Institution: University of Stirling

Unit of Assessment: A6 Agriculture, Veterinary and Food Science

Title of case study: Improving sustainability of UK salmon farming through replacement of marine fish oil while ensuring nutritional quality is preserved through maintenance of omega-3 levels

1. Summary of the impact

Omega-3 long-chain polyunsaturated fatty acids (LC-PUFA) are essential nutrients and have many beneficial effects on human health. Fish are the major source of omega-3 LC-PUFA in the human diet, and its level was maintained in farmed fish through the use of fish oil as a major component of extruded aquafeeds. Around 10 years ago it became clear that demand for fish oil would rapidly outstrip supply, limiting expansion of aquaculture activities, if fish oil use was not reduced. The challenge this presented was that alternatives to fish oil lack omega-3 LC-PUFA. However, replacement of fish oil with more sustainable alternatives is now standard practice in the industry. Research into fish oil replacement and omega-3 metabolism in the Nutrition Group, Institute of Aquaculture has been at the forefront of the scientific research in the UK and Europe that has ensured nutritional quality of farmed fish by developing alternative feed ingredients and feeding strategies that have maintained levels of omega-3 LC-PUFA despite radical changes to feed composition driven by sustainability and food security. This work culminated with recent demonstrations that farmed salmon can be net producers of marine protein (2010) and oil (2011).

2. Underpinning research

Fish are a unique and rich source of omega-3 LC-PUFA, essential nutrients that have well-established beneficial effects in a range of human pathologies including cardiovascular and inflammatory diseases, and neurological disorders. Thus it is crucial that the levels of these fatty acids should be maintained in farmed fish and seafood products. Over-exploitation of wild fisheries has meant that about 50% of fish and seafood for human consumption is now farmed and aquaculture is the fastest growing global food production system. Aquaculture has been highly dependent on dietary fish oil and fishmeal derived from marine fisheries, representing a production system that is, at best, at its sustainable limit. Continued expansion of aquaculture, which is essential to meet the global demand for fish, is only therefore possible by replacing marine-derived resources with alternative nutrient sources. The greatest challenge in replacing fish oil has been that suitable, sustainable alternatives do not contain the health promoting omega-3 LC-PUFA. Research in the Nutrition Group has:

a) produced a large and comprehensive data set on the effects of substitution of fish oil with alternatives including vegetable oils, other marine oils (krill etc) and single-cell oils (*Schizochytrium/C.Chonii,* etc) on growth performance and feed efficiency, composition and product and nutritional quality (esp. omega-3 LC-PUFA level) of farmed fish;
b) developed key criteria for the selection of alternatives to fish oil that will minimise impacts on product omega-3 levels;
c) been key to the development of feeding strategies to maximise substitution without affecting farming performances while minimising impacts on omega-3 LC-PUFA levels (Bell et al., 2003);
d) advanced knowledge of fish lipid and fatty acid metabolism and genetics that has enabled formulation of feeds specifically designed to match the lipid biochemistry and physiology of the fish (Morais et al., 2011);
e) provided heritability data and molecular markers to assist in future breeding programmes to select for high flesh omega-3 LC-PUFA levels (Leaver et al., 2011);
f) delivered molecular tools (e.g. genes of omega-3 biosynthesis) to enable highly strategic approaches including the development of engineered oilseed crops to produce omega-3 LC-PUFA tailored to the aquaculture industry, and the development of fish strains designed for increased endogenous production of omega-3 LC-PUFA (Monroig et al., 2010).

The research has been a combination of near-market, applied science supported by basic, fundamental studies. The applied research has involved the design of novel feed formulations and testing of alternative raw ingredients through trials with key farmed species including Atlantic salmon, rainbow trout, and Atlantic cod. The basic science has studied fundamental biochemical, molecular and genetic mechanisms involved in the control and regulation of lipid and fatty acid metabolism and, particularly, omega-3 LC-PUFA, ‘EPA’ and ‘DHA’.

3. References to the research

The studies related to omega-3 LC-PUFA metabolism and nutrition have resulted in around 80 papers in scientific journals/books, 90 oral and poster presentations at International and national conferences/meetings and, importantly, 36 articles and presentations at industrial/trade forums/meetings and in the trade/popular press. The overall impact of the work on fish oil substitution has been highly influential. The six references here give just a glimpse of the range and depth of influence. Impact on commercial activities was advanced by publications in aquaculture journals, widely read by industry, with underpinning science published in 'high impact' journals. Bell and Tocher have h-indices of 47 and 52 and 12,000 unique citations (11,697; WoK, Sept 2013). Tocher is a highly cited researcher in Thomson Reuters Highly Cited list, globally the top 250 most-cited researchers in a defined discipline.

1. Bell JG, Tocher DR, Henderson RJ, Dick JR, Crampton VO. (2003). Altered fatty acid compositions in Atlantic salmon (*Salmo salar*) fed diets containing linseed and rapeseed oils can be partly restored by a subsequent fish oil finishing diet. *J. Nutr*. 133, 2793-2801.
2. Torstensen BE, Bell JG, Sargent JR, Rosenlund G, Henderson RJ, Graff IE, Lie Ø, Tocher DR. (2005). Tailoring of Atlantic salmon (*Salmo salar* L.) flesh lipid composition and sensory quality by replacing fish oil with a vegetable oil blend. *J. Agric. Food Chem*. 53, 10166-10178.
3. Monroig Ó, Zheng X, Morais S, Leaver MJ, Taggart JB, Tocher DR. (2010). Multiple fatty acyl desaturase (FAD) genes in Atlantic salmon: cloning and functional expression of cDNAs confirm presence of three Δ6 FADs. *Biochim. Biophys. Acta* 1801, 1072-1081.
4. Bell JG, Pratoomyot J, Strachan F, Henderson RJ, Fontanillas R, Hebard A, Guy DR, Hunter D, Tocher DR. (2010). Influence of genotype/phenotype of on effects of on replacement of dietary fish oil with vegetable oils in Atlantic salmon (*Salmo salar*) families/strains selected on the basis of flesh adiposity: growth, flesh proximate and fatty acid compositions. *Aquaculture* 306, 225-232.
5. Leaver MJ, Taggart JB, Villeneuve LAN, Bron JE, Guy DR. Bishop SC, Houston RD, Matika O, Tocher DR. (2011). Heritability and mechanisms of n-3 long chain polyunsaturated fatty acid deposition in the flesh of Atlantic salmon. *Comp. Biochem. Physiol*. 6D, 62-69.
6. Morais S, Pratoomyot J, Taggart JB, Bron JE, Guy, DR, Bell JG, Tocher DR. (2011). Genotype-specific responses in Atlantic salmon (*Salmo salar*) subject to dietary fish oil replacement by vegetable oil: a liver transcriptomic analysis. *BMC Genomics* 12, 255.

Key associated grants:

1. Aquaculture feeds and fish nutrition: paving the way to the development of efficient and tailored sustainable feeds for European farmed fish, ARRAINA. EU FP7 2012-16, £460K.
2. Evaluating novel plant oilseeds enriched in omega-3 long-chain polyunsaturated fatty acids to support sustainable development of aquaculture. BBSRC IPA, 2012-15, £400K.
3. Development of protein-rich and starch-rich fractions from faba beans for salmon and terrestrial animal production, respectively. Technology Strategy Board, 2012-15, £195K.
4. Oxidation, lipids, DNA and mitochondria. EU FP7-PEOPLE-2011-IEF Panel LIF 297964, 2012-14, £145K
5. Fish intestinal nutrigenomics in response to fish oil replacement in Atlantic salmon diets. EU FP7-PEOPLE-2007-2-1-IEF Panel LIF 219667, 2009-11, £130K
6. Sustainable aquafeeds to maximise the health benefits of farmed fish for consumers, AQUAMAX" EU FP6 IP 016249, 2006-10, £550K

4. Details of the impact

Principal objectives of our research were to develop feed formulations and feeding strategies for the replacement of fishmeal and fish oil in feeds for farmed fish without compromising production, fish health and, in particular, the levels of health-promoting n-3 LC-PUFA and the nutritional quality of the products to consumers. This work has resulted in farmed salmon now being potential net producers of marine protein and oil (2010-11). This is a highly successful outcome given the previous situation of salmon farming as the world's biggest consumer of fishmeal and fish oil.

Underpinning studies investigated the effects of various fish oil substitutes and blends, and the levels, duration and timing of substitution, in trials encompassing the entire growth cycle of salmon

from first-feeding fry to market size (1998-2005). The knowledge generated informed industry on best practices for the substitution of fish oil with vegetable oil in aquafeeds, and directly influenced commercial salmon feed formulations that now show levels of fish oil substitution of between 25 and 70%, mainly with rapeseed oil. Different formulations and feeding strategies were devised for minimising negative effects on tissue omega-3 LC-PUFA compositions including partial replacement of fish oil over the entire growth cycle, or complete replacement followed by a pre-harvest 'finishing' phase using feeds with fish oil to restore omega-3 LC-PUFA levels.

The major impact of this work is that these strategies are now employed by the industry with the majority of production utilising partial replacement with oil blends, and the finishing feed strategy being employed to ensure that products comply with the high specifications of premium retailers and quality certification. Recently, it was demonstrated that feed formulations have enabled farmed salmon to be net producers, rather than consumers, of marine protein and oil (Crampton et al., 2010; Bendiksen et al., 2011). The impact of our research into the substitution of fish oil in aquafeeds cannot be underestimated as the global supply of fish oil would have been exceeded several years ago if substitution of fish oil, particularly in salmonid feeds, had not been researched and successfully implemented. Our contribution has not simply been to ensure the continued expansion of aquaculture in a more sustainable manner, but has specifically focussed on ensuring that the nutritional quality of the product was not compromised. Omega-3 LC-PUFA levels are critically low in Western diets and we cannot afford to allow levels in fish, the primary source of these essential nutrients in our diet, to decline significantly.

The applied research was supported by fundamental studies including the application of molecular and genomic technologies such as transcriptomics and proteomics that provided the basic science underpinning our understanding of molecular, biochemical, and physiological aspects of omega-3 LC-PUFA metabolism in fish (2006-12; Monroig et al., 2010; Morais et al., 2011). A major impact of these studies was that retention of omega-3 LC-PUFA in flesh was a heritable trait in Atlantic salmon and so could be enhanced by selective breeding (2009-11; Leaver et al., 2011). Another impact was fish genes cloned in our lab being utilised in studies to introduce the LC-PUFA biosynthesis trait into oilseed crops (Robert et al., 2005).

Six projects had international partners with the Nutrition Group being a core consortium partner in all these projects (coordinator of FOSIS and RAFOA) and the lead partner with respect to fish oil substitution and omega-3 LC-PUFA metabolism and nutrition. Uptake of these research findings has been through very direct pathways as all the research was performed in collaboration with the major global feed companies (BioMar, EWOS and Skretting), either as partners in major RCUK (FOSIS) or EU projects (RAFOA, FORM, AQUAMAX & ARRAINA), or through industry-led collaborative projects with BioMar and EWOS. In most cases the studies were also performed in collaboration with major fish producers, such as Marine Harvest, in their own facilities for semi-commercial scale trials using sea pen cages and fish grown to market size. Many projects included other key players in the aquaculture supply chain including oil producers (Croda, DSM, Technology Crops Inc), fish breeding companies (Landcatch Natural Selection), processors (Pinneys), retailers (Sainsburys), and trade organisations (Scottish Salmon Producers Organisation, Federation of European Aquaculture Producers). All results were disseminated widely in the scientific literature, at conferences and workshops, and in trade and technical reports and the national press. This led to the rapid application of the findings in the form of new commercial formulations and feeding strategy recommendations that were made widely available so that beneficiaries included the entire aquaculture sector from feed ingredients, feed manufacture, fish producers and processors, to retailers and consumers including SMEs. Key to this was the role of the Nutrition Group as principal partners in an EU FP5 Thematic Network (FORM, Fish oil and meal replacement) with a specific KT/KE remit focussed on exchange of information and an output consisting entirely of exploitation and dissemination activities primarily through four annual meetings/workshops where our results were presented to a wide audience of key stakeholders including the aquaculture industry, trade organisations, consumer groups and health and safety authorities.

The Nutrition Group has been at the heart of the consultations and committees defining aquaculture nutrition research not only in the UK and Europe but also globally. In the early phase of EU FP6, the Nutrition Group, along with our key collaborators in Norway (NIFES) and France (INRA), developed an Expression of Interest that was adopted by the EU and resulted in two new

Calls, providing research funding of almost €25 million to the SEAFOODplus and AQUAMAX projects that spearheaded EU research in aquaculture nutrition over the subsequent years (2006-2010). Bell was a key member of the European Aquaculture Technology and Innovation Platform (EATIP) (2008-2010) and was leader of Goal 1 tasked with a remit to "Strengthen sustainability of aquaculture by developing Future Fish Feeds based on a sound scientific basis". The EATIP programme was adopted in an EU FP7 call on aquafeeds that was answered by the ARRAINA project in which the Nutrition Group are members of the core consortium. Recently, Tocher was an appointed member of the US National Academies, National Research Council (NRC) Committee on Nutrient Requirements of Fish and Shrimp. This Committee was convened for the first time in 20 years with responsibility to completely update the NRC Bulletin on Nutrient Requirements of Fish, last produced in 1993. The NRC Report is universally regarded throughout the world as the "Gold Standard", and the new Report "Nutrient Requirements of Fish and Shrimp" was published in August 2011. All of the above contributed to the high regard the aquaculture industry have for the research of the Nutrition Group. This resulted in the Group being in great demand to carry out both contract work and analyses, and the establishment of the Nutrition Analytical Service (NAS), the highly successful commercial arm of the Nutrition Group with over 40 customers around the globe and an annual turnover of almost £0.45 million.

The impact of our work is readily attested by key industrial partners:

"The economic benefits have been far reaching both in reduction of overall production costs and in facilitating increased growth in this sector. As such the research activities of the Nutrition Group, IoA are greatly valued by the Aquaculture industry"; Global Research Director, BioMar Ltd.

"More importantly however has been the nutritional knowledge which has been generated by the IoA Nutrition Group to ensure that eating qualities and human health benefits of eating oily fish containing n-3 LC-PUFA remain in place"; Technical Services Manager, Marine Harvest Scotland.

"Skretting ARC are delighted to provide this endorsement of the outstanding and important contributions that the Nutrition Group, IoA have made in the development of sustainable aquafeeds and their major positive impact on the industry in the UK and globally". Head of Nutrition Research, Skretting Aquaculture Research Centre.

"The work of the Nutrition Group IoA has had a significant impact on our ability to replace fish oil in feeds for Atlantic salmon"; Principal Scientist, EWOS.

5. Sources to corroborate the impact

1. Fish Farmer – cited in CEFAS Report (page 36). IoA (RAFOA) was shortlisted in 2006 for 1st Fish Farmer Fit for the Future award recognising outstanding achievement and innovation in aquaculture.
   http://www.fishfarmer-magazine.com/news/fullstory.php/aid/368/Fish_Farmer__Fit_for_the_Future__awards_shortlist_announced.html

   and http://cefas.defra.gov.uk/publications/shellfishnews/sfn0506.pdf

2. Australian Northern Territory Government Technote – cites FOSIS and RAFOA projects http://www.nt.gov.au/d/Content/File/p/Technote/TN124.pdf

   In addition written statements of corroboration are available from Biomar Ltd, EWOS, Skretting, the Chair of US National Academies, NRC Fish and Shellfish Requirement Committee, the Director of Genetics, Hendrix/Landcatch Natural Selection and Marine Harvest Scotland.