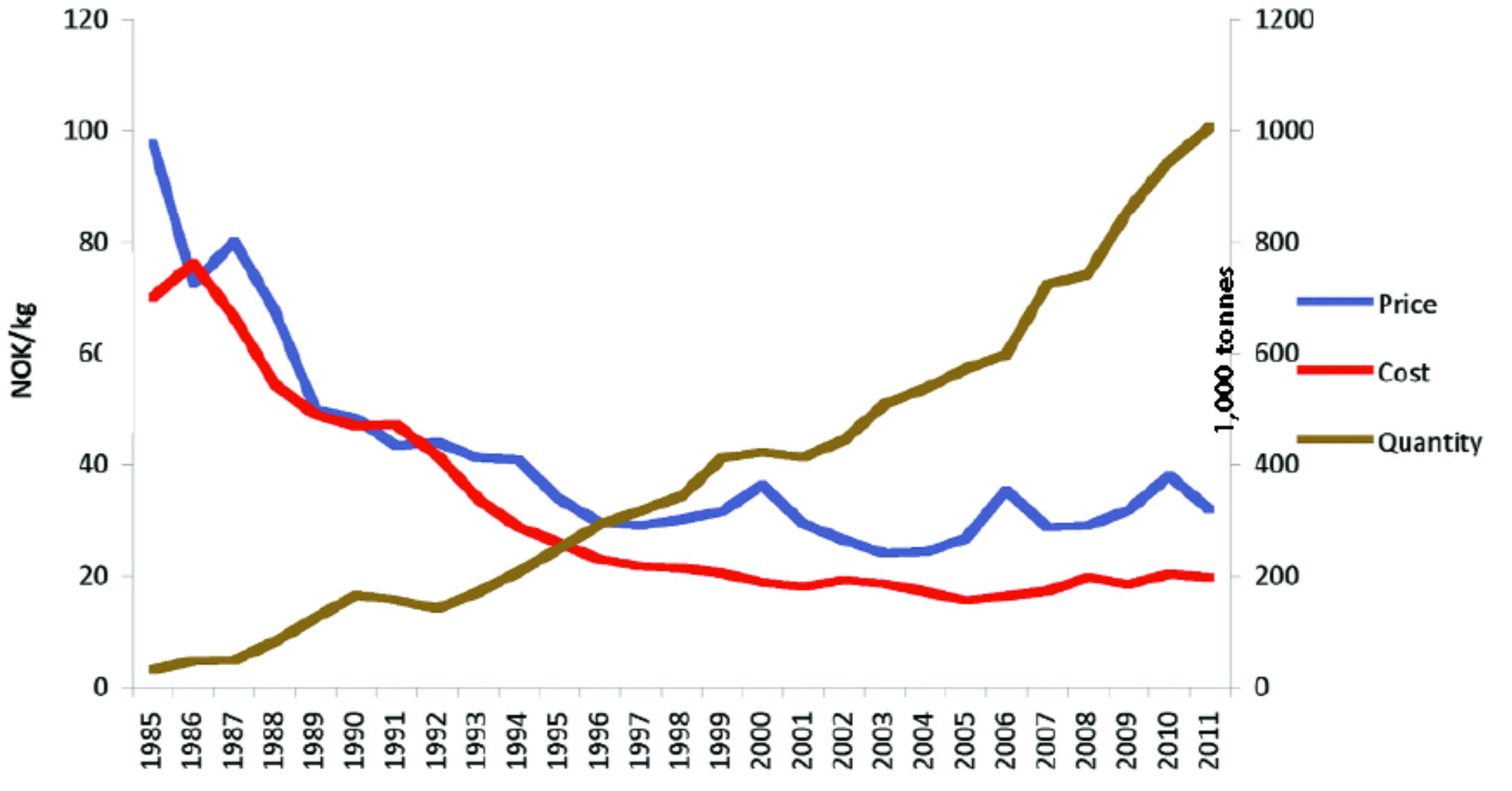

Figure 3.
Figure 3. Norwegian farmed salmon volumes (tonnes x 1,000) compared with production cost and export price (Norwegian Krone) in real terms (2011=1), 1985-2011
Source: Norwegian Directorate of Fisheries: Norwegian Seafood Export Council

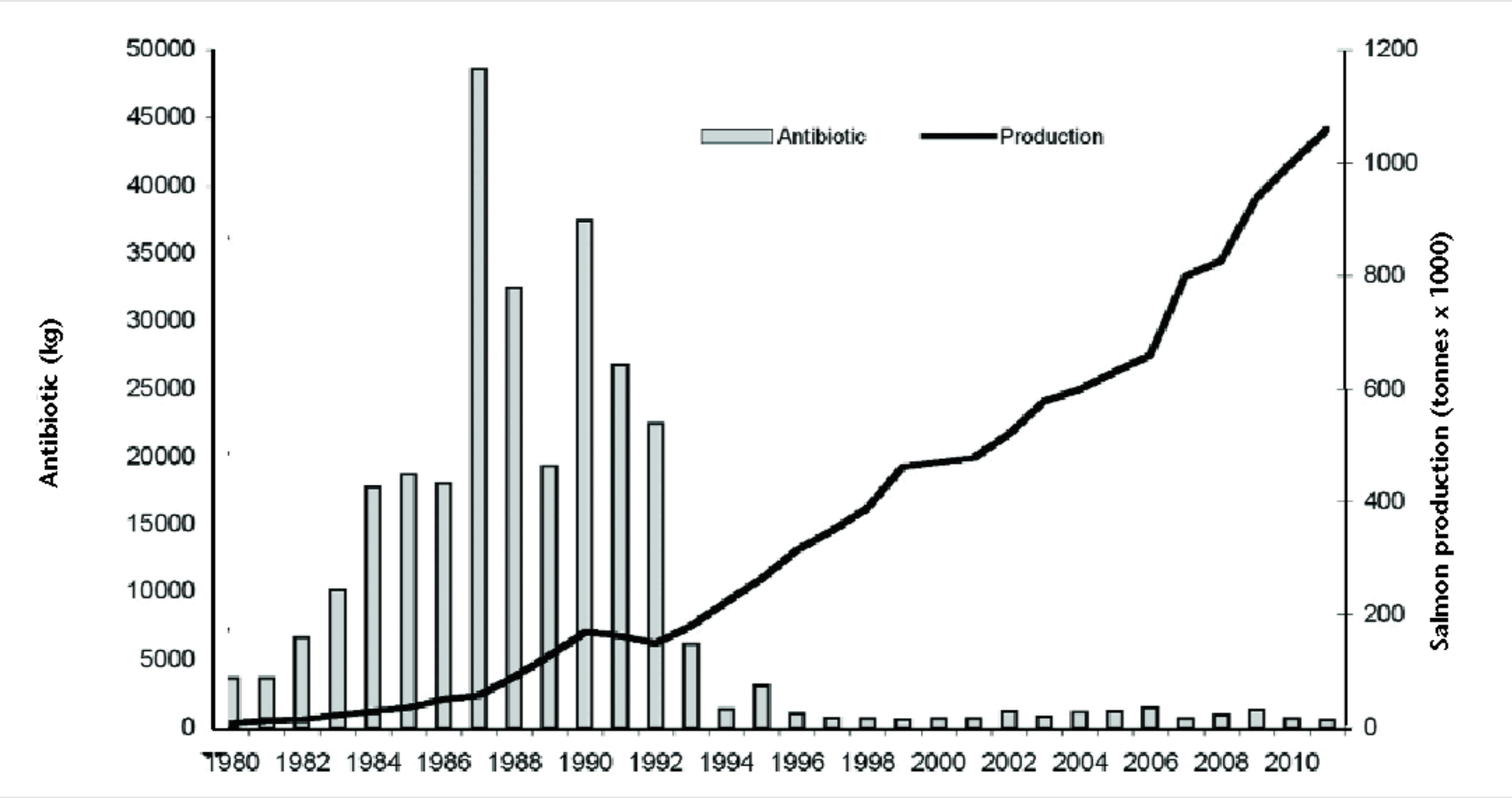

Figure 4.
Figure 4. Annual use of antibiotics (kg) in Norwegian salmon production, 1980-2011
Source: Norwegian Directorate of Fisheries

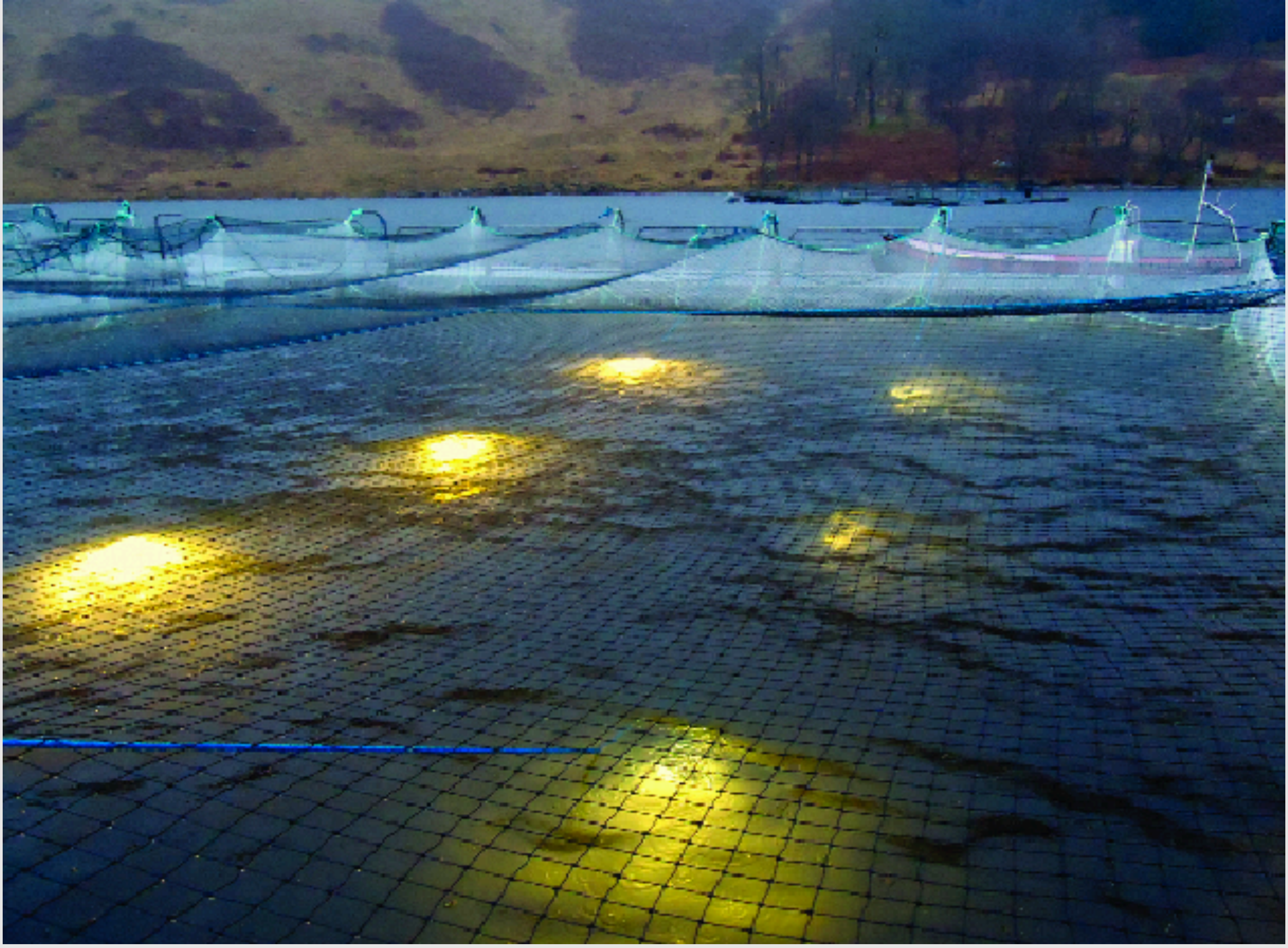

Figure 5.

Freshwater production of salmon smolts – note use of underwater lights for photoperiod control of smoltification (Courtesy of Marine Harvest Ltd., Scotland)

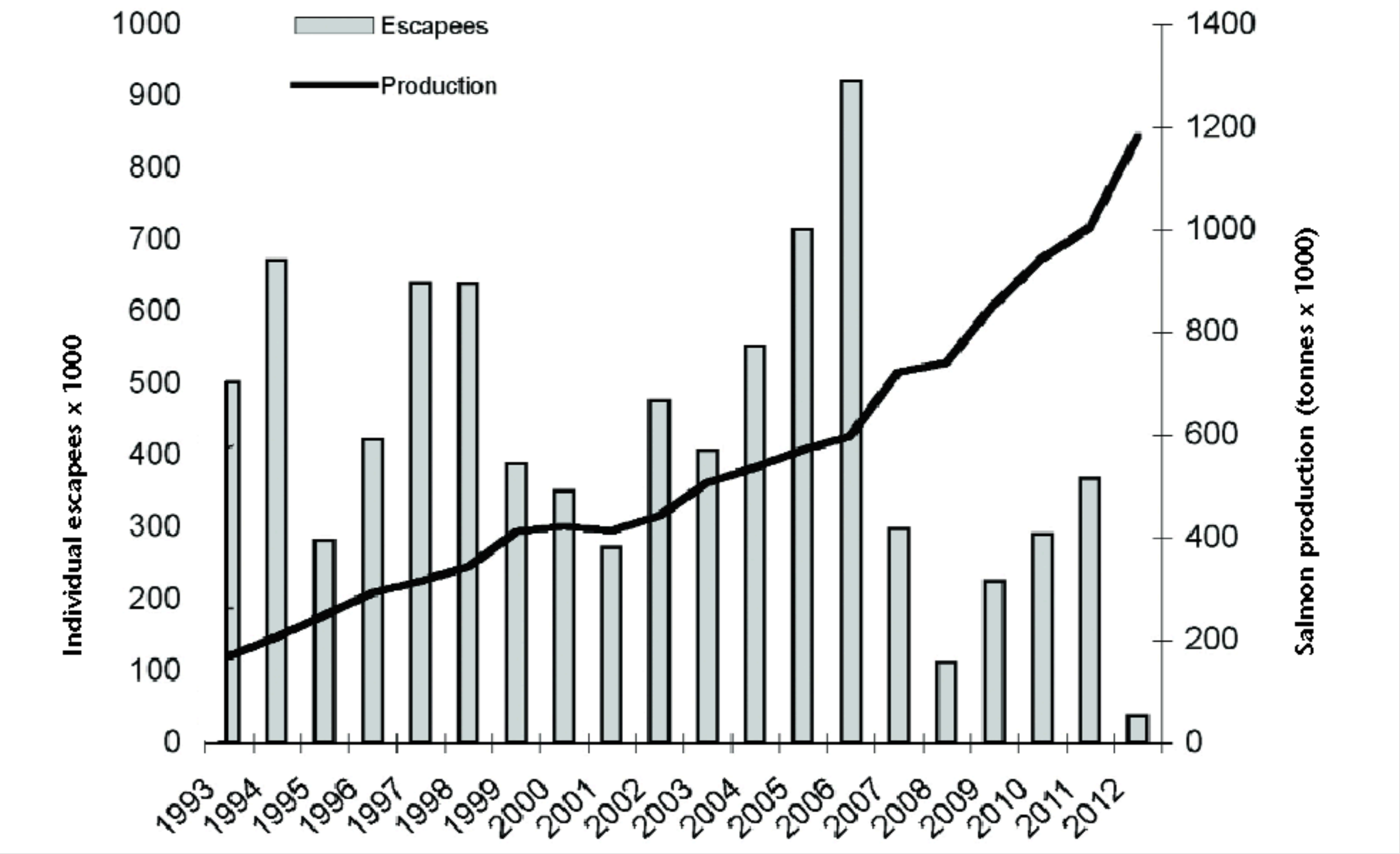

Figure 6.

Figure 5. Number of escaped salmon in relation to Norwegian salmon production, 1993-2012 Source: Norwegian Directorate of Fisheries

Figure 7.
Close up view of salmon farm in Western Isles – note use of circular plastic pens with overhead anti-predator nets and central supports (Courtesy of Marine Harvest Ltd, Scotland)

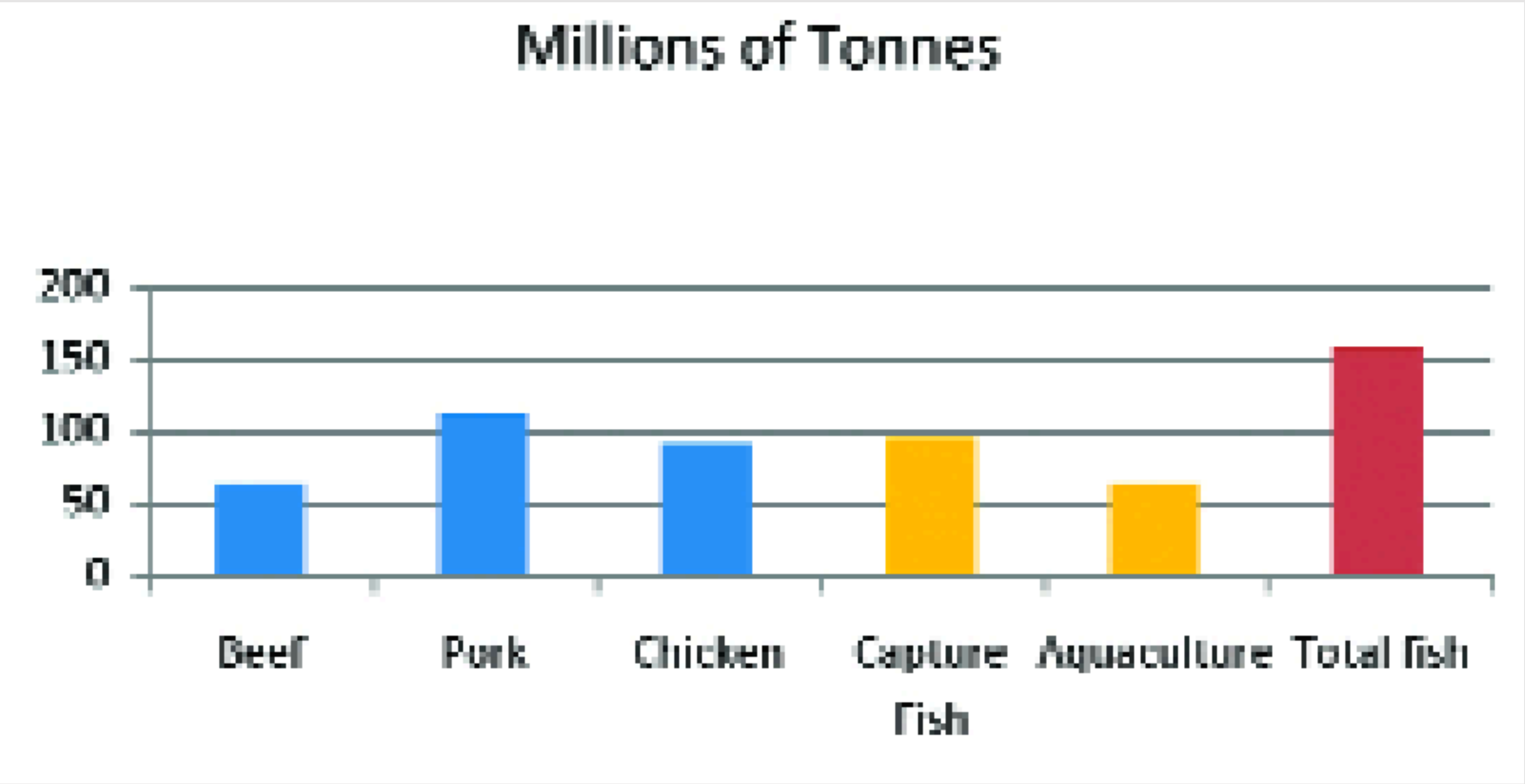

Figure 8.
Figure 6. Global production for 2011 of beef, pork, chicken and fish (capture fish versus aquaculture) Note: Land animal meat as carcass weight (millions of tonnes): capture fish and aquaculture as live weight equivalent (millions of tonnes) Source: FAOSTAT

	Atlantic salmon	Pig	Chicken	Lamb
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

Figure 9.

Table 1. product yield, energy, and protein retention in edible parts of Atlantic salmon, pig, chicken and lamb (Source: Bjorkli 2002)

(a) Harvest Yield is yield 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)

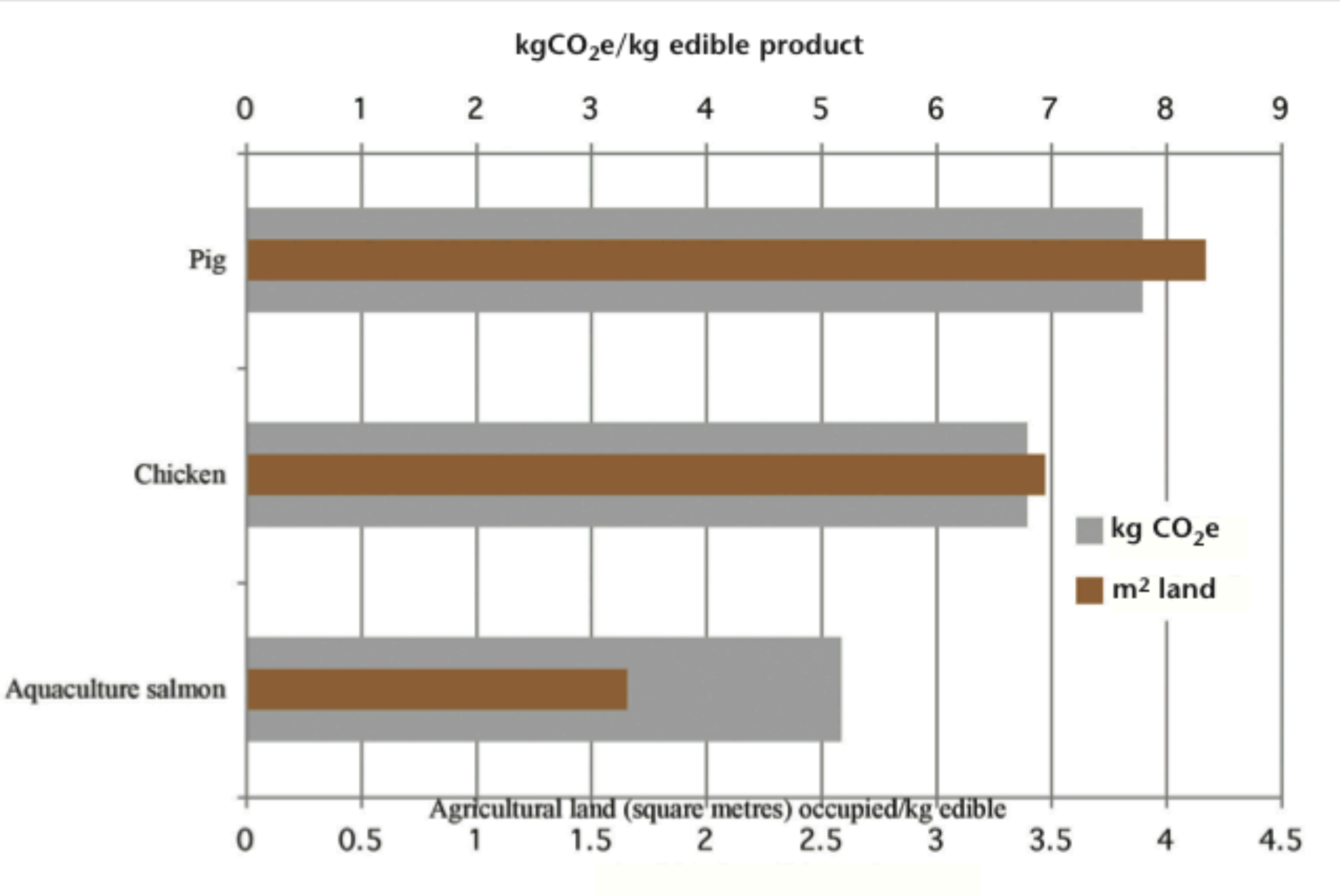

Figure 10.

Figure 7. Carbon footprint and land occupation by Norwegian farmed salmon and Swedish pig and chicken Source: Hognes *et al*, 2011 SINTEF report (see below)

Comparison of occupation of agricultural land (top axis) and greenhouse gas (GHG) emissions (bottom axis) from production of 1 kilo edible Norwegian aquaculture salmon and Swedish chicken and pig. From project with SIK:

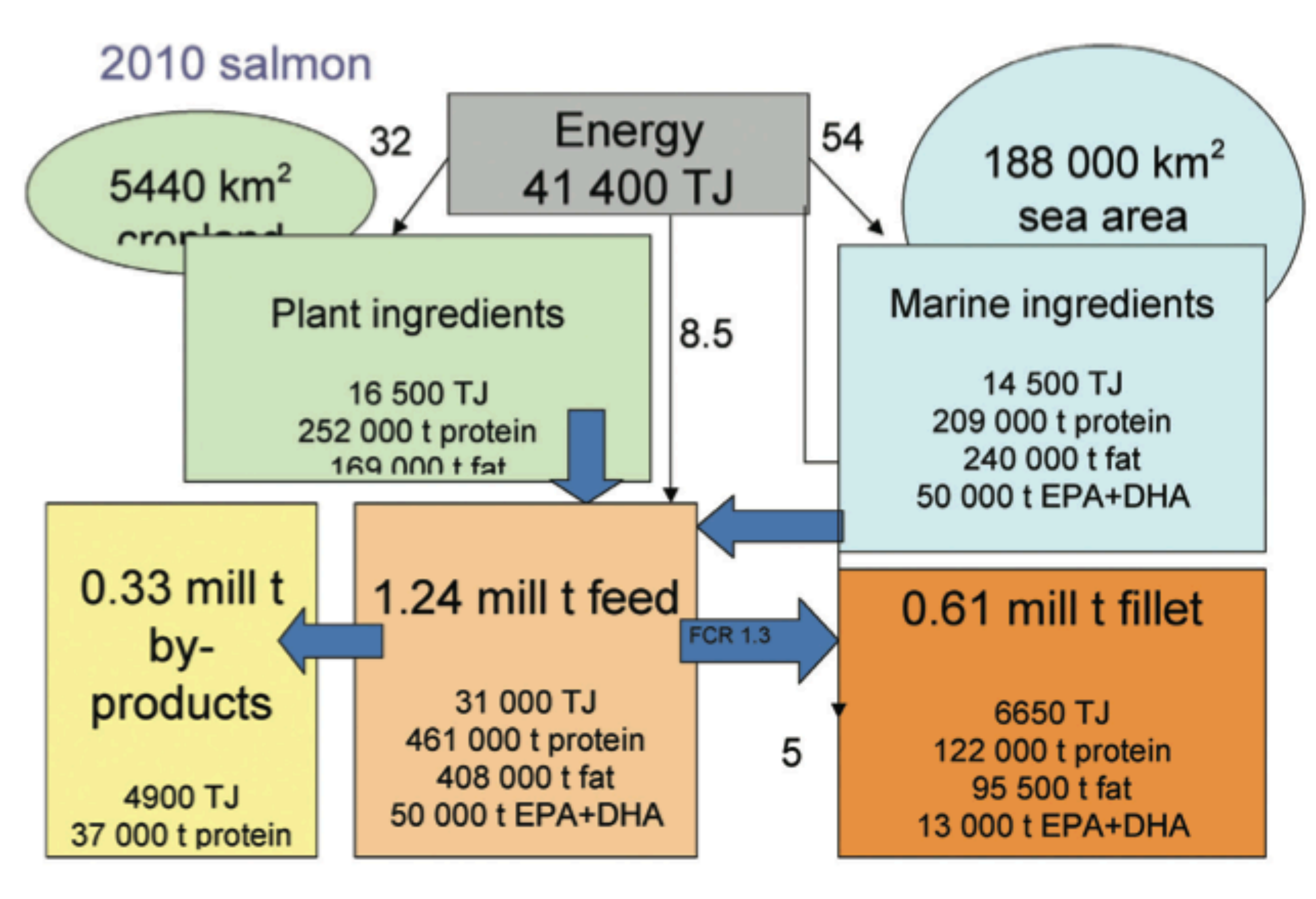

Figure 11.

Figure 8. Overview of the nutrient flows and energy use in Norwegian salmon production in 2010. Source: Ytrestoyl *et al*, 2011 NOFIMA report no. 53/2011 ISBN: 978-82-7251-945- 1. 65pp

	Amino acids, % of protein				
Amino acid	Salmon meal (a)	Salmon hydrolysate (b)	Chicken (c)	Adult human (d)	Schoolchild (d)
Lysine	6.90	7.67	4.72	1.60	4.4
Serine	4.60	6.00	3.89		
Histidine	2.00	1.67	1.44	1.60	1.9
Arginine	4.30	6.33	5.56		
Threonine	4.70	3.67	3.78	0.90	2.8
Tyrosine + Phenylalanine	9.10	7.00	5.56	1.90	2.2
Valine	4.30	5.00	3.44	1.30	2.5
Methionine	3.00	3.00	1.67	1.70	2.2
Isoleucine	3.40	4.00	3.33	1.30	2.8
Leucine	6.00	7.67	5.56	1.90	4.4
Phenylalanine	6.10	3.67	3.00		
Tryptophan	0.45	1.33	0.94	0.50	0.9

Figure 12.

Table 2. Comparison of amino acid content in (a) salmonmeal and (b)hydrolysate with requirements of (c) chickens and (d) humans (Ramirez 2007)

Sources

(a) www.pesquerapacificstar.cl (b) Wright, 204

(c) Nutrient requirement of poultry, 1994 (NRC)

(d) Protein and amino acid requirements in human nutrition, WHO, Technical Report Series [2007(935):1-265]

Figure 13.
Interior view of office on feed barge showing monitors for remote cameras and digital display of temperature and dissolved oxygen” (courtesy of Scottish Salmon Producers’ Organisation)

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Professor D C Little
7th November 2014

Comments