Institution: University of Stirling

Unit of Assessment: A6: Agriculture, Veterinary and Food Science

Title of case study: Management strategies to control salmon puberty: optimised productivity and sustainability of the fish farming sector

1. Summary of the impact

Salmon maturation prior to harvest constitutes an environmental, welfare and production bottleneck for the salmon aquaculture industry. Our research has reduced the number of fish that mature during the grow-out phase so they do not reallocate energy to develop gonads and display secondary sexual characteristics that reduce yield, harvest quality and increase disease susceptibility that can result in downgrading at processing and lost profitability. In addition, reproductively competent fish that escape from on-growing cages may breed with wild stocks, leading to potential introgression. This has a major impact on public perception of farmed salmon and it limits the expansion of the industry. The IoA Reproduction team has undertaken a comprehensive body of work since 1993 to address this critical production bottleneck through an array of management strategies. This work culminated in the REF period by the demonstration that salmon puberty can be reduced to <3% by the use of standardised lighting regimes (2008) followed by the first commercial production of sterile salmon (2012-13).

2. Underpinning research

The fish farming industry has expanded at a fast pace in the last 30 years and Atlantic salmon has reached a production of 1.2 million tonnes a year in Europe (>10% increase/year). With the radical change of scale in production came the necessity to standardise/optimise rearing protocols to ensure reliable, year round, consistent supply of quality fish to a growing market and minimise welfare and environmental impacts. To achieve this it is critical that the industry controls the sexual maturation of its fish in the production phase. Sexually maturing fish will result in losses of growth, increased agonistic behaviour and disease susceptibility, which are major welfare issues and product downgrading because of reduced flesh quality and secondary sexual attributes. In addition, farming of reproductively competent stock can have detrimental effects on the fitness of wild stocks if they escape and interbreed. This is negatively perceived by consumers and wild fisheries managers. Research in the reproduction group over the last 20 years has focused on the understanding of salmon reproductive physiology and the development of stock management strategies to control puberty in farmed fish, especially photoperiod signalling and sterility through triploidy. This has led to new knowledge and tools in:

- fish reproductive physiology and sexual dimorphism (from 1993 to present);
- light sensitivity and seasonal control of puberty in farmed fish through detailed studies of the photoneuroendocrine system (PNES) at endocrine (melatonin pathway, Migaud et al., 2007; Vera et al., 2010) and molecular (clock mechanisms, Davie et al., 2009) levels from in vitro, tank based to full scale commercial testing (from 2002 to now);
- new lighting technologies (LED, narrow bandwidth light, cold cathode) that are more energy and biologically efficient (from 2007 to now, Leclercq et al., 2011);
- triploidy protocols to induce sterility in salmonids and optimisation of production traits from egg to harvest in freshwater and seawater through studies on nutritional requirements, environmental sensitivity and selection (from 2008 to now, Leclercq et al., 2011; Taylor et al., 2013a and b);
- transfer of triploid induction technology to leading salmon breeding companies (Aquagen in Norway and Hendrix Genetics in the UK);
- consumer perception studies and perceived risk-benefit of triploidy leading to marketing strategies. The work aimed to study intrinsic and extrinsic associations and beliefs with respect to triploid salmon products and production and develop appropriate communications means (http://cordis.europa.eu/documents/documentlibrary/117787031EN6.pdf).

The research that has delivered these findings/insights has been a combination of near-market,

applied science and fundamental studies including the application of molecular and genomic technologies that provided the basic science underpinning our understanding of the molecular, biochemical, and physiological control of puberty and light sensing, leading to direct commercial applications.

This work has been coordinated by Professor Migaud (2002-present) and colleagues in the Reproduction and Genetic group including McAndrew, Penman, Taggart and Davie, bioinformatician Bekaert and key post-doctoral fellows including Taylor and Vera.

3. References to the research

The results of these studies have been extensively disseminated since 1993 through over 80 papers in peer reviewed scientific journals, numerous international and national conferences/meetings and, importantly, several articles and presentations each year in/at industrial/trade forums/meetings and trade/popular press. The combined impact of a very substantial and comprehensive 'body of work' has been highly influential. These six references offer glimpse of the range and depth of the research.

1. Migaud H., Davie A., Martinez Chavez C.C., Al-Khamees S., (2007). Evidence for differential photic regulation of pineal melatonin synthesis in teleosts. *Journal of Pineal Research* 43 (4), 327-335.
2. Davie A. Minghetti M., Migaud H., (2009). Seasonal Variations in Clock-Gene Expression in Atlantic Salmon (*Salmo salar*). *Chronobiology International,* 26, 379-395.
3. Leclercq, E., Taylor, J.F., Sprague, M. and Migaud, H., (2011). The potential of alternative lighting-systems to suppress pre-harvest sexual maturation of 1+ Atlantic salmon (*Salmo salar*) post-smolts reared in commercial sea cages. *Aquaculture Engineering* 44 (2), 35-47.
4. Leclercq, E., Taylor, J.F., Fison D., Fjelldal P.G., Diez-Padrisa M., Hansen T. and Migaud, H. (2011). Comparative seawater performance and deformity prevalence in out-of-season diploid and triploid Atlantic salmon (*Salmo salar*) post-smolts. *Comparative Biochemistry and Physiology Part A*. 158, 116-125.
5. Taylor J.F., Sambraus F., Mota-Velasco J., Guy D., Hamilton A., Hunter D., Corrigan D., Migaud H., (2013a). Ploidy and family effects on Atlantic salmon (*Salmo salar*) growth, deformity and harvest quality during a full commercial production cycle. *Aquaculture* 410–411, 41-50.

Grants for research underpinning impact include:

1. 2013-16 SALMOTRIP+, funded by the world's largest salmon producer, Marine Harvest, and feed manufacturer, Biomar 'Impacts of triploidy on production traits in Atlantic salmon' (PI Migaud, £535k).
2. 2013-16 FISHLIGHT-TECH funded by Philips Lighting, "Biological efficiency of light in commercially important fish species" (PI Migaud, £100k).
3. 2012-16 EU FP7 ARRAINA "Aquaculture feeds and fish nutrition: paving the way to the development of efficient and tailored sustainable feeds for European farmed fish" (PIs Bell/ Tocher/Migaud), £5M, IoA budget £460k.
4. 2012 (Jan-Dec) funded by Biomar "Effect of phosphorous supplementation on triploid deformity prevalence" (PIs Taylor/Migaud, £43k).
5. 2011-15 BBSRC Case Award, BB/J500835/1 "Mechanisms underlying the impacts of triploidy on production traits in Atlantic salmon" (PI Migaud, £94k).
6. 2008-11 EC FP7 SALMOTRIP "Feasibility study of triploid salmon production"(PI and coordinator, Migaud): £830k, IoA budget £380k.
7. 2006-09 BBSRC Case Award BBS/S/M/2006/13133 "Characterisation of false maturation and development of diagnostic tools in Atlantic salmon" (PI Migaud, £58k).
8. 2006-09 Norwegian Research Council Contract 174231 "Narrow bandwidth lighting technology in fish farming and effects on performance from early stages to adult fish" (PI Migaud), IoA budget £120k.
9. 2002-06 EC FP6 PUBERTIMING QLRT-2001-01801 "Photoperiod control of puberty in farmed fish: Development of new techniques and research into underlying physiological mechanisms" (PIs Bromage/Migaud), IoA budget £160k.

4. Details of the impact

The basic understanding of fish reproduction acquired by the IoA reproduction group led to the development of protocols for the salmon farming industry to control early maturation. Key strategies have been identified and researched to tackle this problem, e.g. reduction in the prevalence of early maturing fish prior to harvest either using photoperiodic treatment or sterility using chromosome manipulation, a technique unique to aquatic fish and shellfish among farmed animals. The knowledge gained by the group in these areas has led to the implementation of protocols, guidelines and practices within the industry that have significantly improved the sustainability of the sector, generating growth and increased profitability.

Optimised photoperiod regimes developed by the reproduction group in collaboration with leading light manufacturers (BGB Engineering, Akva and recently Philips Lighting) have led to a considerable reduction in the prevalence of early maturation during the first year of salmon on growing at sea from >40% in the late 1990`s to <3% (from 2008 onwards) and reduced energy usage through a combination of timing and duration of the light exposure window as well as the adoption of new lighting technologies and standardised light intensity. This has been implemented globally by the salmon farming industry with companies that operate in all salmon production countries (Marine Harvest, Scottish Seafarms) through knowledge transfer activities (workshop, consultancies, training) and contributed very significantly to reduce costs and improve fish welfare. This knowledge base has subsequently helped us pioneer similar light regimes for Atlantic cod incorporating the use of specialist surface nets to shade ambient sunlight, these were implemented commercially in Scotland and Norway. However, such light regimes do not address the potential environmental concerns associated with salmon escapees interacting with wild salmonid stocks (in Scotland alone, 1.9 million farmed salmon escaped into the natural environment between 2002 and 2009 due to human error, storm damage or holes in nets). Therefore, there is an increasing pressure from retailers, fish welfare standards and accreditation bodies, NGOs and governments towards the development and implementation of sterile stocks. While other strategies delay or limit the prevalence of early maturation in culture, sterility fully suppresses puberty in females and by doing so removes any introgression concerns for wild stocks in the event of escapees.

Work done by the reproduction group is at the forefront of the research on sterility through chromosome manipulation (induced triploidy) since 2008. A suite of projects (Salmotrip, 2008-11, BBSRC, 2011-15 and Salmotrip+, 2013-16) coordinated by Prof. Migaud in collaboration with the world leaders in salmon production, breeding and genetic enhancement (Marine Harvest, Aquagen, and Hendrix Genetics) investigated the commercial feasibility of producing sterile salmon with a focus on breeding and selection, fish performances, nutritional requirements, fish welfare and deformity, and consumer perception towards such a new product. Research performed by the group on triploid salmon led to the first introduction of triploid salmon on the market in 2012 by Aquagen and the first commercial scale farming in Norway (2.5 million triploid salmon eggs produced in 2012) and Scotland (forecast of 1 million triploid eggs produced in November 2013). Research on nutritional requirements of triploid salmon (2010-13) led to the development of triploid diets that reduce skeletal deformities by as much as 50% and completely abolished cataract prevalence (patent pending). These dietary formulations are now being commercially produced by one of the largest feed manufacturer in aquaculture (Biomar) and supplied to farms on growing triploid salmon in UK, Norway and Tasmania. Knowledge transfer activities performed by the group since 2008 had a very significant impact, not only on the fish farming sector (producers, breeders, processors) but also on retailers, non-governmental organisations (NASCO), governmental bodies and the general public at national and international levels. Project results have been disseminated widely through workshops organised during the European Aquaculture Society meetings in 2010 and 2011, trade journal articles and scientific papers in peer-reviewed journals. Importantly, data generated is playing an important role in legislative decision-making regarding future aquaculture policies and the use of triploidy within the salmonid industries (rainbow and brown trout also) and fisheries. A demonstration of this is the introduction by the Norwegian coastal and fisheries ministry of ‘green licences’ for salmon farming where green standards must be met through technological and operational solutions to reduce environmental challenge including a substantial reduction in the negative impact of escapes on wild stocks through genetic (i.e. triploidy) and physical containment. Also, the UK Environment Agency (EA) has introduced new legislation to protect wild brown trout in England and Wales and by 2015 all trout stocked into all but totally enclosed waters

with no significant natural brown trout populations will be with sterile all-female brown trout. This was made possible by research done in the group which standardised triploidy induction technique and develop monitoring tools for confirmation of triploidy status.

The impact of our research into the control of puberty in farmed fish, as demonstrated above in salmon, cannot be underestimated as it is a key milestone in the expansion of a sustainable aquaculture industry in Scotland and worldwide.

5. Sources to corroborate the impact

1. Patent (No. 13183966.1 – 1357) "Composition comprising phosphorous for use in preventing deformities in triploid fish" with Biomar on triploid salmon specific diets.

2. Report of the Meeting of the NASCO/North Atlantic Salmon Farming Industry Liaison Group http://www.nasco.int/pdf/2011%20papers/CNL(11)14.pdf

3. Report on sterile salmon production to the Norwegian Ministry of Fisheries published in 2012.

4. Consultation for the Scottish Aquaculture and Fisheries (Scotland) Bill 2013 http://www.scottish.parliament.uk/S4_RuralAffairsClimateChangeandEnvironmentCommittee/General%20Documents/2013.05.08_-_Letter_from_the_Minister_-_Aquaculture_and_Fisheries_(Scotland)_Bill_-_Stage_2_follow_up.pdf

5. Trade article on preventing reproductive development of farmed finfish (2012) http://www.thefishsite.com/articles/1339/preventing-reproductive-development-of-farmed-finfish

In addition, written statements corroborating the impacts are available from Marine Harvest Scotland, AquaGen, North Atlantic Salmon Conservation Organisation and the UK Environment Agency.