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Future availability of raw materials for salmon feeds and supply chain implications: the case of Scottish farmed salmon

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Abstract

The current range of Scottish salmon feeds is adapted to a differentiated supply of salmon products, including differing omega-3 content, differing content of marine raw materials, etc. The progressive replacement of marine feed ingredients by plant proteins and oils is reducing the content of omega-3 long-chain polyunsaturated fatty acids (LC-PUFA). However the benefits are a more secure and less volatile raw material supply, together with environmental feed contaminants at low or undetectable levels in the resulting salmon product. There is widespread adoption of standards and certification schemes by Scottish salmon farmers and feed suppliers in order to demonstrate environmental sustainability. This has focused in particular on use of certified ingredients from sustainable supply sources ('responsible sourcing'). Future volume estimates of Scottish salmon production, hence feed requirements, are insufficient to threaten raw material supply compared with global markets, although it is argued this is likely to involve greater use of locally grown plant proteins and an increased proportion of fishmeal manufactured from by-product trimmings (derived from processing fish for human consumption). However, UK retail chains will remain reluctant to allow salmon suppliers to utilise land animal by-products due to negative consumer perceptions, with resulting implications for formulation cost and flexibility. Given its world-wide scarcity, the main strategic concern relates to future availability of sufficient omega-3 LC-PUFA, in particular eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), in order to maintain the healthy image of Scottish salmon. To maintain its longer-term reputation and product benefits, the Scottish industry may need to consider adopting a more flexible attitude to using new alternatives to fish oil (e.g. EPA and DHA derived from transgenic oil seed crops, when commercially available). It is concluded that Scottish salmon farming is a successful example of sustainable feed development and the industry can be confident that the changing raw material base will support continuing production of high quality, healthy farmed salmon, but the long-term security of supply of omega-3 LC-PUFA remains an issue.

Keywords: Atlantic salmon; sustainable feeds; fishmeal; fish oil; alternative proteins; alternative oils; omega-3; EPA; DHA; supply chains

1. Introduction to Scottish salmon feeds

1.1 Study aims and methodology

Farmed Scottish salmon has a distinct market position, which has implications for feed requirements. The purpose of this study was to consider trends in the change in composition of Scottish salmon feeds with regard to the availability and use of key feed ingredients, and to consider the resulting implications for farmed salmon supply chains. In particular the study aim was to identify the nutritional, ethical, marketing, and sustainability issues surrounding reduced reliance of the salmon farming industry on marine ingredients. In order to achieve this, over the period from April 2014 to March 2015, meetings and telephone interviews were conducted with industry experts and stakeholders in the UK, Norway, Denmark, France, Ireland, and the USA.

1.2 Global farmed salmon industry and the differentiated supply of Scottish salmon and feeds

Salmon farming is the most highly developed form of large-scale intensive aquaculture owing to its productivity growth and technological change since the industry started in the 1970's in Norway and Scotland; it represents a highly efficient mechanism for transforming marine resources into high quality food that is available on a year round basis (Hognes et al., 2011; Ytrestøyl et al., 2011). Estimated global production of farmed Atlantic salmon in 2013 was approx. 1.8 million tonnes and is dominated by Norway with 1.1 million tonnes (Kontali, 2013). The much smaller Scottish industry (163,234 tonnes in 2013, Table 1) closely parallels Norway in terms of farming technology and is now mainly in Norwegian ownership. The compound annual growth rate (CAGR) for farmed Atlantic salmon was 6 % on a global basis from 2003 – 2013, but is now decreasing (Marine Harvest, 2014). In both Scotland and Norway the growth in salmon farming has resulted in year-round availability of cost-efficient, affordable salmon products on a greatly increased scale, while creating wealth and sustainable employment, including to remote rural locations; the industry therefore demonstrates clear economic and social benefits (Asche and Bjørndal, 2011).

Table 1 compares Scottish with Norwegian farmed salmon production, feed supply, and feed conversion rate (FCR) for 2013 and 2014. At c. 13% of combined Scottish and Norwegian production volume in 2014, it is clear that Scottish production is relatively small. Also the Scottish Government's target for sustainable growth of marine finfish is 210,000 tonnes by 2020. It should be noted that 2014 Scottish salmon production was boosted by premature 4th quarter harvesting for health reasons; as a consequence an FCR of 1.23 appears unrealistically low and industry sources indicate it was close to the 2013 value at c. 1.3. Feed costs dominate production costs for farmed salmon with the 2013 cost of salmon feed in Norway and Scotland for Marine Harvest (the largest global salmon producer) estimated at 50 % and 46 % respectively of production costs; the corresponding figures of 41 % and 43 % respectively for Canada and Chile are mainly due to lower feed costs linked to use of land animal by-products (Marine Harvest, 2014).

Despite being relatively small in volume compared with Norway and Chile, the Scottish salmon industry holds a distinctive position in world markets. Whereas the Norwegian salmon farming industry is the leading world producer and exporter of farmed salmon as a standardised commodity product, including to the UK market, the Scottish industry, lacking comparable economies of scale, supplies more differentiated products at higher unit value to offset potentially higher production costs. These range from standard to high performance products[1], including bespoke supply for niche markets in the UK and overseas (mainly to the USA and France). Scottish production therefore relies on a variety of different feed products, including specialist formulations to support a premium salmon segment, i.e. higher price salmon products with quality characteristics, including label claims on Scottish provenance, the content of omega-3 LC-PUFA in regard to EU intake recommendations, and others (e.g. compliance with responsible farming standards).

2. Changing salmon feed composition

2.1 Historical picture and trends

Historically the two most important ingredients in salmon feed have been fishmeal and fish oil**,** having favourable nutrient compositions and reflecting a major food item for a carnivorous species like salmon (NRC, 2011). Apart from a need for low levels of essential fatty acids for salmon growth, supplied via small quantities of (the oil present in) fishmeal or via fish oil, fishmeal itself is not an essential feed ingredient for aquaculture *per se*, but it provides a near optimal complete feed in a convenient, cost-effective, and highly digestible product form (Tacon and Metian, 2008). However, the pattern of stagnating wild fisheries and the fast growth of aquaculture risked over-dependence on a limited range of feed ingredients, especially fishmeal and fish oil, while the issues involved in replacement by alternative proteins and oils were soon recognised (Sargent and Tacon, 1999; Naylor et al., 2000). For reasons of cost reduction and security of supply, cheaper alternative ingredients (e.g. soyabean meal; rapeseed oil) have therefore been researched and progressively substituted in commercial feed formulations, where technically and economically feasible, and after further

[1] 'high performance diets' are defined as diets with high nutrient density, typically containing relatively high levels of energy and digestible protein

processing as required (NRC, 2011). At the same time increasingly higher inclusion of oil has been made possible by extruded feed technology and driven by the protein sparing effect of oil promoting growth (NRC, 2011).

2.2 Salmon feed composition in Scotland and Norway

Information about salmon feed formulation is more widely available in Norway than Scotland due to reporting requirements and policy issues. However, until recently the same three fish feed companies dominated feed manufacture in both countries (i.e. BioMar, Ewos and Skretting, although Marine Harvest has now also entered feed manufacture in Norway). Therefore, the two salmon farming industries are similar with some key differences in response to UK market focus, e.g. on omega-3. Thus feed formulation trends are broadly comparable between the two countries, with Scottish salmon feeds being more conservative in terms of rate of change and more varied in reflecting bespoke customer requirements. Fig. 1 shows the large changes in composition of Norwegian salmon feed since 1990 when c. 90 % of the diet came from marine ingredients compared with 29.2 % in 2013 (Ytrestøyl et al., 2014, 2015).

The feed comparison between Scotland and Norway is complicated by the proliferation of bespoke diets in Scotland, some of which are driven by external standards (e.g. Organic, Label Rouge etc.), but mostly by farm customer requirements linked in turn to retail requirements. Although the consultation revealed average Scottish salmon diets for 2013/14 comprised approximately 60 % plant and 40 % marine ingredients, this obscures the large range of different Scottish formulations; for instance in 2014 c. 7,000 tonnes (4 %) of salmon production was made for export to the Label Rouge salmon specification with a marine feed content of 51 %, whereas there is also significant salmon volume being produced approximating to lower Norwegian diet specifications. At the same time there has been a move in Scotland during 2013/2014 towards use of high performance diets of variable specification, but generally higher use of fishmeal. The consultation also revealed that nearly all Scottish feeds are being currently formulated to give not less than 22 MJ/kg in order to achieve faster growth and improved feed conversion. Typically this entails diets with 37 % lipid and 36 % protein (with 11% carbohydrate/fibre, 9% ash and 7% moisture), with high salmon prices allowing farmers to invest in higher specification diets at higher cost in order to yield higher marginal productivity. As a consequence the overall average marine protein and oil content of Scottish salmon diets is probably around 25 % and 15 %, respectively, (c.f. around 20 % and 10 %, respectively in Norway), and with higher average eicosapentaenoic acid (EPA, 20:5n-3) and docosahexaenoic acid (DHA, 22:6n-3) required for Scottish farmed salmon. In Scotland (and Norway) there is no use of land animal by-products, which account for over 20 % dietary inclusion in Chile and Canada, or of genetically modified (GM) ingredients (e.g. Chile and Canada use GM soya).

The following ingredients are commonly used in Scottish salmon feeds: soy protein concentrate (SPC); rapeseed oil; fishmeal; wheat starch; fish oil; wheat gluten; sunflower meal; faba beans; pea starch; maize; pea protein concentrate; and other ingredients have been used in minor proportions, e.g. rapeseed protein concentrate, palm oil, tapioca starch etc., with usage based on least cost formulation in order to optimise recipe cost. The volatility of ingredient costs is illustrated by the pattern of changing ingredient prices for five key raw materials in salmon feed during the period from 2006 to 2013, with a rising trend for fishmeal, fish oil, and soya, compared with more stable prices for rapeseed oil and wheat (Fig. 2).

2.3 Effect of reduced marine ingredient inclusion on feed sustainability

The replacement of finite marine feed resources by plant-based ingredients (and fishery by-products), is enabling salmon farming to achieve net fish protein production and possibly net marine oil production (Crampton et al., 2010; Bendiksen et al., 2011; Sanden et al., 2011). This continuing trend towards substitution of marine ingredients, together with increasing evidence that reduction fisheries are not being overexploited, contradicts the traditional view that salmon farming relies on the unsustainable use of marine ingredients (Shepherd and Little, 2014). For global 'fed' aquaculture, there is an overall plateau in fishmeal and fish oil use despite increasing aquaculture production (Fig. 3), which has not been restricted by, at best, a static supply of marine ingredients since 2009. Rising demand for fish feed ingredients has not therefore increased pressure on wild fish resources because of increased use of plant resources. At the same time there is no evidence that plant resources are inherently more sustainable for farming salmon, provided marine feed ingredients are sourced from sustainably managed stocks (or from fishery by-products); hence an increased utilisation of plant ingredients may not be as sustainable as generally assumed (Torrissen et al., 2011). However, all marine ingredients supplied to the Scottish salmon feed industry are required by the supply chains to show that they are responsibly managed and renewable (see section 6).

2.4 Effect of reduced marine ingredient inclusion on salmon nutrition and welfare

If the available EPA and DHA for global salmon feed falls below 4 % of the total dietary oil fraction (equivalent to c. 1.2 % of total feed), this then approaches the 1 % risk area for essential fatty acid deficiency in salmon and could predispose to health problems or reduced performance (Ruyter et al., 2000a,b). This risk is likely to be exacerbated by the increased use of higher performance diets and resulting higher growth rates (NRC, 2011). The implications of falling omega-3 LC-PUFA levels for salmon consumers are considered in section 4. In the case of increased plant protein usage, it is well recognised that the risks relate to the need to supplement with certain amino acids (e.g. lysine and methionine), whereas the presence of anti-nutritional compounds requires prior processing of the raw materials (e.g. by concentration or heat treatment) (Gatlin III et al., 2007). As regards micronutrients, increased plant protein levels may lead to suboptimal levels of certain minerals (e.g. selenium, iodine) and vitamins (e.g. vitamins A, D, and some B vitamins) (NRC, 2011).

2.5 Effect of reduced marine ingredient inclusion on contaminant levels

The Norwegian Scientific Committee for Food Safety concluded that the benefits of eating fish clearly outweigh the negligible risk presented by current levels of contaminants and other known undesirable substances (VKM, 2014). As regards farmed salmon, concentrations of dioxins and dioxin-like polychlorinated biphenyls (PCBs), as well as of mercury, have decreased by about 30 % and 50 %, respectively, compared with the corresponding levels in 2006, due to replacement of marine feed ingredients by plant ingredients. New fish feed contaminants, such as the pesticide endosulfan, polyaromatic hydrocarbons (PAHs), and mycotoxins are unlikely to be a safety issue, since the concentrations are very low and not detectable with sensitive analytical methods (VKM, 2014). The health risk associated with brominated flame-retardants (PBDEs) is low. In contrast to their earlier conclusions, VKM stated that there is now no reason for specific dietary limitations on fatty fish consumption for pregnant women. It is likely that the contaminants picture in Scottish salmon feed closely parallels the Norwegian experience, with the main differences due to local UK sourcing of fishery by-products, the slower rate of replacement of marine ingredients in Scottish diets, and the greater use of bespoke salmon diets in Scotland with higher marine content. The switch from marine to predominately plant-based diets will not mean a greater risk of pesticide contamination of the feed, since any such contamination is unlikely to penetrate through the hull, which is normally discarded from oil seeds during processing.

3. Global supply and local demand for proteins and oils

3.1 Marine ingredients

Fishmeal and fish oil are globally traded commodities similar to other raw materials or primary agricultural products that have long been produced and marketed; aquaculture grew to become the biggest customer for these marine resources (Jackson and Shepherd, 2012). Figs. 4 and 5 detail annual world fishmeal and fish oil production, respectively, by producing region from 2006 to 2015, with Peru the dominant world supplier followed by Chile. There may be a decreasing trend for marine ingredient production (e.g. fishmeal production in 2012 and 2013 was around 12 % less than the 11 year mean at 4.56 and 4.68 million tonnes, respectively (IFFO, 2014)). Production is subject to environmental influences and, whereas the potential impact of climate change is not well understood (Callaway et al., 2012), acute phenomena, such as El Niño, have well-known consequences, especially for the Peruvian anchovy fishery (Shepherd and Jackson, 2013). Given these supply uncertainties in the dominant southern Pacific anchovy fishery, compounded by increased regulatory focus on precautionary catch quotas, continuing growth by major users of marine ingredients (including salmon farming) has only been possible by the increased substitution in feeds by other ingredients.

Based on a 2014 Scottish salmon feed volume of c. 220,000 tonnes, the corresponding estimated usage of marine ingredients at 40 % of feed is 88,000 tonnes (i.e. requirements for fishmeal at 25 % being 55,000 tonnes and for fish oil at 15 % being 33,000 tonnes). UK and Irish production of fishmeal in 2014 was c. 39,000 tonnes (T. Parker, United Fish Products, personal communication), but in practice at least 50 % of fishmeal requirements need to be imported as some of this domestic production is from salmon processing offal and therefore cannot be fed back to salmon. Logistics favour Scottish fishmeal imports from Iceland and Norway, while fish oil is also imported from Peru and Chile to obtain higher levels of EPA and DHA than would be available from fisheries in the North East Atlantic.

3.2 Plant ingredients

3.2.1 Plant proteins

US World Agricultural Supply and Demand Estimates (October 2015) have updated 2015/2016 global crop estimates, as follows: wheat - 732.8 million tonnes; corn - 988 million tonnes (based on 38,898 million bushels); and soybeans - 320.5 million tonnes (USDA, 2015).

The requirement for feeds with a high nutrient density ordinarily favours using plant protein concentrates. These are most readily available from oilseeds, including rapeseed and sunflower seed, but the most widely used is SPC. Although their global availability as bulk commodities is not a constraint on fish feed (e.g. 2015/2016 estimated global supply of oilseeds is 531 million tonnes; USDA, 2015), the availability of protein concentrates is less.

Norway's salmon industry requirements for non-GM soy (as SPC) were 365,000 tonnes in 2013 (Ytrestøyl et al., 2014) and current plant protein requirements for Scotland are estimated at 77,000 tonnes, over 50,000 tonnes as SPC. Although estimated global production of soybeans for 2015/2106 is 320.5 million tonnes, this is mostly GM material, whereas European salmon feed uses only non-GM soya products (see 6.1). Currently 5.5 million tonnes of non-GM soya are being grown, mainly in Brazil, and supplied to world markets at a price premium of US$80 – US$100 or c. 10 % over GM soya (C. Meinich, Chr. Holtermann ANS, personal communication). Given that GM soya is used in Chilean and North American salmon feeds, requirement for non-GM soy for Scottish salmon feed is c. 1 % of global supply and totals only 7.5 % for combined Norwegian and Scottish salmon production; however, these are underestimates as the yield of concentrates is c. 61.5 % of harvested soya. Despite it being a niche product and all imported mainly from Brazil, there are no indications or reasons to suspect that availability of non-GM soya will decline in the short to medium term.

3.2.2 Plant oils

Plant oils are incorporated into salmon feeds to provide energy and blended with sufficient fish oil of the appropriate quality to give the required content of EPA and DHA. The preferred ingredient is rapeseed oil, which is grown in the EU (including the UK), but mainly in North America. Rapeseed has been cross-bred to reduce levels of erucic acid and glucosinolates and is safe for human consumption (e.g. Canola). Global production of rapeseed oil for 2014/15 was 26.98 million metric tons and availability of non-GM rapeseed oil is not a constraint, including from UK crop material (Statista, 2015). Other plant oils, including soya oil and palm oil, have been used at low levels (e.g. to help pellet integrity).

4. Omega-3 LC-PUFA scarcity

4.1 Introduction

World usage of fish oil from 2003 to 2013 is given in Fig. 6, with increasing demand from direct human consumption (so-called 'nutraceuticals') appearing to be at the expense of aquaculture. Aquaculture use averaged around 800,000 tonnes per annum until 2012, but declined to just below 700,000 tonnes per annum in 2013. Therefore around 75 % of total global supply was used in aquaculture, with 21 % going for direct human consumption in 2013. Around 83 % of fish oil used in aquaculture feeds in 2013 was consumed by salmonids (60 %, mainly salmon) and marine fish (23 %) (Fig. 7).

Although prices for fish oil and rapeseed oil were broadly similar a decade ago, demand for fish oil is now largely a derived demand for omega-3 LC-PUFA. This is shown in Fig. 2, which indicates that the fish oil price has been at an increasing premium over rapeseed oil since 2009 which is directly linked to its content of EPA and DHA (Shepherd and Bachis, 2014). Thus rapeseed oil, which has no EPA and DHA, is included as a more cost-effective source of dietary oil for energy purposes only.

4.2 Acute shortage in 2014/2015 and likely recovery

As a result of Peru's industrial fleet being given low anchovy fishing quotas in 2014, the fleet caught only 2.25 million tonnes in 2014, which is around 1/3 of the catch in recent years (Reuters, 2015). This severely impacted on the global availability of EPA and DHA resulting in record price levels reaching US$2,500 - US$3,000/tonne for high omega-3 Peruvian fish oil delivered into Europe (IFFO, unpublished). Table 2a indicates 2014 global production was only 140,000 tonnes of combined EPA and DHA (compared with a 'normal' year of up to c. 200,000 tonnes) giving total availability of 170,000 tonnes including year-end stock carry-over (after Meinich, 2014). Table 2b indicates total consumption of combined EPA and DHA for salmon feed in 2014 was c. 50,000 tonnes, equating to an inclusion rate in the oil fraction of global salmon feed of around 6 % after taking account of consumption by non-salmonid aquaculture, direct human nutrition, and technical uses (after Meinich, 2014).

Although the total Peruvian anchovy catch increased to 3.69 million tonnes in 2015 (E. Bachis, IFFO, personal communication), the anchovy were leaner with a lower oil yield than 2014 due to the El Niño effect; therefore it is considered that the current anchovy oil scarcity is continuing and global EPA and DHA supplies in 2015 or early 2016 may be no more than in 2014 (E. Bachis, IFFO, personal communication).

Due to high fish oil prices, non-traditional sources are now appearing on world markets, e.g. *Sardinella* spp from north-west Africa (C. Meinich, Chr. Holtermann ANS, personal communication), although such sources are unlikely to be satisfactory in regard to certification requirements for UK salmon feed use (see 5.1). High prices will tend to dampen demand from price sensitive segments. Demand growth for human nutrition and non-salmon aquaculture would be expected to be around 2.5 % - 5 % per annum; however, human nutrition growth has stalled since 2013 (A. Ismail, GOED, personal communication) and fish oil inclusion in non-salmonid feeds can be expected to fall at current prices.

Historical precedent provides confidence of a likely strong rebound in Peruvian anchovy stocks following the current oceanic conditions of El Niño, with a recovery now likely during 2016, in which case annual global fish oil supply will then increase towards more 'normal' annual production levels approaching c. 1 million tonnes of crude fish oil (corresponding to up to a maximum of 200,000 tonnes of combined EPA and DHA). History also suggests that such 'normal' levels will be sustained until the next El Niño event, which is unlikely to occur before 2020. Assuming a 2.5% compound annual growth rate (CAGR) for both direct human nutrition and salmon farming and 5% CAGR for non-salmon aquaculture from 2016, this will permit *pro-rata* growth in EPA and DHA demand, with total consumption of 170,000 tonnes in 2016 increasing to 192,000 tonnes in 2020 (including 55,000 tonnes for salmon but with spare capacity to increase to 63,000 tonnes). If another El Niño occurs soon after 2020, by then the resulting scarcity could possibly be offset by an increased supply of EPA and DHA from novel sources (see 4.6)

4.3 Market significance of changing EPA and DHA content of salmon

Onozaka et al. (2012) surveyed the position of farmed salmon in five European countries (including the UK) and found that consumers regard salmon as superior in healthiness compared to other meats. Certain UK retailers reported that their customers take health benefits of salmon into account in their purchasing decisions, hence negative publicity on the health benefits of farmed salmon might reduce demand. However, the health benefits of farmed salmon consumption are not restricted to its content of omega-3 LC-PUFA (Galli and Risé, 2009; Tocher, 2009). Salmon comprises highly digestible protein and essential amino acids and marine lipids, as well as vitamins and minerals, so consumption of salmon is more nutritious compared with consuming omega-3 supplements alone.

The Global Organisation for EPA and DHA (GOED) summarized the international recommendations for EPA and DHA intake (GOED, 2014), while Shepherd and Bachis (2014) showed that, as a result of the combined EPA and DHA content of added oil in Norwegian feeds falling from 20 % in 2002 to 7.2 % in 2012, the number of days recommended requirement met by one portion of Norwegian salmon had fallen proportionately to approximately 6 days (EFSA at 250 mg/day), 3.4 days (SACN at 450 mg/day), and 3 days (ISSFAL at 500 mg/day). The average UK consumer eats less fish than Norwegians and a UK survey showed that, for oily fish, average consumption was well below the recommended one (140 g) portion per week in all age groups, with men and women aged 19 to 64 eating just 52 g and 54 g/week of oily fish, respectively (HM Government, 2014).

In a recent study of different farmed and wild salmon products available during 2013 in retail outlets in Scotland, Henriques et al. (2014) showed that, although wild salmon products had higher relative values of EPA and DHA, farmed salmon products generally delivered a higher dose of EPA and DHA compared to the wild salmon products, due to their higher lipid content, and were therefore better able to deliver recommended dietary intake levels than the wild salmon products; the study also confirmed the elevated levels of omega-6 PUFA, specifically linoleic acid (18:2n-6), but concluded that 18:2n-6 does not have a major impact on the nutritional quality of farmed salmon and does not outweigh the benefits of the high omega-3 LC-PUFA levels recorded.

4.4 Omega-3 LC-PUFA differentiation by UK retailers

The consultation revealed there is clear segmentation in UK farmed salmon supply between those retailers willing to claim that one portion provides the weekly required intake ('formulated to deliver high levels of healthy omega-3 long-chain fatty acids' or similar wording) and those simply stating 'variable omega-3 content' or similar wording. Currently four (out of nine) UK retailers (so-called 'premium suppliers') claim on the pack of some or all of their products that consuming the stated portions will deliver the internationally recommended intake of EPA and DHA, for which EFSA would appear to be the (minimum) target reference of choice. For these premium suppliers/products, there is a clear link being made between the content of omega-3 LC-PUFA on offer and the health of the consumer, with the premium suppliers specifying Scottish farmed provenance, i.e. omega-3 has become something of a Unique Selling Point (USP) linked to Scottish production. This differentiation is used as a competitive tool by retailers, but raises related questions, such as:

- The term 'omega-3 fatty acids' may justifiably include more than EPA and DHA, e.g. docosapentaenoic acid (DPA). In evaluating competing product claims, care must be taken to ensure like-for-like comparisons, since using total omega-3 LC-PUFA content gives higher flesh values than only EPA and DHA.
- There is no indication whether premium salmon is formulated with an overage of omega-3 LC-PUFA to take account of the reduction in levels due to cooking the product (which will vary with cooking method and fat loss, etc.), while intake recommendation levels are based on an assumption of what is actually consumed.
- There is no reference to omega-6 fatty acid levels that have increased in farmed salmon due to vegetable oil inclusion levels.

4.5 The challenge to feed formulation

The existence of a range of bespoke salmon products in response to retail market differentiation represents a complex challenge for farms and feed suppliers. From the consultation it appears that UK feed mills add between 6.5 % and 8.5 % of combined EPA and DHA in the oil fraction of the feed to achieve 1.75 g in a 130 g fillet portion of salmon (EFSA target), depending on salmon bodyweight and fat level (or proportionately more assuming a 100 g portion). The lower end of the Scottish farmed range is in the normal range of standard Norwegian practice during 2014 and is claimed to be typical of current UK imports of Norwegian salmon (supplying an estimated 60 % of the UK market). At these lower levels there is no certainty that the EFSA claim will be met consistently (unless consumers eat more salmon each week) and this lower range corresponds to the majority of UK (non-premium) salmon volume labelled on the basis of 'variable omega-3 levels'.

4.6 Future availability of LC-PUFA sources

GM sources of LC-PUFA (EPA and DHA), such as EPA-containing GM yeast, are being used in Chilean salmon feeds; 'Verlasso salmon' (http://www.verlasso.com/). In addition, commercial production of EPA and DHA from GM oilseeds could be a reality by around 2020 (section 8.2.2) (Tocher, 2015). Other potential sources of LC-PUFA are:

4.6.1 Fishery and aquaculture by-products

Increasing use of fishing industry by-products will continue to supply marine ingredients, including fish oil. The recycling of salmon oil for salmon production, which is prohibited by some codes of practice, is being used in aquaculture feeds (e.g. for gilthead bream, *Sparus* *aurata*) and could potentially supply c. 150,000 tonnes of global salmon oil. With 70 % vegetable origin it would contain a maximum 10,000 tonnes of EPA and DHA, but its use would reduce the total demand from non-salmonid aquaculture, making more EPA and DHA available for salmon. In conclusion, increased EPA and DHA from fishery and aquaculture sources is unlikely to have major volume significance in the short to medium term (Tocher, 2015).

4.6.2 Whole cell DHA-rich algal biomass

'DHA Gold' (http://www.dhagold.com/) is a dry biomass sold by DSM as a non-GM feed product approved for sale in the EU.

4.6.3 Microalgal DHA

Fermentation of heterotrophic organisms (e.g. *Schizochytrium*) (Tocher, 2015) requires fermentation use of energy-dependent organic substrates (e.g. sugar), with current commercial developments by DSM, ADM, Alltech, etc. The potential applicability of DHA to salmon feed is by blending fish oil to achieve a similar 1:1 ratio of EPA to DHA as seen in wild Atlantic salmon. As Peruvian anchovy has an 18:12 ratio of EPA to DHA, DHA can be added to anchovy oil to achieve a 1:1 EPA to DHA ratio, before balancing the blend with rapeseed oil; hence 25-30 % of the resulting 'fish oil' can come from microalgal DHA but still remain in the natural range of fish oil composition of wild Atlantic salmon.

4.6.4 Longer term options

In the long term it is recognised that cultivation of autotrophic/phototrophic algae using photosynthesis is the most efficient solution, but it is proving highly complex and difficult to scale up (Tocher, 2015).

4.7 Options and implications for the Scottish salmon industry

The current shortage of marine sources of LC-PUFA (EPA and DHA) (section 4.2) should start to reverse soon and supplies are likely to become normal during 2016 and thereafter until the next El Niño occurs around 2020, by when alternative novel sources of EPA and DHA may be available from GM and non-GM sources; otherwise the current acute shortage becomes a chronic shortage. Total 2015 supply of fish oil (including farmed salmon oil) is estimated at 834,800 tonnes (E. Bachis, IFFO, personal communication) and the expectation is that average salmon feed inclusion will have remained close to 6 % combined EPA and DHA level in feed oil, corresponding to the bare minimum needed to meet EFSA weekly intake recommendation. The main difficulty for the Scottish industry from the current shortage is if the premium segment needs to reassess its claim about one portion of fish meeting weekly recommended requirements for omega-3 LC-PUFA; if product relabelling becomes necessary, this could negatively impact salmon's image as a healthy product.

It is relevant for the industry to consider the marginal cost of additional EPA and DHA in Scottish feed. For example, assuming the replacement cost of anchovy oil (c. 26 % combined EPA and DHA) is US$3,000/tonne and it is necessary to add 7 % of the oil fraction of the feed as EPA and DHA to reliably meet the EFSA claim, this is equivalent at 30 % oil inclusion to 2.1 % of the total feed, hence costing US$240/tonne. On this basis should the market be supplying only 5 % of the oil fraction of the feed to conserve material, the additional 2 % to regain scope for the EFSA claim would cost c. US$69/tonne (or US$34.50 for each percent inclusion of combined EPA and DHA), which may be viewed as a minor cost premium set against the reputational cost and risks of doing otherwise. On the same basis, if current salmon feed cost/tonne is c. US$1,250/tonne, an additional 2 % of combined EPA and DHA at US$69/tonne would increase feed cost by 5.5 %. Note (i) calculations should take into account the inclusion of fishmeal, which contains 9 % oil with high levels of EPA and DHA; (ii) if some producers are using more EPA and DHA, others will have to use less due to scarcity limits.

5. Role of certification and standards in responsible sourcing

5.1. Demonstrating responsible sourcing of marine feed ingredients

Standards and certification schemes have become important tools to manage concern issues, such as economic, social and environmental sustainability (e.g. Gail Smith, 2008). The main focus for Scottish salmon is long-term sustainability from an environmental standpoint, especially use of marine feed ingredients. An overview of the sustainability of reduction fisheries is published annually (Sustainable Fisheries Partnership, 2015) and there are well-established food chain standards controlling process quality, food safety, and a particular focus on fish welfare in Scotland (Munro and Wallace, 2015).

In developing a consensus approach to responsible practice, the Code of Good Practice for Scottish finfish aquaculture (CoGP) seeks 'to enhance the industry's reputation for respecting the environment through adoption of best practice and greener technologies and reducing the impact on wild fisheries by increasing use of alternative feed sources' (CoGP, 2015). In addition to recommendations on feed formulation and use, the CoGP requires that fish-catch supplies used in fishmeal manufacture are from fisheries which are responsibly managed, either by reference to the FAO (Food and Agriculture

Organisation of the United Nations) Code of Conduct for Responsible Fisheries (FAOCRF; FAO, 2015) or the Marine Ingredients Organisation (IFFO) RS scheme (IFFO, 2015), or by another globally recognised standard. The CoGP also makes fish welfare provisions, which are influenced by husbandry conditions, including use of suitable feeds and feeding methods.

To demonstrate responsible sourcing, the use of certified ingredients has been adopted by Scottish feed suppliers and farmers (SSPO, 2013). For marine feed ingredients used in aquaculture there are six commonly used standards; GlobalGap is more focused on food safety, while the other five claim to be based on the key principles underlying the FAOCRF (FAO, 2015). They are Aquaculture Stewardship Council (ASC) (http://www.asc-aqua.org), Best Aquaculture Practice (GAA BAP) (http://www.gaalliance.org/bap/standards.php), Friend of the Sea (http://www.friendofthesea.org/), IFFO RS, and Marine Stewardship Council (MSC) (http://www.msc.org). For marine ingredients, IFFO RS certification is probably universal in Scotland providing evidence of traceability back to responsibly managed fish stocks, avoidance of illegal, unreported, and unregulated fish (IUU), and control of by-product raw material, with an associated chain of custody. For sourcing of fishmeal and fish oil, the following were required for the processors and retailers interviewed during this study:

- Traceability to species and country of origin
- No endangered species used, as defined by the International Union for Conservation of Nature (IUCN) 'Red List' (IUCN, 2015)
- Preference for feed manufacturers to provide evidence of responsible sourcing
- Avoidance of IUU fish

5.2 Demonstrating responsible sourcing of plant feed ingredients

Three standards are currently used for plant ingredients for Scottish salmon feeds:

- The Roundtable on Responsible Soy (RTRS) Association approved its Standard for Responsible Soy Production versions in 2010 (RTRS, 2011)
- The new ProTerra Foundation Standard Version became effective in January 2015 and includes soya (ProTerra, 2015).
- Cert ID is focused on Non-GMO certification and has become the benchmark for Non-GMO identity preservation (Cert ID Europe Ltd., 2015).

The use of these three schemes for fish feed, primarily for soya, is seen as work in progress. Given the growing recognition of potential environmental problems (e.g. rain forest degradation associated with uncontrolled soya production, especially in South America), it is perhaps surprising that environmentalist pressure has focused on use of marine ingredients in aquaculture and largely ignored plant ingredients until recently.

5.3 UK supply chain perspective - salmon farmers and feed manufacturers

It was clear from the consultation that sustainability issues are a strategic concern for the owners of the three principal UK salmon feed companies and lie at the heart of their day-to-day operations, including raw materials purchase; also that salmon purchasing firms increasingly oblige their suppliers to provide evidence demonstrating responsible management and use of renewable resources. The salmon farm and feed-related certifications used currently by Scottish salmon farms and their associated supply chains are given in Supplementary File 1. Key findings include the following:

(i) Over 90 % of Scottish salmon farms are members of the Scottish Salmon Producers Organisation (SSPO) and subscribe to the CoGP.

(ii) Widespread adoption of 'Freedom Food'/'RSPCA Assured' certification (http://www.freedomfood.co.uk/) is an international differentiator specifying 'sustainable feed' and IFFO RS certification of marine ingredients

(iii) The most widely (but not exclusively) used Scottish salmon farming certification is GlobalGap (http://www.globalgap.org/uk_en/), which is focused on food safety and feed assurance.

(iv) The ASC salmon standard (http://www.asc-aqua.org/index.cfm?lng=1) has received global endorsement by Marine Harvest with two Scottish salmon farms now certified. ASC is likely to be adopted by other Scottish producers

(v) IFFO RS certification is currently only accepted in a chain of custody role by the ASC salmon standard.

(vi) The GAA BAP certification is not currently adopted by any Scottish producers despite its leading position in North and South American aquaculture (http://gaalliance.org/what-we-do/bap-certification/).

(vii) Greater harmonisation between different standards would be beneficial; the Global Sustainable Seafood Initiative plans to benchmark them to facilitate sourcing decisions (http://sustainableseafoodcoalition.org/news/new-gssi-website-launches).

5.4 UK supply chain perspective - salmon processors and retailers

To discover salmon sourcing policies of leading multiple retailers and processors, eight of the nine major UK retailers and two leading UK seafood processors were consulted. This confirmed that UK retail salmon standards are a complex set of competing codes aimed at increasing retailers' control over the supply chain. Aquaculture focus on sustainable feed issues is partly driven by competing UK retailers and is influenced by pressure from environmental NGOs, which often compete for support from consumers and supply chains. The existence of different private standards can cause confusion (e.g. to retail fish buyers) and is poorly understood by consumers. It appears sustainability issues are being used as a competitive tool by firms highlighting responsible sourcing credentials, so salmon farming and feed standards continue to be driven up; however, this has implications in restricting choice among different raw material sources.

5.5 Relevance of input/output indices for marine resource use

Although the main driver for replacement of marine ingredients by plant raw materials has been the combination of nutritional innovation and market forces in the face of fluctuating supply and highly volatile price, replacement has impacted on the different indicators used to relate marine ingredient input to farmed salmon output. These 'marine sustainability indicators' include fish-in fish-out ratio (FIFO), marine protein dependency ratio (MPDR), forage fish dependency ratio (FFDR), etc., and their use has been reviewed by various authors (e.g. Ytrestøyl et al., 2015). Although FIFO and FFDR have been used as a proxy for sustainability, it is not clear why this should be since sustainability must be based on responsible harvesting of fish that are used for fishmeal and fish oil according to international regulations (backed up by private standards if necessary). Nor has the FIFO ratio any obvious nutritional basis and it is not therefore a measure of production efficiency (Tocher, 2015).

As one of its indicators ASC has included FFDR, calculated as the quantity of forage fish required to produce the amount of fishmeal and fish oil to produce a unit of farmed fish. For 2013 the corresponding FFDRs for Norwegian salmon were 1.54 and 0.69 for fish oil and meal, respectively, well within the ASC standards of < 2.95 for fish oil and < 1.35 for fishmeal (Ytrestøyl et al, 2014); by comparison the equivalent (unpublished) values for one Scottish producer in 2013 of 2.09 for fish oil and 0.76 for fishmeal were higher than Norway, but well within the ASC permitted range.

5.6 Effect of changing raw materials on salmon farming sustainability

As regards protein retention, Torstensen et al. (2008) and Bendiksen et al. (2011) have found similar levels in Atlantic salmon fed either mainly marine diets or mainly plant-based diets, explaining why salmon can be produced with feeds containing high inclusions of plant ingredients and only low inclusions of marine ingredients. Changing the salmon diet composition from 88 % marine ingredients to 85 % plant ingredients resulted in almost the same carbon footprint (Ytrestøyl et al., 2011), which supports the view of Torrissen et al. (2011) that increased utilisation of plant ingredients may not provide an increase in sustainability as often claimed. The increased use of fishery by-products influences sustainability; although they have little, if any, alternative use, the effect on dietary carbon footprint will depend on whether the life cycle analysis (LCA) calculation adopts economic or mass allocation. As stated by Ytrestøyl et al. (2015), several methods must be used to evaluate eco-efficiency and sustainability of salmon production as no single method is sufficiently robust.

6. Scope for alternative feed ingredients, including land animal products, genetically modified, and fermentation products

Considerable research has been performed to assess a large range of alternative protein and oil/fat sources as ingredients for aquaculture feeds, including salmon (Gatlin III et al., 2007; Turchini et al., 2011). Focus here will be on alternative current and emerging protein and oil ingredients that have large-scale potential in Scottish salmon farming, but where there are supply chain concerns about their use or the technical basis is not sufficiently established. For alternative protein feed ingredients found to be suitable and cost-effective, it is important to be able to concentrate the protein in order for it to replace SPC in practical feed manufacture.

6.1 Land animal by-products (LAPs)

6.1.1 Current status and availability of LAPs in Europe

Before year 2000 animal proteins were widely used in fish feeds, but due to Bovine Spongiform Encephalopathy (BSE), most animal proteins were banned from terrestrial and aquatic animal feeds. From June 2013, due to improved testing methods, use of non-ruminant Processed Animal Protein (PAP) has been approved for use in aquaculture in the EU (Regulation 56/2013). The following are the main non-ruminant PAP products in the UK and EU now legally available for inclusion in aquaculture feeds: Poultry PAP; Feather meal PAP; Porcine PAP; Porcine blood meal PAP; and Porcine blood products. EU production of poultry-derived PAP and of porcine PAP and blood products in 2013 was

365,000 tonnes and 275,000 tonnes, respectively (Woodgate, 2014). To ensure lack of ruminant protein contamination, segregation, security, and traceability of 'Category 3' animal by-products is the subject of detailed controls at the slaughterhouse and downstream.

6.1.2. Current use of LAPs in salmon feed

Despite the legal relaxation, since 2001 no LAPs have been used in salmon feeds in Europe, with a marked reluctance by supply chains to incorporate animal by-products in feed for farmed salmon (see 6.1.4), despite technical benefits (e.g. blood meal's histidine content preventing cataracts). The situation outside Europe with fewer BSE-related problems is very different (e.g. current Chilean salmon diet formulations with 3 % poultry oil and 19 % LAPs).

A voluntary ban on use of LAPs in salmon feed in UK (and Norway) is reinforced by the CoGP prohibiting use of LAPs in Scottish salmon. This strict policy appears contradictory in view of retail supply of imported farmed warm water prawns (*Penaeus* spp.), 'River Cobbler' (*Pangasius* spp.), and Pacific salmon (*Oncorhynchus* spp.) from enhancement programmes, which may all have been fed LAPs. The rationale of the ban is fear of negative consumer reaction, variously linked to: BSE concerns, the horsemeat contamination issue, the supposed 'unnaturalness' of such ingredients, and associations of animal by-products with use of waste material otherwise destined for landfill disposal. The retailers consulted pointed out this is not a food safety issue and would give access to global salmon production, but accept their customers do not wish the policy to change. All respondents referred to the constraints of halal and kosher requirements, which prohibit use of porcine material (e.g. pig blood), hence further supply chain segregation. In practice this means that use could only be made of poultry products, such as poultry offal meal, feather meal and poultry oil. The non-governmental organisations (NGOs) consulted supported the use of LAPs in salmon feed as representing a sustainable solution; also the ASC salmon farming standard supports the use of LAPs.

6.1.3 Conclusions and implications for LAPs/PAP

Consultation, especially with retailers, showed strong resistance to using LAPs in salmon feed by UK and continental European consumers. It is therefore not under consideration in Scotland and this is unlikely to change in the foreseeable future, despite the EU having removed legal obstacles for PAP use. If this is reconsidered in the future, robust source assurance guarantees would be required and porcine material would need to be excluded. As regards cost savings from an open salmon feed formulation with poultry by-products, estimates from feed companies consulted were in the range of £60 - £80/tonne (i.e. up to 10 % of feed cost), depending on feed size and specification.

6.2. Use of genetically modified feed ingredients

6.2.1 Scope for GM protein ingredients

6.2.1.1 UK use in land animal feeds versus salmon feeds

Following supply concerns about non-GM soybeans in 2013, all but one of the eight UK retailers consulted changed their sourcing policies to permit the inclusion of GM plant ingredients in terrestrial livestock feeds, especially for chicken. Although inclusion of approved GM feed ingredients is legally permissible in the UK, currently salmon producers and feed companies have a strict non-GM policy. This appears to reflect the following:

- (i) Negative consumer attitudes to GM in Europe, especially in France, Germany, Austria and Italy, with potentially severe export implications for Scottish salmon.
- (ii) The current lack of a clear commercial disadvantage to sourcing non-GM ingredients, such as reduced availability and substantially increased cost for non-GM SPC.
- (iii) The current consensus to maintaining non-GM fed salmon status in Scotland being shared by the SSPO, some NGOs, and the Scottish Government, as part of a 'green and clean' stance (while English and Welsh Government policies on GM are more flexible).
- (iv) The Norwegian salmon farming industry has a non-GM policy.

However, seven of the eight UK retail respondents consulted were willing to consider adopting a more flexible GM feed policy if market circumstances changed. They accepted that UK consumer attitudes were becoming less hostile to GM, but the largest supply chain concern relates to the risk of losing key export markets, especially France.

6.2.1.2 Availability of non-GM proteins

As shown in 3.2.1, although the 5.5 million tonnes of non-GM soy protein is less than 3 % of global soya supplies, dominated by GM material, there is no current threat to availability, or sufficient of a price driver for switching to GM SPC in salmon feeds. Discussions in Norway about whether it is logistically possible to supply GM and non-GM feed at the same time by using different mills concluded this is more a matter of policy and additional cost than logistics, but it would be more difficult (but possible) to segregate the resulting fish streams post-harvest. This is not seen as being feasible in Scotland and any move to abandon the non-GM policy would need to be agreed jointly by all three UK feed producers.

6.2.2 Scope for GM oil containing EPA and DHA

Commercial production of so-called 'Verlasso' salmon in Chile involves the use of yeast, which has been genetically modified to produce EPA (Xue et al., 2013). The transgenic yeast cells are produced by fermentation using glucose and killed before the whole dead cells are added to salmon feed as a partial replacement for fish oil (Hatlen et al., 2012; Berge et al., 2013).

Camelina oil (from the oilseed crop False Flax, *Camelina sativa*) has been suggested as commercially suitable for salmon feeds since it contains about 30 % α-linolenic acid (a precursor of EPA and DHA), with relatively low levels of omega-6 PUFA, and has been used experimentally to replace fish oil in salmon diets (Hixson et al., 2014). However, it is the recent success in producing EPA and DHA at levels equivalent to those in fish oil by inserting algal DNA into *Camelina* that has aroused most interest (Ruiz-Lopez et al., 2014) (http://www.rothamsted.ac.uk/camelina). It has been estimated that 1 hectare of the new transgenic crop would produce about 750 kg of oil containing around 12 % EPA and 8 % DHA and it should be highly scalable, hence 1 million hectares could produce 750,000 tonnes of oil or 150,000 tonnes of EPA and DHA (Ruiz-Lopez et al., 2014). Oil from transgenic Camelina has been demonstrated to successfully replace fish oil in feeds for Atlantic salmon (Betancor et al., 2015a,b). Although the European Parliament agreed in January 2015 to allow individual member states to determine their GM policy, regulatory approval for growing the transgenic crop would be simpler outside the EU (e.g. in Canada or USA). Transgenic oil might become available in the UK (and Norway via its EU agreements) by around 2020, subject to commercial agreements and to regulatory approval in the country where the crop is grown and in the EU as a GM feed additive. A similar timescale seems likely for the production of EPA and DHA from transgenic canola (rapeseed) by a joint venture between BASF and Cargill. In Australia the focus on transgenic canola is mainly on DHA (Kitessa et al., 2014) with claims that commercial supply could be available by 2017 (CSIRO, 2013). The existence of an entire logistical system for handling oilseed products means that the supply chain is already present and GM oil's production cost need be no higher than conventional oilseeds. The continuing decline in EPA and DHA levels is a potential driver for change if GM oil becomes commercially available and the lack of any cellular material, protein, or nucleic acid in oil may help market acceptance.

6.2.3 Conclusions and implications for GM feed ingredients

Unless non-GM protein becomes less competitive in terms of supply and price, given the current premium for non-GM SPC (used at 20 % - 30 % of the diet) is under 10 %, there is little commercial incentive for the Scottish industry to change policy today. The position with omega-3 LC-PUFA is different as the potential commercial availability of GM oilseed crop sources by around 2020 offers a potential technical solution to a chronic shortage, which might otherwise undermine the healthy profile of Scottish farmed salmon. A switch to using GM oil might be seen as worthwhile to avoid the risk of fish oil supply interruptions, if and when transgenic oils become commercially available. If the next El Niño causes a repeat of the current acute scarcity, and consumer attitudes continue to soften, it might become appropriate for policy-makers and the industry in Scotland to review current policy, but the potential risk to salmon export markets, especially France, from using GM feed ingredients is likely to be a key commercial consideration.

6.3 Use of novel non-GM feed ingredients

6.3.1 Insect-based feed ingredients

Since wild salmon eat insects during the freshwater stage, there is current R&D investment on the potential of using insects as safe and healthy ingredients for salmon feed. Makkar et al. (2014) reviewed existing research on five major insect species that are claimed to have potential for animal feed concluding that black soldier fly larvae have most promise for replacing soybean meal in pig and poultry diets. The recent 'Aquafly' project in Norway is exploring the potential to tailor insect nutrient profile to meet salmon nutritional requirements (http://nifes.no/en/counting-insects-future-fish-feeds/). It is claimed that many insect species are highly nutritious and their production has less environmental impact compared with traditional sources of animal protein. At an EU level, EFSA has been commissioned to review available safety evidence around insect protein, while the Commission is funding the PROteINSECT project to investigate quality, safety, processes, and human acceptance around the use of insects in animal feed (http://www.proteinsect.eu). In addition to salmon nutritional studies, there is a need for cost-effective mass insect-rearing facilities and a regulatory framework and sanitary procedures for the safe use of bio-wastes (including managing the risks of diseases, heavy metals and pesticides, etc.). The scope for insect use as a potential protein replacement in salmon feeds is clearly at an early stage of evaluation.

6.3.2 Fermentation products

As an alternative to DHA-rich algal biomass produced by fermentation of non-GM heterotrophic organisms, the current low cost of energy has renewed interest in natural proprietary fermentation as a means of producing microbial protein based on methane as the main source of carbon and energy. In particular *Methylococcus capsulatus,* a naturally occurring single cell organism, is now being used to produce a stable powder or dry pelleted product with 71 % protein, 10 % fat, and <1 % fibre, and a shelf life of over a year. The resulting product ('FeedKind'™) is already approved for use in the EU and it is claimed that it will be released commercially in 2018 and prove a superior alternative to fishmeal and soy in aquaculture diets (http://calystanutrition.com/feedkind-protein/). Assuming the product proves cost-effective in use, this has some clear advantages to conventional protein sources in salmon feeds. It remains to be seen if the product will remain feasible in practice if and when energy costs escalate once more, although the manufacturers claim they could switch to alternative feedstocks, such as biogas.

7. **Projected forward requirements for salmon feed ingredients**

7.1 Future farming and feed requirements

The Scottish Government's farmed salmon target of 210,000 tonnes by 2020, (see 1.2) represents a realistic CAGR of c. 2.5 %, provided new production sites are available, etc. This is also in line with global salmon projections where annual growth rate has recently diminished, resulting in a projected 3 % CAGR from 2013 to 2020 (Kontali, 2013). If the overall FCR in 2013/2014 was c. 1.3 (see 1.2), and annual salmon harvest volume is expected to increase from c. 165,000 tonnes to 210,000 tonnes in 2020, it seems not unreasonable to assume an improved FCR within the range of 1.1 - 1.2, corresponding to a 2020 Scottish salmon feed requirement in the range of 231,000 - 252,000 tonnes.

7.2 Forward supply of marine ingredients

OECD-FAO (2013) constructed an annual global forecast from 2013 to 2022 of total fishmeal and fish oil production, production from whole fish, consumption, variation in stocks, and price. Using the OECD-FAO fish model for 2022, FAO (2014) projected total fishery production, aquaculture, fishmeal and fish oil production assuming that about 16 % of capture fishery production will be reduced to fishmeal and fish oil (down 7 % on the 2010-2012 average, the base period), but total 'baseline' 2022 production will be 7.02 million tonnes and 1.08 million tonnes, respectively (i.e. up 15 % and 10 % on the base period, with almost 95 % of the additional gain for fishmeal coming from improved use of fish waste, cuttings and trimmings) (Table 3). OECD-FAO estimate that fishmeal from by-products should represent 49 % of total fishmeal production in 2022 and that, with global demand stronger than supply, prices of fishmeal and fish oil will increase by 6 % and 23 %, respectively, in nominal terms by 2022 (OECD-FAO, 2013). Although the OECD-FAO model is the best available, this is no guarantee of its predictive ability, especially if there is a possibility that the base period may be somewhat overstated. For instance IFFO data give lower estimates for the 2010 – 2012 base period than FAO with 4.92 million tonnes of fishmeal as the 2010 – 2012 year average versus 6.10 million tonnes from FAO (due mainly to lower assumptions on Chinese production by IFFO), while IFFO data for fish oil is close at 0.96 million tonnes versus 0.98 million tonnes for the same 3-year average (IFFO, 2014). Also IFFO data are suggestive of a recent downward trend in fishmeal production most likely linked to more precautionary fishing (Fig. 4). Although this is less evident in the data on fish oil production, the trend will be for less fish oil being available for aquaculture due to competition from the human nutrition sector (Figs. 5 and 6).

Supply and demand forecasts for fishmeal and fish oil need to take into account *inter alia* demand for pelagic fish for direct human consumption, the effect on reduction fisheries of increased regulatory curbs, climatic events (e.g. El Niño), increased exploitation of fish processing wastes for reduction purposes, etc. At the same time demand for fishmeal and fish oil is a function of price and availability of alternative proteins and alternative oils, particularly novel sources of omega-3 LC-PUFA, as well as the rate of growth, not only of fed aquaculture species, but also of young pigs and day-old chicks (Shepherd and Jackson, 2013). This is in turn influenced by innovation of feed formulators, plant protein processors, and geneticists, as they seek to reduce fishmeal inclusion rates to save on scarce, fluctuating, and costly ingredients, and also by the efforts of civic society (e.g. NGOs) to discourage use of marine ingredients on alleged sustainability grounds. Since fish oil demand has become a derived demand for EPA and DHA, salmon feed buyers compete strongly with the human nutrition market, while supply is linked to that of its co-product fishmeal, with both products subject to the volatility of the dominant Peruvian catch due to El Niño. However, Olsen and Hasan (2012) concluded that the limited supply of pelagic fishmeal will not be a major obstacle for a continued moderate growth in global aquaculture production; it is reasonable to make the same conclusion in regard to global salmon production.

On the somewhat conservative assumption of a 30 % marine/70 % plant content of feed ingredients (lower in marine content than today's Scottish average, but the same as current Norwegian feeds), 231,000 - 252,000 tonnes of salmon feed for Scotland in 2020 would require annually 69,000 - 76,000 tonnes of marine ingredients and 162,000 - 176,000 tonnes of plant ingredients. On this basis the reduced fishmeal inclusion rate projected for 2020 will more than offset the increased feed production. If the UK annual fishmeal requirement in 2020 is 45,000 - 50,000 tonnes (compared with c. 55,000 tonnes demand and 39,000 tonnes supply in 2014, – see 3.1) and domestic supply is likely to rise over time, most, if not all, fishmeal requirements could be sourced locally if desired. However, salmon by-products could not be recycled (3.1) and sourcing criteria for farm certification (e.g. by ASC), may become more exacting over time (5.2), restricting raw material.

7.3 Forward plant protein and oil supply

OECD and FAO secretariats analysed the price ratios of aquaculture species relative to oilseed products and concluded that tight supplies of fishmeal and fish oil are likely to contribute to an increased price ratio between fish and oilseed products over the medium term due to continuing demand from early rearing of pigs and salmon farming and from continuing omega-3 demand (OECD-FAO, 2013). They recognised the price ratios will be exacerbated in El Niño years, further constraining supply and supporting higher prices. Also they project a 26 % increase in world production of oilseeds and a switch in distribution of land from coarse grains to oilseeds. Global protein meal output is projected to increase by 25 % or 67 million tonnes by 2022; this envisages consumption growth of protein meal slowing somewhat due to slower absolute growth in global livestock production and slower growth in the relative use of protein meal in feed rations. The overall availability and price of terrestrial ingredients will also depend on factors such as freshwater availability.

In the short-term, demand from Scottish and global salmon production for the principal plant feed ingredient, non-GM soy (as SPC) is only c. 1 % or 7.5 %, respectively, of global supply, suggesting security of supply is not an issue. The European salmon industry imports non-GM soya mainly from Brazil as already crushed concentrate (see 3.2.1), paying a premium which may increase over time. Hence the strategic logic of avoiding over-reliance on imported soya products by greater focus on locally grown protein substitutes, including legumes, beans and peas, as well as focusing on novel sources of EPA and DHA, especially from algal fermentation and transgenic oilseed crops. If microbial protein (e.g. FeedKind™) is shown to be cost-effective and available on a large scale, this could potentially start to replace fishmeal and SPC in salmon feeds from as early as 2018.

8. Overall conclusions

8.1 The Scottish salmon farming industry occupies a distinctive international market position supplying a differentiated product range to offset potentially higher production costs compared with the much larger and more standardised Norwegian industry. Scottish production therefore relies on a variety of feed products, including specialist formulations with a higher than standard content of marine ingredients and omega-3 LC-PUFA, etc. Despite its recognised economic and social benefits, this has raised questions about the industry's environmental sustainability in regard to salmon feed.

8.2 Finite marine feed resources are now being replaced by plant-based ingredients in salmon feed, hence enabling salmon farming to achieve net fish protein production. Although it is continuing to fall, the relatively higher marine content of some Scottish feeds (averaging around 40 % marine and 60 % plant ingredients) compared with Norwegian farmed salmon reinforces a 'healthy and natural' reputation and may be seen as a necessary trade-off against increased feed costs.

8.3 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, provided they are sourced from sustainably managed stocks (or from the growing proportion of fish processing by-products, which currently represent 25 – 30 % of marine ingredients); hence an increased utilisation of plant ingredients in salmon feed may not be more environmentally sustainable.

8.4 The Scottish salmon industry has sought to adopt best farming practice in response to its producer organisation and to supply chain pressures, including responsible sourcing. Scottish certification focus on sustainable raw materials has helped to counter claims of an unsustainable use of marine ingredients, hence the growing recognition that sustainability issues for farmed Scottish salmon are now more related to sea lice rather than feed ingredients. Certified evidence on use of renewable feed ingredients is underpinned by third party auditing. Retailers require suppliers to comply with external certification schemes as well as their in-house standards, with the result that farming standards are demanding and continue to be driven up. The recent ASC certification of two farm sites in Scotland suggests that this may become a future benchmark of responsible practice. In addition the Scottish ethical commitment to fish welfare (via Freedom Food/RSPCA Assured status) demonstrates the industry's willingness to step beyond traditional boundaries of best practice.

8.5 Increased demand for fish oil from aquaculture and the human nutrition industry has coincided with acute scarcity due to El Niño conditions affecting the anchovy fishery in Peru and Chile. In the short-term this issue will temporarily resolve itself in Peru as the anchovy fishery recovers. In the medium-term interim solutions are needed to manage this situation cost-effectively and DHA from algal fermentation is now available albeit at relatively high cost and being studied as one solution. In the longer term, in view of the food security and consumer health implications, it is appropriate for the Scottish industry to consider reviewing its policy on GM feed ingredients for when new transgenic plant sources of EPA and DHA become available. However, it is recognised that, use of GM feed ingredients at the present time would risk lost sales to France, which is the second most valuable export market for Scottish salmon.

8.6 There is evidence some consumers take into account the health benefits when choosing to buy salmon and some UK retail packs indicate that eating a product portion will allow the consumer to meet international recommendations for weekly consumption of omega-3 LC-PUFA. This creates a risk for Scottish salmon since the content of EPA and DHA has fallen because of increasing replacement of fish oil by plant oils in salmon feed. In current scarcity conditions fish oil supplementation of feed to meet the label claim is costly and difficult, but may be necessary to maintain industry and brand reputations. At the same time the health attributes of Scottish salmon are not solely based on EPA and DHA, but could take more account of the content of amino acids, vitamins and minerals, etc., as well as extremely low levels of environmental contaminants due to replacing marine by plant ingredients.

8.7 Despite its potential benefits (e.g. cost savings and formulation flexibility), and its widespread use in salmon farming in the Americas, there is strong supply chain resistance to incorporating terrestrial by-products into salmon feeds in the UK. EU approval has been granted for use of PAP in aquaculture feeds, although in commercial practice this would mean poultry material as porcine by-products are problematic for religious and cultural reasons. However, UK retailers are currently unwilling to accept the high risk of a negative customer reaction. It is recognised that this policy restricts sourcing and runs counter to sustainability options, but is unlikely to change in the near future. The potential for insect-based ingredients has yet to be evaluated and developed, but could meet similar consumer objections.

8.8 As regards the use of GM feed ingredients, a similar embargo exists today in European salmon farming. This is despite their use in UK chicken feeds, signs of a weakening in UK consumer hostility to the GM issue, and a more flexible approach by the EU and the English and Welsh governments. Given the availability of non-GM soya at a relatively small price premium today, there is no current incentive to alter this policy on grounds of protein availability, although this situation could change in the future. The position with omega-3 LC-PUFA is different as the likely commercial availability of GM oilseed crop sources by around 2020 from outside Europe offers a possible solution to a chronic shortage. Avoiding GM could mean that the Scottish industry is accused of supplying a less healthy product than in those countries using GM feed ingredients. It does not appear to be logistically feasible for the UK fish feed and fish farming industries to maintain both GM fed and non-GM fed supply lines at the same time.

8.9 Although forward supply of proteins is not seen as a major issue, there should be continuing focus on cost-effective local alternatives to non-GM SPC in particular. Provided it becomes available on schedule and remains cost-effective, the development of microbial protein is of strategic interest, offering a novel alternative to fishmeal and SPC of strategic interest.

8.10 As regards research bottlenecks, continuing focus is required on how best to maintain EPA and DHA levels in farmed salmon given the increased price and reduced availability of fish oil of appropriate certification status and lack of contaminants. The most feasible alternative source may be GM oil by 2020, but algal and microbial sources should be kept under review and interim solutions are required to manage this situation cost-effectively. Although alternative plant protein feed ingredients (e.g. beans and peas) are being studied, especially those that can be grown in the UK, it is important to be able to concentrate the protein in order for it to replace SPC. The technical process and associated logistics therefore need to be defined and offer a cost-effective solution.

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Tables

Table 1. Comparison of farmed salmon production (tonnes), feed supply volume (tonnes), and corresponding feed conversion ratio (FCR) for Scotland and Norway in years 2013 and 2014 (source: Kontali AS).

	2013		2014	
	Scotland	**Norway**	**Scotland**	**Norway**
Farmed salmon production as whole fish equivalent	163,234	1,143,500	179,022	1,198,900
Salmon feed supply	214,000	1,487,600	221,000	1,598,800
Feed Conversion Ratio	1.31	1.30	1.23	1.33

Table 2. Estimated global production (a) and consumption (b) of combined EPA and DHA (tonnes) in 2014 (after Meinich, 2014).

Table 2a

Estimated global production of crude fish oil	800,000
Estimated global production of EPA + DHA	140,000
Estimated global year-end carryover of EPA + DHA	30,000
Estimated global availability of EPA + DHA	170,000

Table 2b

Estimated global consumption of EPA + DHA in salmon feed	50,000
Estimated global consumption of EPA + DHA by non-salmon aquaculture	50,000
Estimated global consumption of EPA + DHA for direct human consumption	61,000
Estimated technical usage of EPA + DHA (e.g. hardening, tanning, energy)	9,000

Table 3. FAO fish model: overall trends to 2022 for world (million tonnes in live weight equivalent) (FAO, 2014).

	Base period 2010 - 2012	**2022 scenarios**			
		Baseline	**Intermediate**	**Optimistic**	**Mixed**
Total fishery production (World)	**153.940**	**181.070**	**188.093**	**194.800**	**194.792**
Aquaculture	62.924	85.124	92.402	99.330	99.330
Capture	91.016	95.946	95.692	95.474	95.462
Fishmeal production (*product weight*)	6.103	7.021	7.358	7.679	7.734
Fish oil production (*product weight*)	0.980	1.079	1.087	1.094	1.088
Fish trade for human consumption	36.994	45.082	45.566	46.237	46.566
Fish supply for human consumption	131.741	160.514	167.397	173.969	174.032
Per capita apparent fish consumption (*kg*)	18.9	20.7	21.6	22.4	22.4

Figures

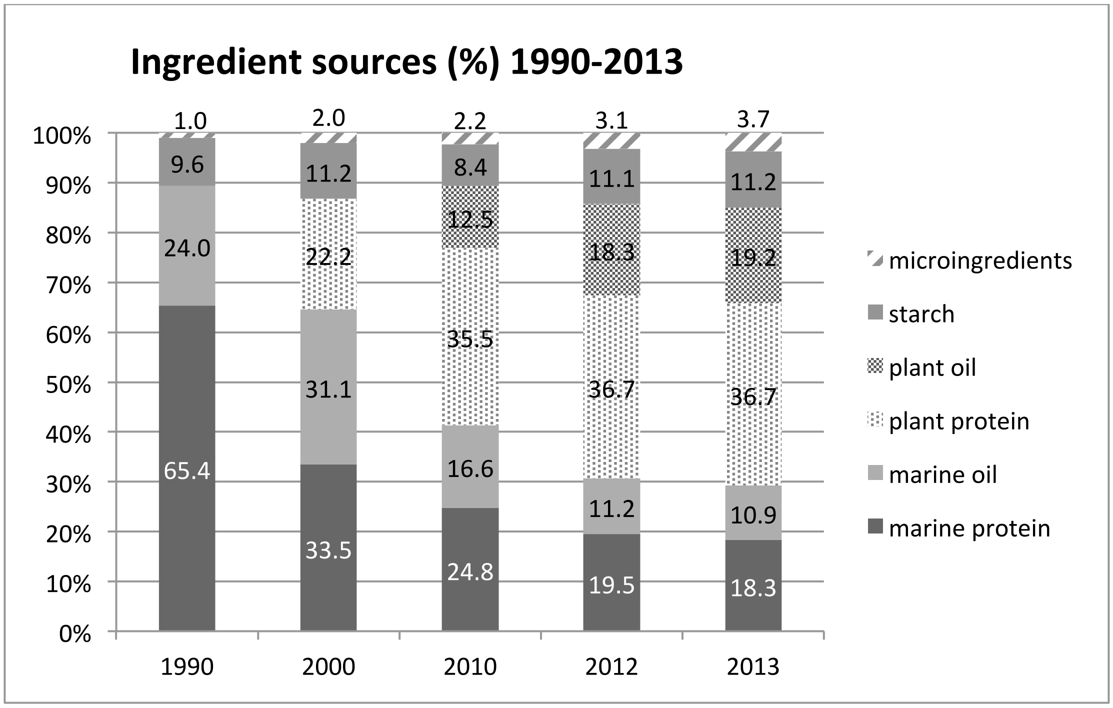

Fig. 1. Nutrient sources in Norwegian salmon farming from 1990 to 2013. Each ingredient type is shown as its percentage of the total diet (Ytrestøyl et al., 2015).

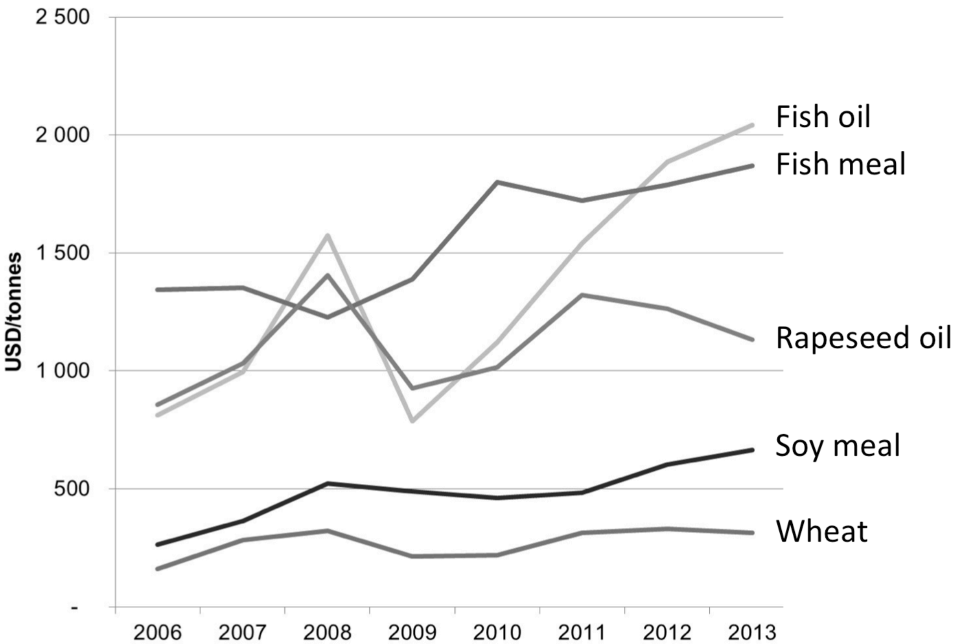

Fig. 2. Prices of fishmeal, fish oil, rapeseed oil, soymeal and wheat delivered Europe, from 2006 to 2013 (source: Marine Harvest, 2014, after Chr. Holtermann).

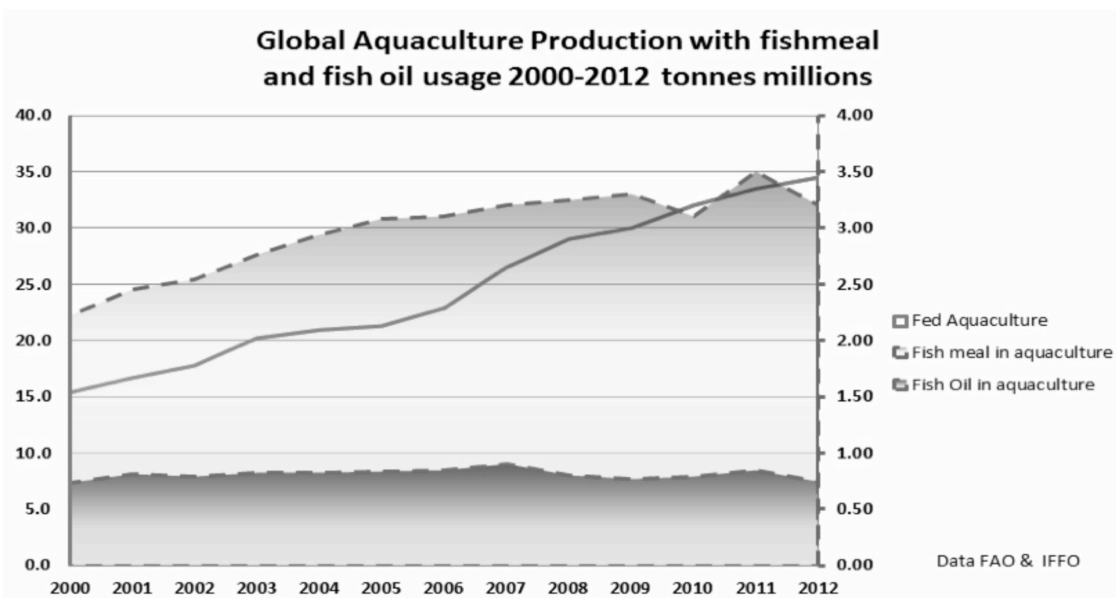

Fig. 3. World fishmeal and fish oil consumption by aquaculture (right axis) (---) compared with growth in 'fed' aquaculture (left hand axis) (—) 2000 – 2012 (million tonnes) (sources: IFFO data and FAO, 2014).

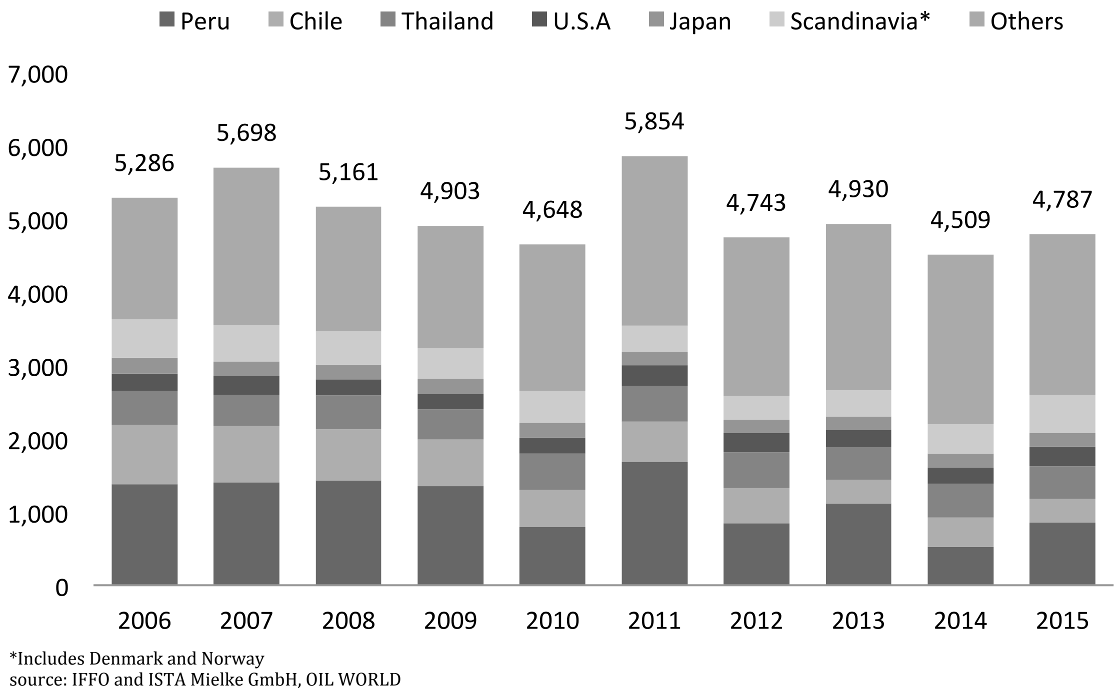

Fig. 4. Annual world fishmeal production by major national producer from 2006 to 2015 (tonnes x 1000).

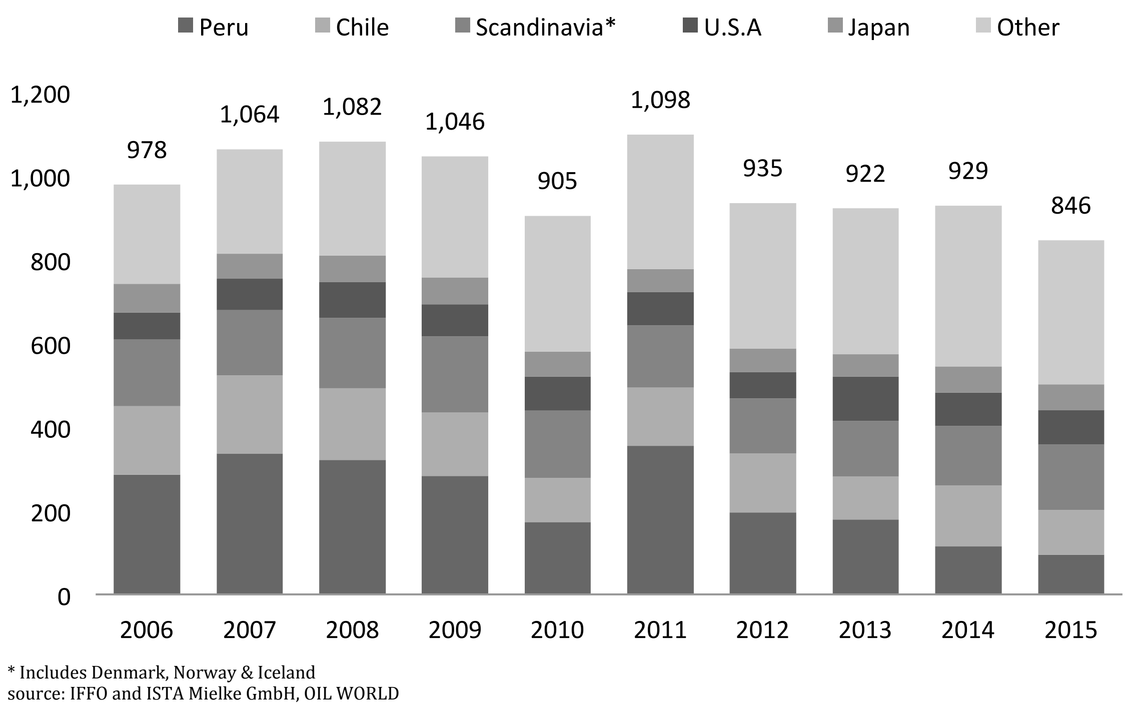

Fig. 5. Annual world fish oil production by major national producer from 2006 to 2015 (tonnes x 1000).

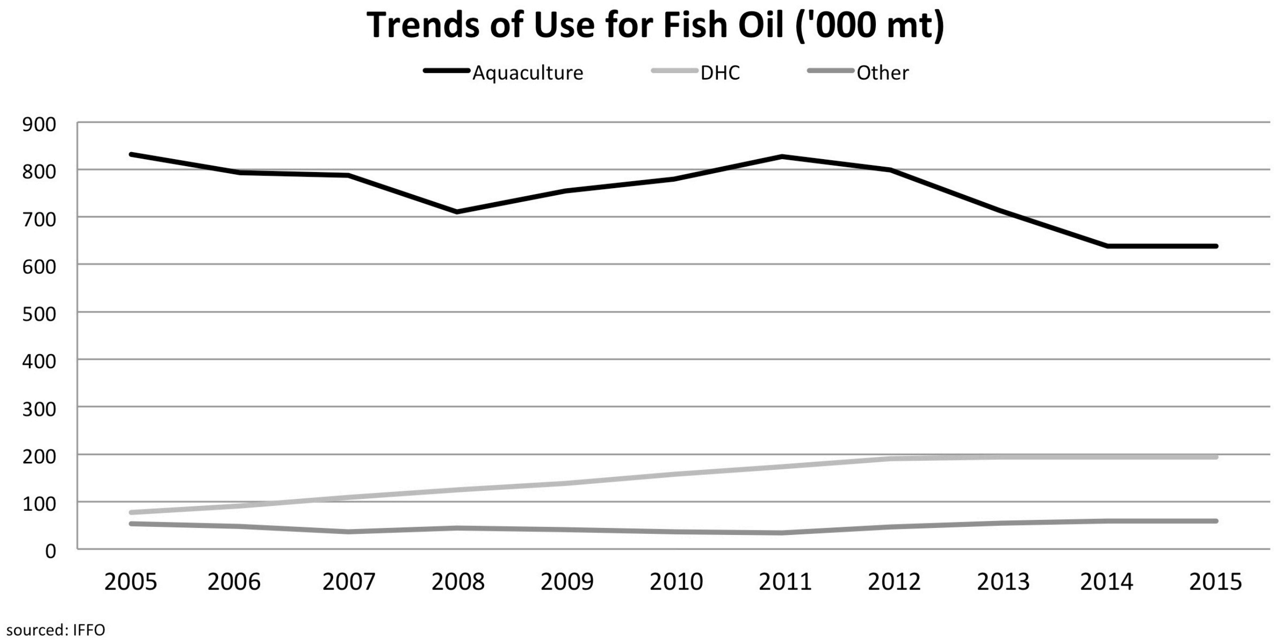

Fig. 6. World fish oil consumption (tonnes x 1000) by aquaculture, direct human consumption (DHC), and other uses from 2005 to 2015 (source: IFFO).

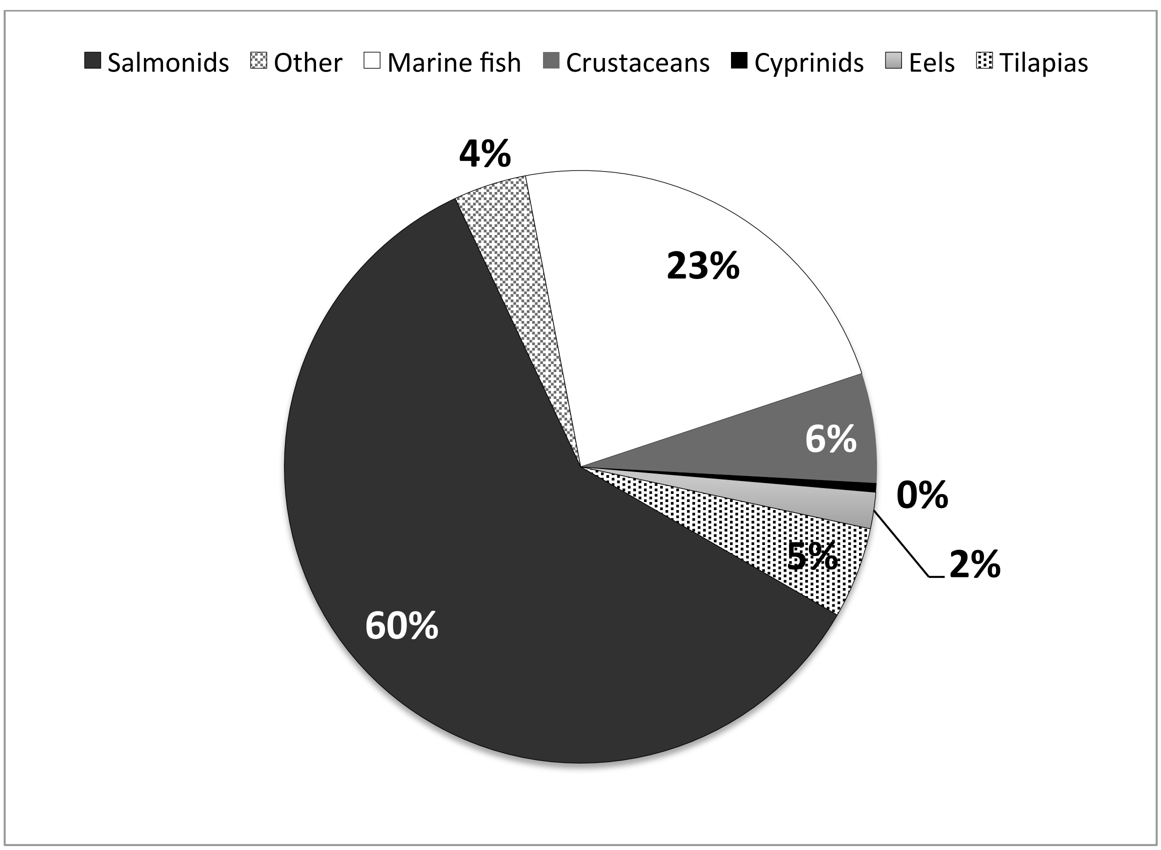

Fig. 7. Use (% of total aquaculture use) of fish oil by different categories of farmed fish and crustaceans in 2013 (source: IFFO).