Sustainable Aquaculture

Evidence for the effects of interventions to enhance the sustainability of aquaculture using Atlantic salmon (*Salmo salar*) as a case study

Aisla Jones, Angela Mead, Melanie Austen & Michel Kaiser

Photo: A.C. Jones

This document should be cited as Jones, A.C., Mead, A., Austen, M.C.V. & Kaiser, M.J. (2013) Aquaculture: *Evidence for the effects of interventions to enhance the sustainability of aquaculture using Atlantic salmon (Salmo salar) as a case study.* Bangor University.

Contents

1. About this synopsis……………………………………………………………………………………………….5

2. Interventions within each theme ……………………………………………………..……………………..11

3. THEME: Pathogen transfer and therapeutic treatments………………………………………………...14
3.1 Use natural control agents: cleaner wrasse……………………………………………………………...15
3.2 Use probiotics and immunostimulants…………………………………………………………………..16
3.3 Use vaccinations………………………………………………………………………………………….17
3.4 Breed for resistance traits………………………………………………………………………………..19
3.5 Bathe in freshwater……………………………………………………………………………………….20
3.6 Use aerobic training……………………………………………………………………………………...21
3.7 Alter lighting………………………………………………………………………………………………22
3.8 Alter cage size…………………………………………………………………………………………….22
3.9 Establish fallowing to reduce parasites/disease ………………………………………………………..23

4. **THEME: Artificial feed……………………………………………………………………………………...25**
4.1 Reduce fish meal in diet………………………………………………………………………………….26
4.2 Use an alternative protein source: krill…………………………………………………………………27
4.3Use an alternative protein source: bacteria……………………………………………………………..28
4.4 Use an alternative protein source: yeast………………………………………………………………..29
4.5 Use an alternative protein source: animal……………………………………………………………...30
4.6 Use an alternative protein source: plant-based…………………………………………………………31
4.7 Use an alternative oil source: plant-based………………………………………………………………36
4.8 Use genetically modified alternatives……………………………………………………………………40
4.9 Use supplements…………………………………………………………………………………………..41

5. **THEME: Pollution………………………………………………………………………………………….43**
5.1 Integrated aquaculture systems………………………………………………………………………….44
5.2 Construct artificial reefs………………………………………………………………………………….46
5.3 Dry sludge in beds…………………………………………………………………………………………47
5.4 Use exclusion nets…………………………………………………………………………………………47
5.5 Establish fallowing to reduce pollution…………………………………………………………………..48

6. THEME: Bioinvasive species……………………………………………………………………………...50
6.1 Eco friendly biofouling prevention……………………………………………………………………….50

7. THEME: Wild escapes……………………………………………………………………………………..53
7.1Domestication: sterility/triploidy…………………………………………………………………………53

Funding

The synopsis was funded by the Natural Environment Research Council, as part of a Knowledge Exchange Programme on Sustainable Food Production.

Advisory Board

Thank you to the following people for advising on the scope and content of this synopsis:

Dr Neil Achterlonie, Centre for Environment, Fisheries and Aquaculture Science (CEFAS)
Dr Edward Allison, University of East Anglia
Professor Kenny Black, Scottish Association for Marine Science
Professor Gavin Burnell, University of Cork
Professor Gary Carvalho, Bangor University
Dr Piers Hart, WWF Scotland
Mr Daniel Lee, Bangor University
Professor Jimmy Turnbull, Stirling University
Dr Paul Williams, Seafish

The advisory board has been drawn from across a wide range of the aquaculture specialisms. This synopsis is the first in a range of aquaculture synopses that will be written.

Acknowledgements

This synopsis was prepared with funding from the Natural Environment Research Council (NERC).
We also thank Professor William Sutherland and Dr Lynn Dicks for their help and advice.

1. About this synopsis

The purpose of Conservation Evidence synopses

'Aquaculture: evidence for the effects of interventions to enhance the sustainability of aquaculture - Case study: Atlantic salmon, Salmo salar.' is part of a series of synopses produced by Conservation Evidence and the NERC Knowledge Exchange Programme on Sustainable Food Production. These synopses synthesise scientific research in an accessible format, concentrating on the actions potentially taken by practitioners. They are based on reviews of scientific literature, carried out using transparent, unbiased search methods.

By making evidence accessible it is hoped this synopsis will enable stakeholders (with an interest in salmon aquaculture and UK food security) to make evidence-based decisions about change in practice that will enhance the sustainability of aquaculture. Gaps in scientific knowledge are also highlighted.

Conservation Evidence synopses **do**	Conservation Evidence synopses **do not**
• Bring together scientific evidence captured by the NERC Sustainable Food project on the effects of interventions to enhance sustainable food production	• Include evidence on the basic ecology of species and habitats or anthropogenic interactions with the natural environment
• List all realistic interventions for the food production system in question, regardless of how much evidence for their effects is available	• Make any attempt to weight or prioritise interventions according to their importance or the size of their effects
• Describe each piece of evidence, including methods, as clearly as possible, allowing the reader to assess the quality of evidence	• Weight or numerically evaluate the evidence according to its quality
• Work in partnership with practitioners, policymakers and scientists to develop the list of interventions and ensure it covers the most important literature	• Provide answers to conservation and management issues. It provides scientific information to facilitate decision-making

Who is this synopsis for?

This synopsis is targeted at stakeholders who have an interest in aquaculture and UK food security. They may have to make decisions on how best to enhance the sustainability of salmon aquaculture and the associated supply chain. This includes marine managers, farmers, policymakers, processors, the retail industry, active researchers and conservationists. Relevant scientific evidence is summarised. The aim of the synopsis is not to make decisions on behalf of the stakeholder. It aims to support stakeholder decisions related to the effects of practice methods and planned actions, ensuring they are both informed and evidence-based.

When decisions have to be made with particularly important consequences, it is recommended that a systematic review is carried out. It is likely to be more comprehensive than the summary of evidence presented here. Guidance on how to carry out systematic reviews can be found from the Centre for Evidence-Based Conservation at Bangor University (**www.cebc.bangor.ac.uk**).

The Conservation Evidence project

The Conservation Evidence project has three parts:

1) An online, **open access journal** *Conservation Evidence* that publishes new pieces of research on the effects of conservation management interventions. All our papers are written by, or in conjunction with, those who carried out the conservation work and include some monitoring of its effects.

2) An ever-expanding **database of summaries** of previously published scientific papers, reports, reviews or systematic reviews that document the effects of interventions.

3) Synopses of the evidence captured in parts one and two on particular species groups or habitats. Synopses bring together the evidence for each possible intervention. They are freely available online and available to purchase in printed book form.

These resources currently comprise over 4,000 pieces of evidence, all available in a searchable database on the website www.conservationevidence.com.

The NERC Knowledge Exchange Project on Sustainable Food Production

The Programme aimed to enhance the use of science in efforts to make UK food production systems more environmentally sustainable. It ran from June 2012-September 2013, and its main outputs are openly accessible.

The outputs from the Programme include:

- Synopses of evidence on aquaculture, maintaining fertile soil, enhancing natural pest control and farming for wildlife, freely available and searchable on a web-based information hub[1] and in downloadable documents
- Papers presenting priority knowledge needs for sustainable agriculture Dicks *et al*., (2013) and aquaculture in the UK (Jones *et al*., in preparation), as well as priority research questions for the UK food system as a whole Ingram *et al*., 2013 (available as an online pdf)
- Working partnerships built between research scientists and food businesses to address issues of sustainable production
- An analysis of evidence for tradeoffs between different aspects of sustainability, to inform and guide the food industry
- An online catalogue of NERC research related to the UK food system[1]

The programme adopted the Conservation Evidence methods of summarising and disseminating evidence and the natural pest control synopsis was developed at the Conservation Evidence project's home in the Department of Zoology, University of Cambridge. The programme worked with Lancaster University, Plymouth Marine Laboratory, Bangor University, University of Leeds and the Global Food Security programme to deliver the soils and aquaculture synopses and other outputs.

[1] www.nercsustainablefood,com

Synopsis scope

Atlantic salmon (*Salmo salar*, subsequently referred to as salmon) is one of the top five aquatic species consumed in the UK (FAO 2012). The vast majority of salmon and salmon-based products consumed within the UK are produced and supplied by aquaculture rather than wild capture fisheries (FAO 2012). This synopsis presents evidence from the scientific literature for the effects of interventions which potentially alter the interaction of Atlantic salmon *Salmo salar* aquaculture with the environment. In order to be sustainable, food production systems must have a minimal impact on the environment and maximum benefit to society (Subasinghe *et al.,* 2009). Actions may be taken by practitioners that potentially reduce the environmental impact of salmon farming on the environment. These interventions may well be implemented for reasons other than to reduce environmental impact e.g. to increase production or to be more economically efficient.

Unlike agriculture, aquaculture has experienced recent rapid growth; the aquaculture sector has expanded almost 12 fold in the last three decades (FAO, 2012). Much of this expansion has focused on optimising production which is often not backed up by scientific research (Frankic and Hershner, 2003). In recent years, there has been a demand for reliable information to support the expansion of aquaculture, the implementation of new technologies and management strategies (Frankic and Hershner, 2003; Subasinghe *et al*., 2009; Hall *et al*., 2011).

Salmon is supplied to the UK from farms that produce salmon within the UK and produced elsewhere (Ireland, Norway, Chile, Canada and Australia (Tasmania)), thus evidence is presented for all relevant regions. Any bias towards evidence from particular countries reflects a current bias in the published research captured by our search. The synopsis does not include evidence from the substantial literature on the 'background science' behind interactions between aquaculture, biodiversity and the marine environment. In addition, it does not include evidence on the sustainability of fish stocks used in fish meal. However, the efficacy of the use of alternative sources of protein and oil to replace fish meal and fish oil in salmon feeds is included.

How we reviewed the literature

To identify the scientific literature relevant to sustainable aquaculture we used two approaches: a journal trawl (looking at every published article in selected journals and picking out relevant papers, based on title or abstract) and a literature search (querying databases with search terms).

- ISI Web of Knowledge was used to search through all journals using key search terms (Appendix I), from the date of first publication to 2012 inclusive.
- Seven specialist aquaculture and marine conservation journals were trawled, from 2003 to 2012 inclusive (*Aquaculture, Aquaculture International, Aquaculture Research, Aquatic Conservation, Biological Invasions, Journal of the World Aquaculture Society* and *Marine Pollution Bulletin*).

In total, 67 individual studies are addressed in this synopsis, all of which are included in full or in summary on the NERC Sustainable Food website. The criteria for the inclusion of studies in the NERC Sustainable Food database are as follows:

- They must involve an intervention that practitioners could do to potentially limit the negative environmental impacts of salmon aquaculture
- The intervention must have been experimentally tested
- We DO NOT include studies describing background science or collecting data which is not part of a pre- defined experiment

How the evidence is summarised

Interventions are grouped primarily according to the relevant interactions between salmon farms and the natural environment (themes). This was developed in accordance with a report listing indicators for sustainable aquaculture *(FAO 2013)*. Within the synopsis, evidence presented fits into each theme under the various interventions listed. The themes are as follows: pathogen transfer and therapeutic treatments, artificial feed, pollution, bio-invasive species, predator attraction, wild escapes and climate change. No evidence was captured for the interventions listed under the themes predator attraction and climate change.

Ordinarily, no intervention is listed in more than one place. For example, interventions to prevent the escape of farmed species into the wild are very different from those intended to reduce the incidence and spread of pathogens. However, one intervention, ‘Establish fallowing’ is relevant to a number of threats.

Under each intervention listed, relevant studies are grouped together and presented in chronological order, so the most recent evidence is presented at the end. The summary text at the start of each section groups studies according to their findings. The summary text and **key messages** provide a rapid overview of the evidence per intervention. These messages are condensed from the summary text provided for each piece of evidence. Background information is provided to facilitate interpretation of the evidence. A reference list is given at the end of each intervention section.

Access to the synopsis

The information in this synopsis is available in two formats:

- As a pdf to download from **www.nercsustainablefood.com**
- As text for individual interventions on the searchable database at **www.nercsustainablefood.com**

Terminology used to describe evidence

Unlike systematic reviews of particular conservation questions, the evidence is not quantitatively assessed or weighted according to quality. However, to allow you to interpret evidence, we make clear the size and design of each study reported. The table below defines the terms we use.

The strongest evidence comes from randomised, replicated, controlled studies with paired sites and before and after monitoring. Terms relevant to this synopsis are as follows:

Term	Meaning
Site comparison	A study that considers the effects of interventions by comparing sites that have historically had different interventions or levels of intervention.
Replicated	The intervention was repeated on more than one individual or site. In conservation and ecology, the number of replicates is much smaller than it would be for medical trials (when thousands of individuals are often tested). If the replicates are sites, pragmatism dictates that between five and ten replicates is a reasonable amount of replication, although more would be preferable. We provide the number of replicates wherever possible, and describe a replicated trial as 'small' if the number of replicates is small relative to similar studies of its kind.
Controlled	Individuals or sites treated with the intervention are compared with control individuals or sites not treated with the intervention.
Paired sites	Sites are considered in pairs, within which one was treated with the intervention and the other was not. Pairs of sites are selected with similar environmental conditions, such as soil type or surrounding landscape. This approach aims to reduce environmental variation and make it easier to detect a true effect of the intervention.
Randomised	The intervention was allocated randomly to individuals or sites. This means that the initial condition of those given the intervention is less likely to bias the outcome.
Before-and-after trial	Monitoring of effects was carried out before and after the intervention was imposed.
Review	A conventional review of literature by experts. Generally, these have not used an agreed search protocol or quantitative assessments of the evidence.
Systematic review	A systematic review follows an agreed set of methods for identifying studies and carrying out a formal 'meta-analysis'. It will weight or evaluate studies according to the strength of evidence they offer, based on the size of each study and the rigour of its design. All environmental systematic reviews are available at: www.environmentalevidence.org/index.htm

IMPORTANT NOTE - defining the phrase "we found no evidence"

For some interventions we were unable to present any evidence for their effectiveness. This was because either no research had been done in these areas, or previous work did not meet the criteria for this synopsis, in that interventions were not tested directly and quantitatively, or results may not have been reported or made publicly available. This does not mean that these interventions may not be effective in the aquaculture of salmon, or that such measures should be abandoned. In some cases the latter applied to what is currently considered to be 'best-practice' by industry. This situation highlights the importance of making evidence more readily accessible so that it can be evaluated independently.

References

Dicks L., Bardgett R., Bell J., Benton T., Booth A., Bouwman J., *et al*. (2013) What do we need to know to enhance the environmental sustainability of agricultural production? A prioritisation of knowledge needs for the UK food system. *Sustainability*, 5: 3095-3115.

FAO. (2012). *The state of world fisheries and aquaculture 2012*. FAO Fisheries and Aquaculture Department, Food and Agriculture Organization of the United Nations. Rome. 230 pp.

FAO. (2013). *Indicators for sustainable aquaculture in Mediterranean and Black Sea countries. Guide for the use of indicators to monitor sustainable development of aquaculture*. Studies and Reviews. General Fisheries Commission for the Mediterranean. Rome. 60 pp.

Frankic, A. and Hershner (2003). Sustainable aquaculture: developing the promise of aquaculture. *Aquaculture International*, 11: 517- 530.

Hall, S.J., A. Delaporte, M. J. Phillips, M. Beveridge and M. O'Keefe. (2011). Blue Frontiers: Managing the Environmental Costs of Aquaculture. *The World Fish Center, Penang, Malaysia*.

Ingram J.S.I., Wright H.L., Foster L., Aldred T., Barling D., Benton T.G., *et al*. (in press) Priority research questions for the UK food system. *Food Security*, 1-20

Jones, A.C., Mead, A., Kaiser, M.J., Austen, M.C.V. *et al*., (in preparation) Prioritisation of knowledge-needs for sustainable aquaculture: a national and global perspective.

Subasinghe, R., Soto, D. and Jia, J. (2009) Global aquaculture and its role in sustainable development. *Reviews in Aquaculture*, 1: 2- 9.

2. Interventions within each theme

The list of interventions relevant to salmon aquaculture has been agreed in partnership with an Advisory Board comprised of internationally recognised academics with expertise in aquaculture. The final list below may not be exhaustive. However, it includes a range of interventions that have been carried out or advised, which may enhance the sustainability of salmon production and supply from aquaculture. Some interventions may be possible in theory but at present remain too expensive to implement and hence are not used in a commercial context at present. It is indicated in the table below whether evidence has been captured for each intervention. The remaining document contains summaries for those interventions where evidence has been captured under each theme.

Theme	Intervention	Was evidence captured within searches?
Pathogen transfer and therapeutic treatments	Use natural control agents: cleaner wrasse	Yes
	Use probiotics and immunostimulants	Yes
	Use vaccinations	Yes
	Breed for resistant traits	Yes
	Bathe in freshwater	Yes
	Use aerobic training	Yes
	Alter lighting	Yes
	Alter cage size	Yes
	Establish fallowing	Yes
	Apply environmentally low impact/biodegradable chemical treatments	No
	Apply environmentally low impact/biodegradable chemical preventatives	No
	Use of lice traps	No
	Area Management Agreements, zonal management	No[2]
	Definition of zone carrying capacities	No
	Surveillance programmes, alert systems	No[3]
Artificial feed	Reduce fish meal in diet	Yes
	Use an alternative protein source: krill	Yes
	Use an alternative protein source: bacteria	Yes
	Use an alternative protein source: yeast	Yes
	Use an alternative protein source: animal	Yes
	Use an alternative protein source: plant-based	Yes

[2] Although we found no papers that showed the effectiveness of area management agreements, these are now the norm and have contributed greatly to control of transmission of lice between different year classes of fish and increased the development of resistance to therapeutants by synchronous and strategic treatments

[3] http://www.asimuth.eu/en-ie/Pages/default.aspx ASIMUTH (Applied Simulations and Integrated Modelling for the Understanding of Toxic and Harmful Algal Blooms) is the first step to develop short term harmful algal bloom alert systems for Atlantic Europe.

	Use an alternative oil source: plant-based	Yes
	Use genetically modified alternatives	Yes
	Use supplements	Yes
	Certification of sustainable status of raw materials (e.g. organic, MSC certified, IFFO RS certified, certified soy products)	No
	Use capture fishery discards and trimmings in feed	No
Pollution	Integrated aquaculture systems	Yes
	Artificial reefs	Yes
	Sludge drying bed	Yes
	Exclusion nets	Yes
	Establish fallowing	Yes
	Re-use of organic waste as biofuel/in agri-industry	No
	Biofilters	No
	Antimicrobials in feed	No
	Bioflocs Natural extracts for organic matter breakdown	No No
	Digestion of organic waste (anaerobic digestors)	No
	Alter artificial feed composition (***see Artificial feed***) (e.g. modern salmon diets contain much less nitrogen)	No
	Wetland bioremediation	No
	Facility location	No
Bio-invasive species	Eco friendly biofouling prevention	Yes
	Biofouling prevention on equipment using biological control (grazers)	No
	Screening and quarantine of spat supply	No
	Screening of local biodiversity for invasives	No
	Use of native species in aquaculture[4]	No
	Prevent or minimise escapes/escape impacts of non-native cultured species	No
Wild escapes	Domestication: acclimation to captive conditions	No
	Domestication: sterility/triploidy	Yes
	Gene bank creation: wild stocks	No
	Minimise escapes: aquaculture facility & cage design/technology	No
	Minimise escapes during harvesting/transfer (handling techniques)	No
	Management of escapes: surveillance(tagging)	No
	On-shore closed recirculation systems	No[5]
Climate change	Greenhouse gas emission reduction	No
	On-site processing units	No
	Selective breeding to minimise waste on carcass	No
	Reduce waste during feeding	No

[4] Aquaculture is regarded as a key vector for non-native and invasive species and diseases and so the import and transportation of aquaculture stock is subject to regulation and codes of good practice.

[5] Many smolts are produced in on-shore closed facilities where it is relatively easy to ensure complete containment.

	Use of feed ingredients with lower GHG ratings	No
	Use of food processing by-products in feeds	No
Predator attraction	Stock conditioning	No
	Aquaculture facility design	No
	Aquaculture facility location	No
	Control predators through culling	No
	Deterrence methods	No[6]

[6] There are two main ways that seal predation is managed at present. These are efficient net tensioning (http://www.sarf.org.uk/cms-assets/documents/28923-913107.sarf054---volume1.pdf) and acoustic deterrent devices (http://www.sarf.org.uk/cms-assets/documents/28820-18834.sarf044---final-report.pdf).

3. THEME: Pathogen transfer and therapeutic treatment

Millions of US dollars are lost annually as a result of lice and disease risk in commercial aquaculture (Shariff 1998). Concern has been raised over the perceived threat of environmental damage caused by the chemical treatments used to treat Atlantic salmon pathogens and lice (Jones *et al.* 1992; Karunasagar *et al.* 1994). Practitioners also have concerns related to drug resistance (Jones *et al.* 1992; Karunasagar *et al*. 1994). Escaped fish or waste from salmon farms may also facilitate disease transfer within the surrounding environment (Heggberget *et al.* 1993). This section refers to interventions aimed at reducing lice and disease outbreaks in cultured and wild salmon stocks, without exposing them to residuals and toxins through traditional therapeutic treatments.

Heggberget, T.G., Johnsen, B.O., Hindar, K., Jonsson, B., Hansen, L.P., Hvidsten, N.A., Jensen, A.J. (1993). Interactions between wild and cultured Atlantic Salmon—a review of the Norwegian experience. *Fisheries Research,* **18** (1– 2): 123–146.

Jones, M.W., Sommerville, C., Wootten, R. (1992). Reduced sensitivity of the salmon louse to the organophosphate dichlorvos. *Journal of Fish Diseases,* **13**: 303- 310.

Karunasagar, I., Pai, R., Malathi, G.R., Karunasagar, I. (1994). Mass mortality of *Penaeus monodon* larvae due to antibiotic resistant *Vibrio harĺeyi* infection. *Aquaculture,* **128**: 203–209.

Shariff, M. (1998). Impact of diseases on aquaculture in the Asia–Pacific region as exemplified by epizootic ulcerative syndrome (EUS). *Journal of Applied Ichthyology*, **14**: 139–144.

Key messages

Use natural control agents: cleaner wrasse

Evidence on whether cleaner wrasse reduced the number of sea lice on salmon is mixed. Two studies conducted in Ireland found two species of cleaner wrasse were as effective at reducing the number of lice as chemical treatments, although a third wrasse species could not prevent increasing infestation levels in caged salmon.

Use probiotics and immunostimulants

A study in Scotland found the use of *Carnobacterium* bacteria sp. as a probiotic improved survival rates in salmon exposed to several disease-causing bacteria. A study in Norway established that salmon fed a diet containing 28% plant-based protein and other supplements had lower levels of lice infection. In addition, the diet prevented the development of soybean meal-induced enteritis. Thus the diet was an effective immunostimulant.

Use vaccinations

Studies from Norway, Iceland, Canada and Australia demonstrated that vaccination increases survival rates in salmon exposed to a range of disease-causing bacteria and viruses.

Breed for resistant traits

A study in Norway determined that when salmon were bred for high resistance to infectious pancreatic necrosis, they showed increased levels of survival compared to salmon bred for low resistance to the disease.

Bathe in freshwater

Evidence on whether freshwater bathing reduces levels of amoebic gill disease is mixed. A study in Australia demonstrated a reduction in live amoebae in the gills after bathing. In contrast, a second Australian study found similar levels of amoebic gill disease between bathed and un-bathed salmon.

Use aerobic training

A study in Norway found salmon exposed to infectious pancreatic necrosis had higher survival rates if they underwent aerobic training, compared to an untrained group. Interval training was more effective than continuous intensity training.

Alter lighting

A study in Norway established salmon kept in low intensity artificial light or at natural light levels had less lice per fish compared to salmon kept at medium to high intensities of artificial light.

Alter cage size

A study in Australia recorded lower levels of amoebic gill disease in salmon kept in large *cages compared with small cages.*

Establish fallowing to reduce parasites/disease

A study in Scotland recorded lower lice numbers on Atlantic salmon in cages using a fallowing system. Another study in Australia found no difference in mortality from Amoebic Gill Disease in cages where a fallowing system had been used.

3.1 Use natural control agents: cleaner wrasse

- Two controlled studies (one also replicated) in Ireland found mixed effects of cleaner wrasse on sea lice numbers infesting salmon. One study[1] found corkwing and goldskinny cleaner wrasse were as effective at controlling lice infestation as chemical treatments. Another study[2] found rockcook cleaner wrasse were ineffective at preventing lice outbreaks.

Background

Commercial salmon farms are susceptible to outbreaks of sea lice. Traditionally, control of sea lice has involved pesticide use, either through oral administration or as a bath treatment. This approach may affect the surrounding environment. Corkwing, goldsinny and rockcook cleaner wrasse feed on sea lice (Caligus elongates). Therefore, the use of this species as an alternative control agent to pesticides has been investigated.

Between 1991 and 1992, a controlled study (1) at two salmon farms off the west Irish coast found the numbers of lice, *Caligus elongates*, infesting salmon, *Salmo salar*, were low in cages containing corkwing and goldsinny cleaner wrasse. Similar levels of lice were found in wrasse stocked cages and those chemically treated with a pesticide. Infestation levels were on average five lice per fish. Cleaner wrasse were as effective as chemical treatment at wrasse: salmon ratios as low as 1:250. The first farm used eleven 'Polar Circle' cages (12m depth, 20m diameter). One cage was stocked with 188 cleaner wrasse and 47,000 salmon smolts. All other cages were given chemical treatment for the duration of the study. At the second farm, two groups of eight square 'Turmec' cages (10m depth, 10m width) were stocked with 5,000- 8,000 salmon smolts each. Eight cages were stocked with 500-800 cleaner wrasse. The remaining cages were chemically treated for sea lice. On both farms, random samples of 15 salmon were removed from each cage every 1-2 weeks to monitor lice infestation levels.

In 1992, a replicated, controlled study in Ireland (2) found rockcook cleaner wrasse failed to consistently reduce numbers of lice, *Caligus elongates*, in sea-caged salmon, *Salmo salar*. When compared to control cages, the wrasse controlled infestation levels, preventing an outbreak on only one of the seven sampling periods. Each of five circular salmon cages (50-70m circumference, 10m depth) was stocked with between 13,000 and 24,000 salmon smolts. Wrasse were added to four cages at wrasse: salmon ratios between 1:37 and 1:49. Wrasse were not added to the control cage.

1) Deady, S., Varian, S. J. A. and Fives, J. M. (1995). The use of cleaner- fish to control sea lice on two Irish salmon (*Salmo salar*) farms with particular reference to wrasse behaviour in salmon cages. *Aquaculture*, **131**: 73- 90.
2) Tully, O., Daly, P., Lysaght, S., Deady, S. and Varian, S. J. A. (1996). Use of cleaner- wrasse (*Centrolabrus exoletus* (L.)) and *Ctenolabrus rupestris* (L.)) to control infestations of *Caligus elongatus* Nordmann on farmed Atlantic salmon. *Aquaculture*, **142**: 11- 24.

3.2 Use of probiotics and immunostimulants

- Increased survival was observed in salmon fed a probiotic before exposure to four different disease-causing bacteria over a 28 day period compared with controls in a replicated Scottish study[1].
- A replicated, controlled study in Norway[2] found the number of salmon infected with lice was reduced by 28% when fed a diet composed of fish meal and 28% plant-based protein. Adding beta-glucans to the diet decreased lice infection levels by a further 28% compared with controls.
- The same study[2] found the addition of mannan oligosaccharides improved gut function by preventing the development of soybean-induced enteritis compared with controls.

Background

Atlantic salmon cultured in commercial farms are at an increased risk of contracting and transferring infectious bacterial diseases and other pathogens. Immunostimulants and probiotics are administered with the aim of improving immune response and gut health, in turn improving survival rates and condition of the fish. The bacteria Carnobacterium sp. has been used as a probiotic against several disease-causing bacteria. Diet formulations with added supplements such as beta-glucans and mannan oligosaccharides, have also been tested for their role as immunostimulants.

In 1999, a replicated, controlled experiment in Scotland (1) found that the survival rates of salmon fry, *Salmo salar*, increased when *Carnobacterium* bacteria sp. was used as a probiotic. After 14 days of diets with the probiotic, survival was improved when salmon fry were challenged with three different disease-causing bacteria, A*eromonas salmonicida*, *Vibrio ordalii*, and *Yersinia ruckeri*. Survival rates were 20%, 74% and 71% respectively compared to 0%, 23% and 42% in untreated controls. However, when exposed to the disease-causing bacteria, *Vibrio anguillarum*, salmon survival was not improved (46%) compared to the control group (42%). After 28 days of the diet with probiotic, improved survival was seen against all bacterial species tested compared to the control groups. 200 salmon fry were fed diets with or without the probiotic for 28 days. At seven day intervals during this 28 day period, a group of 25 salmon fry were exposed to four different disease-causing bacteria then monitored for a further 28 days.

In 2009, a randomised, replicated, controlled study in Norway (2) found that salmon, *Salmo salar*, fed a fish meal-based diet formulated with 14% soybean meal and 14% sunflower meal showed a 27% reduction in lice (*Lepeophteirus salmonis* and *Caligus elongates*) infection compared to the control diet. Adding beta-glucans to the experimental diet resulted in a further 28% reduction in infection rates whereas adding mannan oligosaccharides did not affect lice infection rates. It did improve gut function by preventing the salmon from developing soybean-induced enteritis and diarrhoea. Nine experimental diets were fed to salmon over a period of 69 to 71 feeding days. The basal diets were either based on pure fish meal or soybean and sunflower meal-soybean meal mixed with fish meal.

1) Robertson, P.A.W., O'Dowd, C.O., Burrells, C., Williams, P. and Austin, B. (2000). Use of Carnobacterium sp. as a probiotic for Atlantic salmon (*Salmo salar* L.) and rainbow trout (*Oncorhynchus mykiss, Walbaum*). *Aquaculture*, **185**: 235- 243.
2) Refstie, S., Baeverfjord, G., Seim, R. R. and Elvebø, O. (2010). Effects of dietary yeast cell wall β-glucans and MOS on performance, gut health, and salmon lice resistance in Atlantic salmon (*Salmo salar*) fed sunflower and soybean meal. *Aquaculture*, **305**(1-4): 109-116.

3.3 Use vaccinations

- Controlled studies from Iceland[1] and Norway[5] found higher survival rates in vaccinated salmon compared to unvaccinated control groups. This was post exposure to the disease-causing bacteria, A*eromonas salmonicida* spp.*achromogenes*[1] and *Yersinia ruckeri*[5], respectively.
- An Australian and Canadian controlled study[3, 4] each reported higher survival in salmon infected with marine flexibacteriosis[3] and bacterial kidney disease[4], post vaccination.
- Two Norwegian controlled studies[2, 6] reported similar results for salmon vaccinated against infectious salmon anaemia.

Background

Atlantic salmon cultured in commercial farms are at an increased risk of contracting and transferring infectious bacterial diseases and other pathogens. Administering vaccinations that target specific infections aims to reduce or eliminate disease contraction. Disease can spread within the salmon farm, from wild salmon to cultured salmon and vice versa. Vaccines are derived from specific strains of the target pathogen. Examples of vaccines are: IBBO for furunculosis disease, pEGFP-HE for infectious salmon anaemia virus, Lipforte V1 for bacterial kidney disease and Yersinivac-B is for the disease-causing bacteria, Yersinia ruckeri, which causes yersiniosis.

In 1997, a replicated, controlled study in Iceland (1) found that vaccinating salmon, *Salmo salar*, with IBOO improved survival rates of fingerlings when exposed to a disease-causing bacteria, *Aeromonas salmonicida* spp. *achromogenes*. After 16 days, the lowest level of mortality (51%) was observed in groups vaccinated with IBOO compared with the unvaccinated control groups (81% mortality). Infection with the bacteria leads to the development of furunculosis in salmon. Vaccines were made from *A.salmonicida* spp. *achromogenes* strain M108-91, furunculosis vaccine and an oil adjuvant. Salmon were exposed to *A.salmonicida* spp. *achromogenes* 70 days post vaccination.

In 2005, a replicated, controlled study in Norway (2) found that the pEGFP-HE vaccine increased survival in salmon, *Salmo salar*, exposed to infectious salmon anaemia virus. Mortality levels in groups given the vaccine were lower than the unvaccinated control groups (16.3% and 25% versus 45% and 41.3%, respectively). Fingerling salmon were injected with a dose of a DNA vaccine expressing the virus. Dosage was repeated after week three and six. Three weeks after the final immunisation, salmon were exposed to infectious salmon anaemia virus and mortality levels were recorded for 54 days.

In 2007, a randomised, replicated, controlled study in Tasmania, Australia (3) found vaccination against marine flexibacteriosis increased survival rates in salmon, *Salmo salar*. Salmon injected with a vaccine and adjuvant showed significantly lower mortality levels (11%) than a group given the vaccine only (39%), a group given the adjuvant only (54%) and an unvaccinated control group (50%). Four groups of salmon (32-38 individuals in each) were given different treatments: a vaccine against marine flexibacteriosis, a vaccine and an adjuvant, an adjuvant only and no injection. Salmon were exposed to marine flexibacteriosis eight weeks after vaccination. Fish were placed in 100l seawater tanks and exposed for one hour. Mortality levels were recorded.

In 2010, a randomised, replicated, controlled study in Canada (4) found the vaccine, Lipogen Forte V1, increased salmon, *Salmo salar*, survival during an outbreak of bacterial kidney disease when compared with an industry standard. Four other vaccines were not successful, relative to the industry standard vaccine. Groups of salmon were given one of four commercially available vaccines: Lipogen Forte V1, Renogen, Bayovac

5.1 Vet and Alpha Ject 4000. Mortality was measured weekly or biweekly for eight months.

In 2011, a replicated, controlled study in Tasmania, Australia (5) found increased survival rates in salmon, *Salmo salar*, vaccinated (using Yersinivac-B) and then exposed to the disease-causing bacteria, *Yersinia ruckeri*. Vaccinated salmon showed higher rates of survival than the unvaccinated control group. A trypsinated version of the Yersinivac-B vaccine produced higher survival rates than an untrypsinated vaccine (65% and 52% survival respectively). *Y. Ruckeri* causes yersiniosis. Groups of salmon were given one of two vaccinations; either Yersinivac-B or a trypsinated version of Yersinivac-B. A control group received no vaccination. Six weeks after vaccination, salmon from each treatment were exposed to *Y.ruckeri* and mortality levels were monitored for 14 days.

In 2011, a randomised, controlled study conducted in Norway (6) found that vaccinated salmon, *Salmo salar*, showed increased levels of survival after exposure to infectious salmon anaemia compared to an unvaccinated control group. Survival levels were lower with increasing strength of vaccine. After 45 days, mortality levels in the vaccinated groups were 55.0%, 28.3% and 10.0% respectively, for vaccines at strengths of 4%, 20% and 100%. Three groups were given one of three different strengths of vaccine at 100%, 20% and 4%. Two control groups were given a mock vaccine and saline. Six weeks after vaccination, all groups were infected with the infectious salmon anaemia virus and mortality was recorded daily for 45 days.

1) Gudmundsdottir, B. K. and Gudmundsdottir, S. (1997). Evaluation of cross protection by vaccines against atypical and typical furunculosis in Atlantic salmon, *Salmo salar* L. *Journal of Fish Diseases*, **20**: 343-350.
2) Mikalsen, A. B., Sindre, H., Torgersen, J. and Rimstad, E. (2005). Protective effects of a DNA vaccine expressing the infectious salmon anemia virus hemagglutinin-esterase in Atlantic salmon. *Vaccine*, **23**(41): 4895-4905.
3) van Gelderen, R., Carson, J. and Nowak, B. (2009). Experimental vaccination of Atlantic salmon (*Salmo salar* L.) against marine flexibacteriosis. *Aquaculture*, **288**(1-2): 7-13.
4) Burnley, T. A., Stryhn, H., Burnley, H. J. and Hammell, K. L. (2010). Randomized clinical field trial of a bacterial kidney disease vaccine in Atlantic salmon, *Salmo salar* L. *Journal of Fish Diseases*, **33**(7): 545-557.
5) Costa, A. A., Leef, M. J., Bridle, A. R., Carson, J. and Nowak, B. F. (2011). Effect of vaccination against yersiniosis on the relative percent survival, bactericidal and lysozyme response of Atlantic salmon, *Salmo salar*. *Aquaculture*, **315**(3-4): 201-206.
6) Lauscher, A., Krossoy, B., Frost, P., Grove, S., Konig, M., Bohlin, J., Falk, K., Austbo, L. and Rimstad, E. (2011). Immune responses in Atlantic salmon (*Salmo salar*) following protective vaccination against infectious salmon anemia (ISA) and subsequent ISA virus infection. *Vaccine*, **29**(37): 6392-6401.

3.4 Breed for resistance traits

- A replicated, controlled Norwegian study[1] found increased survival levels in salmon exposed to infectious pancreatic necrosis when the family was bred for high resistance to the disease compared to a family bred for low resistance to the disease.

Background

Atlantic salmon cultured in commercial farms are at risk of contracting and transferring infectious bacterial diseases and other pathogens. Breeding programs aim to increase resistance against infectious diseases which may spread within the salmon farm, from wild salmon to cultured salmon and vice versa. Infectious pancreatic necrosis is an example of such a disease.

In 2005, a study comprised of two replicated, controlled trials was conducted in Norway (1). Both trials determined that families of salmon, *Salmo salar*, bred with high resistance to infectious pancreatic necrosis, showed higher survivorship compared to salmon bred with lower resistance. Mortality levels in fry were 29.3% and 66.6%, respectively. The unexposed controls were 1.0% and 3.2%, respectively. The same result pattern was observed in smolt (32.0% and 79.0% mortality levels, respectively). Salmon used in the experiment were offspring from the 2001 and 2004-2005 breeding seasons. Families were selected either for high or low resistance to infectious pancreatic necrosis. The first experiment used fry in fresh water. Groups of high resistance and low resistance fish were exposed through bathing. One group of each remained unexposed as the control. Mortality levels were observed between 30-50 days after infection.

1) Storset, A., Strand, C., Wetten, M., Kjøglum, S. and Ramstad, A. (2007). Response to selection for resistance against infectious pancreatic necrosis in Atlantic salmon (*Salmo salar* L.). *Aquaculture*, **272**: 62-68.

3.5 Bathe in freshwater

- Two studies in Australia[1, 2] provide mixed evidence of the effect of freshwater bathing to reducing amoebic gill disease. One study found a reduction in numbers of amoebae on salmon gills persisting for up to 10 days after bathing. A second replicated, controlled study[2] found similar levels of amoebae in the gills of treated and untreated salmon.

Background

Atlantic salmon cultured in commercial farms are at risk of contracting and transferring infectious bacterial diseases and other pathogens such as amoebic gill disease. Freshwater bathing aims to lower the risk of this disease by removing live amoebae from the gills.

In 2002, a study on a salmon farm in Tasmania, Australia (1) found an 86% reduction in the number of live amoebae found on the gills of salmon, *Salmo salar*, after freshwater bathing. The presence of amoebae increases the risk of amoebic gill disease. The lower levels of amoebae persisted for 3 days before gradually increasing to pre-bathing levels on day 10. Salmon were given freshwater baths for two hours then monitored for 10 days. Samples were removed from fish before bathing and at 1, 3, 5 and 10 day intervals after bathing to determine the number of amoebae present on the gills.

Between 2000 and 2002, a replicated, controlled study in Tasmania, Australia (2) found similar levels of amoebic gill disease in groups of salmon, *Salmo salar*, that had undergone freshwater bathing compared to those which had not. By the end of the study, amoebic gill disease occurred within 35% of fish within both groups. Monthly samples were removed from salmon in three groups receiving freshwater baths and three un-bathed groups. Average biomass per pen was 11, 663 kg for bathed groups and 20, 929 kg for un- bathed groups. Signs of clinical disease were assessed monthly using the routine Tasmanian salmon farmers gill assessment method.

1) Clark, G., Powell, M. and Nowak, B. F. (2003). Effects of commercial freshwater bathing on reinfection of Atlantic salmon, *Salmo salar*, with Amoebic Gill Disease. *Aquaculture*, **219**(1-4): 135-142.
2) Douglas-Helders, G. M., Weir, I. J., O'Brien, D. P., Carson, J. and Nowak, B. F. (2004). Effects of husbandry on prevalence of amoebic gill disease and performance of reared Atlantic salmon (*Salmo salar* L.). *Aquaculture*, **241**(1-4): 21-30.

3.6 Use aerobic training

- A randomised, replicated, controlled study in Norway[1] found higher survival rates in salmon exposed to infectious pancreatic necrosis if they had undergone aerobic training. Interval training was more effective than continuous training.

Background

Atlantic salmon cultured in commercial farms are at risk of contracting and transferring infectious bacterial diseases and other pathogens. Aerobic training aims to mitigate susceptibility of salmon to infectious diseases by enhancing fitness levels. Infectious pancreatic necrosis is an example of a viral disease.

In 2011, a randomised, replicated, controlled study in Norway (1) found increased survival rates in salmon, *Salmo salar*, exposed to infectious pancreatic necrosis virus due to endurance training. Fish that had undergone aerobic interval training showed higher survival rates (74%) compared with those that had undergone aerobic continuous intensity training or the non-trained control group (64% and 61% survival, respectively). Mortalities began to occur 11 days after exposure and continued until the end of the 31 day experiment. 120 fish were split into the three treatment groups; control untrained fish swimming in tanks with a constant average water speed of 0.05 body lengths/second, continuous intensity training salmon exposed to a constant average water speed of 0.8 body lengths/second and interval trained fish exposed to an average speed of 0.8 body lengths/second for 16 hours per day (including 4 h light–12 h dark). After training, fish were maintained for 6 weeks at a constant average water speed of 0.05 body lengths/second before cohabitation with 60 salmon infected with infectious pancreatic necrosis. Mortality levels were recorded daily for 31 days.

1) Castro, V., Grisdale-Helland, B., Helland, S. J., Kristensen, T., Jorgensen, S. M., Helgerud, J., Claireaux, G., Farrell, A. P., Krasnoy, A. and Takle, H. (2011). Aerobic training stimulates growth and promotes disease resistance in Atlantic salmon (Salmo salar). *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, **160**(2): 278-290.

3.7 Alter lighting

- A replicated, controlled study in Norway[1] reported lower numbers of lice on salmon kept in low intensity artificial light or natural lighting. The more intense the artificial light was, the higher the number of lice found on fish.

Background

Commercial salmon farms are susceptible to outbreaks of sea lice. Traditionally, control of sea lice has involved pesticide use, either through oral administration or as a bath treatment. An example is azamethiphos. Light has been investigated as an alternative to pesticides as a control agent.

In 1996, a replicated, controlled study in Norway (1) found salmon, *Salmo salar*, kept under intense artificial light had higher lice numbers than those kept under low intensity artificial or natural light. Salmon kept under medium and high artificial light intensities had the highest number of lice increasing from three to a maximum of 26 lice per fish over the full sampling period. Salmon in low artificial and natural light conditions both had an average of between 5 and 10 lice per fish by the end of sampling. Four salmon cages, each containing 2,300 salmon, were used in the study. Three were lit with continuous artificial light at low (0.24 W/m^2), medium (1.9–4.1 W/m^2) and high (22.2 W/m^2) intensity from January until harvest in June, 1996. The fourth group was kept under natural light conditions for the duration of the experiment. All groups were given a single chemical treatment for sea lice infection in March and May. Azamethiphos at a concentration of 0.2 parts per million was applied. Samples of salmon were inspected for lice started on day 76. Every third week, 20–30 fish from each cage were inspected for numbers of lice.

1) Hevrøy, E. M., Boxaspen, K., Oppedal, F., Taranger, G. L. and Holm, J. C. (2003). The effect of artificial light treatment and depth on the infestation of the sea louse *Lepeophtheirus salmonis* on Atlantic salmon (*Salmo salar* L.) culture. *Aquaculture*, **220**(1-4): 1-14.

3.8 Alter cage size

- A replicated study in Australia[1] recorded lower levels of amoebic gill disease in salmon kept within larger compared to smaller cages.

Background

Atlantic salmon cultured in commercial farms are at risk of contracting and transferring infectious bacterial diseases and other pathogens. Altering cage size aims to reduce levels of infectious disease by reducing stress levels in fish and contact time between fish in the same cage.

In 2000, a replicated study in Tasmania, Australia (1) found higher levels of amoebic gill disease salmon, *Salmo salar*, stocked in 60m diameter round cages compared to those in 80m diameter cages. Levels of amoebic gill disease were 47% and 22%, respectively. Two cages with a diameter of 60m and three of 80m diameter were used for the study. Average biomass per pen was 2337 kg for the 60m cages and 2806 kg for the 80m cages. Monthly samples were taken from August to November. Signs of clinical disease were assessed using the routine Tasmanian salmon farmers gill assessment method.

1) Douglas-Helders, G. M., Weir, I. J., O'Brien, D. P., Carson, J. and Nowak, B. F. (2004). Effects of husbandry on prevalence of amoebic gill disease and performance of reared Atlantic salmon (*Salmo salar* L.). *Aquaculture*, **241**(1-4): 21-30.

3.9 Establish fallowing to reduce parasites/disease

- A study in Scotland[1] recorded lower lice numbers on Atlantic salmon in cages using a fallowing system. Another study in Australia[2] found no difference in mortality from Amoebic Gill Disease in cages where a fallowing system had been used.

Background

Husbandry practice on salmon farms is important in reducing the spread of disease within and beyond the farm. Fallowing has been practiced in terrestrial agriculture for centuries to reduce the incidence of disease. Many salmon farms use fallowing as a technique for disease control and some to reduce the build- up of sediments below cages. Chemical and biological remediation of benthos near salmon farms has been proven. A two month fallowing cycle is mandatory to break parasite cycles on salmon farms.

A study of four fish farms on the west coast of Scotland between 1990 and 1992 (1) found that fallowing was effective in controlling lice numbers on Atlantic salmon. The salmon at site 1 were heavily infected with lice throughout the period of the study and therefore required regular treatment. Lice numbers were low in new smolts at sites 2-4 (where fallowing took place) and treatment wasn't required as often as for site 1 (where there was no fallowing). Treatment for lice wasn't required as often for salmon at sites 2 and 3 (long fallow periods of at least 16 weeks) compared to site 4 (fallow period of around 9 weeks) suggesting longer periods of fallowing were more effective in controlling lice numbers. The four farms had fallowing periods of 0, 17, 16 and 9 weeks respectively (hereby sites 1, 2, 3 and 4 respectively). Sites 2-4 contained only one intake of salmon at a time whereas site 1 contained salmon of multiple year classes. Samples of salmon were taken from each farm every two weeks for 20 months and lice numbers (of species *L.salmonis* and *C.elongatus*) were counted.

A replicated study from 2000- 2002 in Tasmania, Australia (2) found no difference in mortality from amoebic gill disease (AGD) in Atlantic Salmon using the method of fallowing cages. Cumulative mortality at the end of the trials was 2.06% for the rotated cages and 2.88% for the stationary cages which was not significantly different in both years of the experiment. The fallowing period in different cages ranged from 4 to 97 days and the experiment was repeated in 2 growing seasons (December to March 2000/2001 and December to April 2001/2002). Average biomass per pen was 15, 026 kg and 20, 304.4 kg for the stationary treatment groups in the two seasons respectively. Average biomass for the rotated pens was 17, 115 kg and 21, 000.9 kg per pen. Signs of clinical disease were assessed monthly using the routine Tasmanian salmon farmers gill assessment method by examining at least 20 fish for the presence of AGD.

1. Bron, J. E., Sommerville, C., Wooten, R. & Rae, G.H. (1993). Fallowing of marine Atlantic salmon, *Salmo salar* l., farms as a method for the control of sea lice, *Lepeophtheirus salmonis* (Kroyer, 1837). *Journal of Fish Diseases*, **16**: 487- 493.

2. Douglas-Helders, G. M., Weir, I. J., O'Brien, D. P., Carson, J. & Nowak, B. F. (2004). Effects of husbandry on prevalence of amoebic gill disease and performance of reared Atlantic salmon (*Salmo salar* L.). *Aquaculture*, **241**(1- 4): 21- 30.

4. THEME: Artificial feed

Atlantic salmon feeds in aquaculture have traditionally included fish meal and fish oils from small, pelagic marine fish due to their relatively low price and high nutritional value (Naylor *et al.* 2009; Bendiksen *et al.* 2011). However, the majority of global stocks of these fish are now considered to be either fully or over-exploited (FAO 2009). In order to reduce reliance on these stocks and as a result of the increasing cost of fish meal and fish oil products, it is necessary for alternative protein and oil sources to be developed for inclusion in feeds (Naylor *et al.* 2009).

Bendiksen E, A., Johnsen C.A., Olsen H.J., Jobling, M. (2011). Sustainable aquafeeds: Progress towards reduced reliance upon marine ingredients in diets for farmed Atlantic salmon (*Salmo salar* L.). *Aquaculture,* **314**: 132–139.

FAO. (2009). *The State of World Fisheries and Aquaculture, 2008*. FAO Fisheries and Aquaculture Department, Food and Agriculture Organization of the United Nations. Rome. 176 pp.

Naylor R.L., Hardy R.W., Bureau D.P., Chiu A., Elliott M., Farrell A.P., Forster I., Gatlin D.M., Goldburg R.J., Hua K., Nichols P.D. (2009) Feeding aquaculture in an era of finite resources. *Proceedings of the National Academy of Science,* **106** (15): 103–110.

Key messages

Reduce fish meal in diet

Studies in Norway found that feeding salmon modified diets containing reduced amounts of fish meal did not alter the final weights achieved.

Use an alternative protein source: krill

Studies in Norway found that feeds incorporating whole krill and partially de-shelled krill as a substitute for fish meal did not negatively affect growth rate and weight gain in salmon.

Use an alternative protein source: bacteria

Studies in Norway found mixed evidence for the effects of replacing fish meal with bacterial protein meal in salmon feed. Whereas low level substitutions did not negatively affect growth rates and weight gain, higher level substitutions reduced growth rates and weight gain.

Use an alternative protein source: yeast

One study in Norway found no effect on weight of Atlantic salmon that were fed diets containing yeast compared to a diet containing fishmeal.

Use an alternative protein source: animal

Studies in Canada and Scotland found mixed evidence for the effects of replacing fish meal with animal based protein. One study found no difference in oxygen consumption or swimming speed of fish fed diets containing either fish meal or animal based protein. Another study found fish fed a fishmeal diet weighed more than fish fed diets with alternative proteins.

Use an alternative protein source: plant-based

Studies in Norway, Scotland, Canada and the USA found mixed evidence for the effects of replacing fish meal with plant-based proteins in salmon feed. Across the studies, growth rates, final average body weights, digestibility, morphology, feeding efficiency and salmon condition were both similar and different in fish fed plant-based protein or fish meal diets. Appetite and survival rates were not affected by using plant-based protein.

Use an alternative oil source: plant-based

Studies in Norway found mixed effects on growth rates of salmon that were fed diets containing vegetable oil compared to fish oil. Average final body weights were similar in both diet types. Three Norwegian studies found fatty acid profiles in salmon flesh reflected oil source in diet. Vegetable oil in diets positively affected liver lipid content but negatively affected plasma lipoprotein levels. Two studies also found that n-3 highly unsaturated fatty acid levels were higher in salmon fed vegetable oil diets. A study in Norway found that oil source in diets did not affect salmon broodstock fecundity levels, egg weights, fertility rates, as well as the weights and development of resultant fry. A Scottish study found that salmon fed vegetable oil-based diets had lower levels of dioxin and polycarbonated biphenyls compared to those fed fish oil.

Use genetically modified alternatives

Studies in Norway found that feeds containing GM soybeans did not negatively affect growth rate or histology of the fish.

Use supplements

Studies in Australia and Norway found no effects of dietary supplementation of phytase and phosphate and taurine respectively on weight gain of Atlantic salmon. Another study in Australia found that fish fed diets supplemented with phytase has greater final weights than those given no supplement.

4.1 Reduce fish meal in diet

- Two replicated studies in Norway[1, 2] found similar final weights in salmon that were fed diets containing low, medium or high levels of fish meal.

Background

Aquaculture feeds were originally based on fish meal in order to provide salmon with the protein and oil sources they require. Removing this biomass from marine ecosystems impacts pelagic fisheries biodiversity which has top-down effects on ecosystems. By reducing the fish meal content, reliance on over-exploited, high-priced fish stocks is avoided. However, practitioners would expect this reduction to produce the same quality and quantity of salmon as fish meal protein.

In 2007, a replicated study in Norway (1) found similar final weights in salmon, *Salmo salar*, fed low, medium and high fish meal diets. Final weights of salmon in three groups fed diets containing 10%, 15% and 20% fish meal were 4.59kg, 4.63kg and

4.66kg, respectively. Fish were fed a diet containing 20% fish meal for six weeks before being fed one of the three experimental diets for 9 months. Weights were recorded.

Between 2007 and 2008, a replicated study in Norway (2) found similar final weights in salmon, *Salmo salar*, fed low, medium and high fish meal diets. Weights across all groups increased 4-fold from an average of 1,216g to 4,625g over 275 feeding days. Three experimental feeds were fed to fish; high-fish meal diet (20% of total feed ingredients), medium-fish meal diet (15% of total feed ingredients) and low-fish meal diet (10% of total feed ingredients). Salmon were stocked in 60m circular sea cages and fed using automated feeders for a period of 275 days. Weights were recorded.

1) Bendiksen, E. Å., Johnsen, C. A., Olsen, H. J. and Jobling, M. (2011). Sustainable aquafeeds: Progress towards reduced reliance upon marine ingredients in diets for farmed Atlantic salmon (*Salmo salar* L.). *Aquaculture*, **314**(1-4): 132-139.
2) Johnsen, C. A., Hagen, Ø. and Bendiksen, E. Å. (2011). Long-term effects of high-energy, low-fishmeal feeds on growth and flesh characteristics of Atlantic salmon (*Salmo salar* L.). *Aquaculture*, **312**(1-4): 109-116.

4.2 Use an alternative protein source: krill

- Two replicated studies in Norway[1, 2] found similar final weight gain between salmon that were fed diets containing fish meal only or a krill meal substitute. When the krill were de-shelled, growth rates were closer to salmon fed fish meal, compared to leaving the krill whole[2].
- Feed conversion ratios were found to be similar in both the fish meal and krill meal diets[1].
- The number of aerobic bacteria in the hindgut of salmon fed fish meal and krill meal were higher and composition of the bacterial flora was different[1].

Background

Aquaculture feeds were originally based on fish meal in order to provide salmon with the protein and oil sources they require. Removing this biomass from marine ecosystems impacts pelagic fisheries biodiversity which has top-down effects on ecosystems. By reducing the fish meal content and replacing it with krill, reliance on over-exploited, high-priced fish stocks is avoided. However, practitioners would expect alternative protein sources to produce at least the same quality and quantity of salmon as fish meal protein. Krill are highly productive with a high population turnover.

In 2002, a replicated, controlled study in Norway (1) found that salmon, *Salmo salar*, had similar final weights and feed conversion ratios when fed diets containing fish meal or fish meal and krill meal. Fish weighed an average of 105g at the start of the study and increased to 169.0g and 167.2 g in the fish meal and krill meal groups, respectively. Feed conversion ratios were 0.68 and 0.69, respectively. There was a difference in the composition and number of aerobic bacteria colonizing the hindgut of salmon between fish meal and krill meal diets (2.2×10^6 and 8.5×10^4, respectively). Salmon were fed either a diet containing fish meal as the protein source (58.9% of the diet) or a diet containing a 1:1 mix of fish meal and krill meal (64%) for 46 days. Three hundred salmon were stocked in 1.5 m^3 x 1.5 m^3 x 1m^3 fibreglass tanks for the duration of the experiment. On day 46, fish were anaesthetized and measured for weight and feed conversion.

A replicated study in Norway (2) found that salmon, *Salmo salar*, fed partially de-shelled krill meal had similar growth rates to those fed a whole krill meal diet. During the first 56 days, growth rates of 0.86% and 0.76% were recorded, respectively. Average final weights of salmon were 1060g, 1100g and 956g in fish fed diets containing fish meal, de-shelled krill and whole krill meal, respectively. Three diets were fed to 225 salmon for 100 days: a control diet based on high-quality fish meal or one of two experimental diets where the fish meal was substituted with either partially de-shelled or whole krill meal. Growth rates and final weights were recorded.

1) Ringø, E., Sperstad, S., Myklebust, R., Mayhew, T. M., Mjelde, A., Melle, W. and Olsen, R. E. (2006). The effect of dietary krill supplementation on epithelium-associated bacteria in the hindgut of Atlantic salmon (*Salmo salar* L.): a microbial and electron microscopical study. *Aquaculture Research*, **37**(16): 1644-1653.
2) Hansen, J. Ø., Penn, M., Øverland, M., Shearer, K. D., Krogdahl, Å., Mydland, L. T. and Storebakken, T. (2010). High inclusion of partially deshelled and whole krill meals in diets for Atlantic salmon (*Salmo salar*). *Aquaculture*, 310(1-2): 164-172.

4.3 Use an alternative protein source: bacteria

- Evidence for the effects of replacing fish meal with bacterial protein is mixed.
- Two replicated, controlled studies in Norway[1, 3] found similar growth rates in salmon fed either a 100% fish meal (control) diet or experimental diets containing up to 25% bacterial protein to replace fish meal. In the diet containing 50% bacterial protein, growth rates were lower compared to the control[1].
- Another replicated, controlled study reported higher growth rates in salmon that were fed diets containing 18% and 36% bacterial protein compared to the control or a diet containing 4.5% bacterial protein[2].

Background

Aquaculture feeds were originally based on fish meal in order to provide salmon with the protein and oil sources they require. Removing this biomass from marine ecosystems impacts pelagic fisheries biodiversity which has top-down effects on ecosystems. By reducing the fish meal content and replacing it with bacteria-produced protein, reliance on over-exploited, high-priced fish stocks is avoided. However, practitioners would expect alternative protein sources to produce at least the same quality and quantity of salmon as fish meal protein.

A controlled, replicated study in Norway (1) found mixed results when comparing growth rates in salmon fry, *Salmo salar*, fed diets containing 100% fish meal (control) compared to those fed experimental diets containing up to 50% bacterial protein as a fish meal replacement. After 112 days, fish fed a diet containing 6.25 % bacterial protein weighed more (3.69kg) than fish fed diets containing 12.5 %, 25 % and 50 % bacterial protein (3.24kg, 3.03kg and 2.63kg, respectively) or the control diet (3.44kg). From days 113 to 364, growth rates in fish fed the control diet and bacterial protein replacement diets up to 25% were similar. In the 50% replacement diet, growth rates were lower. Salmon were fed diets in which bacterial protein made up 6.25%, 12.5%, 25% and 50% of total dietary amino acids, replacing fish meal or a control diet made up of 100% fish meal. Each diet was fed to groups of salmon fry for 364 days and fish were weighed every 28 days.

A controlled, replicated study in Norway (2) found that salmon, *Salmo salar*, fed diets containing 18% and 36% bacterial protein had faster growth rates than those fed a 100% fish meal control diet or experimental diet containing 4.5% bacterial protein. Growth rates were 1.59, 1.56, 1.38 and 1.37, respectively). Salmon were fed diets in which bacterial protein made up 4.5%, 9%, 18% or 36% of the ingredients, replacing fish meal or a control diet made up of 100% fish meal. They were fed using automated feeders for 48 days. Weights were recorded.

A replicated, controlled, randomised study in Norway (3) found similar growth rates in salmon, *Salmo salar*, fed diets containing 10% and 20% bacterial protein compared to a 100% fish meal diet (control). Salmon weight in the three groups increased on average 3.6-3.9kg over the five month experiment. Three diets were fed to groups of 1,000 caged salmon (two groups per diet) in which bacterial protein grown on natural gas made up 10 or 20 % of the ingredients replacing fish meal. For the first two months, fish were fed by automated feeders four times a day for 30 minutes, followed by three meals a day for the rest of the experiment. Fish weights were recorded at 0, 2, 4 and 5 months.

1) Storebakken, T., Baeverfjord, G., Skrede, A., Olli, J.J. and Berge, G.M. (2004). Bacterial protein grown on natural gas in diets for Atlantic salmon, *Salmo salar*, in freshwater. *Aquaculture*, **241**(1-4): 413-425.
2) Aas, T.S., Grisdale-Helland, B., Terjesen, B.F. and Helland, S.J. (2006). Improved growth and nutrient utilisation in Atlantic salmon (*Salmo salar*) fed diets containing a bacterial protein meal. *Aquaculture*, **259**(1-4): 365-376.
3) Berg, A., Rødseth, O.M. and Hansen, T. (2007). Fish size at vaccination influence the development of side-effects in Atlantic salmon (*Salmo Salar* L.). *Aquaculture*, **265**(1-4): 9-15.

4.4 Use an alternative protein source: yeast

- One replicated, controlled experiment in Norway[1] found no differences in weight between Atlantic salmon that were fed diets containing the yeast *Yarrowia lipolytica* compared to a control diet containing fishmeal.

Background

Aquaculture feeds were originally based on fish meal in order to provide salmon with the protein and oil sources they require. Removing this biomass from marine ecosystems impacts pelagic fisheries biodiversity which has top-down effects on ecosystems. By reducing the fish meal content and replacing it with yeast- based protein, reliance on over-exploited, high-priced fish stocks is avoided. However, practitioners would expect alternative protein sources to produce at least the same quality and quantity of salmon as fish meal protein.

A replicated, controlled experiment in Norway (1) found no differences in weight between Atlantic salmon that were fed diets containing a heat killed dried yeast biomass from the yeast *Yarrowia lipolytica* or a control diet. The average fish weight increased from 179 to 419g across all groups during the experiment. Three experimental diets containing the yeast were fed to groups of Atlantic salmon and included a heat killed dried yeast biomass containing 6% eicosapentaenoic acid and 20% oil. The yeast biomass was included at three dietary levels; 10%, 20% and 30% of the diet. Another group was fed a control diet containing fishmeal, wheat gluten, rapeseed oil and wheat meal. Fish were kept in tanks containing 50 fish under continuous light and fed with automatic feeders. Fish were counted and bulk weighed at the start of the experiment, and after 27 days, 56 days and 95 days of feeding the experimental diets.

1) Hatlen, B., Berge, G.M., Odom, J.M., Mundheim, H. and Ruyter, B. (2012). Growth performance, feed utilisation and fatty acid deposition in Atlantic salmon, *Salmo salar* L., fed graded levels of high-lipid/high-EPA *Yarrowia lipolytica* biomass. *Aquaculture*, **364-365**: 39-47.

4.5 Use an alternative protein source: animal

- One study in Canada[1] found no difference in oxygen consumption or swimming speed of Atlantic salmon that were fed diets containing anchovy oil or alternative lipid sources.
- One study from Scotland[2] showed that fish fed a fishmeal diet weighed more than fish fed diets with alternative proteins.

Background

Aquaculture feeds were originally based on fish meal in order to provide salmon with the protein and oil sources they require. Removing this biomass from marine ecosystems impacts pelagic fisheries biodiversity which has top-down effects on ecosystems. By reducing the fish meal content and replacing it with terrestrial animal protein, reliance on over-exploited, high-priced fish stocks is avoided. Sources may include by-products of the meat processing industry. Practitioners would expect alternative protein sources to produce at least the same quality and quantity of salmon as fish meal protein.

A controlled, replicated study in British Columbia, Canada (1) found no differences in oxygen consumption or swimming speed of Atlantic salmon that were fed diets with different dietary lipid sources. There were similar swimming speeds (0.69- 0.76 m s^{-1}) and oxygen consumptions (MO_2 max 7.31± 0.24 mg O_2 kg^{-1} min^{-1}) for the five dietary treatments. Five experimental diets containing 45% protein and 26% lipid) were each fed to 150 Atlantic salmon (across three tanks) for 24 weeks. The control diet contained 100% anchovy oil and in three diets 75% of the anchovy oil was replaced by poultry fat, cold pressed flaxseed oil, or crude super de-gummed canola oil. The fifth diet contained a 1:1 blend of anchovy oil and poultry fat and the protein component was a 1:1 blend of fishmeal and poultry by-product meal. After 24 weeks on the experimental diets, ten fish of similar weight from each trial were tested by measuring oxygen consumption rates, prolonged swimming performance, and recovery from exhaustive exercise in a closed circuit respirometer over a seven week period.

Between 2007 and 2008, a controlled, randomised, replicated trial in Scotland (2) found that Atlantic salmon fed alternative protein to fishmeal had lower final weights than fish fed a fishmeal diet. The final weight of the groups fed fishmeal diets was 3.8kg compared to between 3.4 and 3.6kg in fish fed alternative protein diets. Five diets were formulated to satisfy the nutritional requirements of salmonid fish; the four experimental diets contained 11% fishmeal and 55% of either wheat gluten, pea protein, blood meal or kidney bean. A control diet containing 25% fish meal was also given to one group. Two thousand two hundred and fifty Atlantic salmon were fed the experimental diets by automatic feeders for nineteen weeks.

1) Wilson, C. M., Friesen, E. N., Higgs, D. A. and Farrell, A. P. (2007). The effect of dietary lipid and protein source on the swimming performance, recovery ability and oxygen consumption of Atlantic salmon (*Salmo salar*). *Aquaculture*, **273**(4): 687-699.
2) Pratoomyot, J., Bendiksen, E. Å., Campbell, P. J., Jauncey, K. J., Bell, J. G. and Tocher, D. R. (2011). Effects of different blends of protein sources as alternatives to dietary fishmeal on growth performance and body lipid composition of Atlantic salmon (*Salmo salar* L.). *Aquaculture*, 316(1-4): 44-52.

4.6 Use an alternative protein source: plant-based

- Four studies from Norway[1, 3, 4, 9], a study from Scotland[8] and study from the USA[11] found that inclusion of plant-based proteins within feed led to decreased growth rates in salmon. Three studies from Norway[2], Canada[5] and Scotland[6] found similar growth rates in salmon fed either plant-based or fish meal diets.
- Three studies from Norway[4, 9, 10] and a study from Scotland[8] found reduced final body weights in salmon fed plant-based protein diets compared to fish meal-based diets. Two studies from Norway[2, 7] found similar final body weights in salmon fed either plant-based or fish meal diets.
- Two studies from Norway[1, 9] found lowered levels of feeding efficiency, whereas another Norwegian study[3] found increased levels of feeding efficiency in salmon fed plant-based protein diets compared to fish meal diets. A Canadian and Scottish study[5, 6] found similar levels of feeding efficiency across both diet types.

- Digestibility of feed components by salmon was found to be lower in two studies[4, 9] when the diets contained plant proteins compared to fish meal. Similar levels of digestibility across both diet types were identified by a Scottish[8] and Norwegian[10] study.
- Survival rates and appetite were not affected by plant- or fish meal-based protein diets[2, 6]. However morphology of the distal intestine was altered in two studies where salmon were fed diets containing plant-based proteins[8, 9]. Condition of the salmon was increased in plant-based protein diets in one study[4] but reduced in two other studies[1, 6].

Background

Aquaculture feeds were originally based on fish meal in order to provide salmon with the protein and oil sources they require. Removing this biomass from marine ecosystems impacts pelagic fisheries biodiversity which has top-down effects on ecosystems. By reducing the fish meal content and replacing it with plant-based protein sources, reliance on over-exploited, high-priced fish stocks is avoided. However, practitioners would expect alternative protein sources to produce at least the same quality and quantity of salmon as fish meal protein. Fish meal replacements include full-fat soybean meal, maize gluten meal, low SGA potato protein, sunflower meal and pea protein concentrate.

A replicated, controlled study in Norway comprised of two salmon, *Salmo salar*, feed trials (1). In trial one the digestibility of crude protein from fish meal, full-fat soybean meal and maize gluten meal were similar at 89.3%, 76.9% and 87.0%, respectively. In trial two, increasing levels of fish meal substitution by plant-based protein led to a decrease in growth rates, protein digestibility and salmon condition. Additionally, the feed conversion ratio increased. Therefore salmon that were fed diets containing the highest levels of plant protein required 50g more feed to gain 1kg of weight. Trial one was conducted over 14 days. Groups of salmon were fed one of four different diets: a reference diet containing 89% fish meal and three experimental diets where 45 % of the reference diet was substituted by fish meal, full-fat soybean meal and maize gluten meal. Digestibility of protein was determined. Trial two was conducted over 104 days. Three diets were formulated that fish meal with a combination of full-fat soybean meal and maize gluten meal. Fish meal derived crude protein content in the three diets was 89%, 65% and 40% respectively. Eighty salmon were present in each treatment tank and were fed by automatic feeders under controlled environmental conditions. Growth rates and digestibility were measured.

A randomised, controlled study in Norway (2) found that salmon, *Salmo salar*, fed diets containing a mix of fish-meal, wheat and low SGA potato protein concentrate grew at similar rates to salmon that were fed diets of fish meal and wheat. At the end of the experiment average final body weights ranged from 249-256g across all groups. In addition, food intake and feed conversion ratio were not adversely affected. Over 84 days, groups of salmon were fed one of four experimental diets: 0% SGA potato protein concentrate (fish meal control diet) and increments of 7%, 14% and 21% SGA potato protein concentrate. Fish were fed using automated feeders under controlled environmental conditions. Growth rate was measured.

A randomised, replicated study in Norway (3) found lower final average body weights when salmon, *Salmo salar*, were fed diets containing reduced fish meal content, replaced with a vegetable protein blend. Salmon fed 34.7% fish meal were 13.3% lighter than those fed 85.1% fish meal. Growth rates, feeding efficiency and digestibility of protein also decreased with increasing percentages of vegetable protein. Feed intake was higher when food contained a lower proportion of fish meal. Salmon were fed eight diets (four high and four lower quality fish meal) where the percentage of fish meal to vegetable protein was either 85.1%, 68.6%, 51.9% or 34.7%. The vegetable protein blend was composed of full-fat soybean meal and maize gluten meal at a ratio of 1:2. Fish were fed for 11 weeks using automated feeders under controlled environmental conditions. Final body weight, growth rates, feeding efficiency and protein digestibility were measured.

In 2002, a randomised, replicated, controlled study in Norway (4) identified slower growth rates in salmon, *Salmo salar*, fed three plant-based protein diets compared to a control diet containing fish meal. This was attributed to a reduced intake of the plant-based feed. Feed conversion ratios did not differ. Flesh fat content was higher in salmon fed the fish meal-based diets. Over three months, groups of 40 salmon were fed one of four diets: a reference diet containing 49% fish meal and three diets containing 5% solubilised fish protein and different levels of plant protein coming from plants. Growth rates were 0.97, 0.87, 0.86 and 0.87, respectively. Salmon were fed using automated feeders. Growth rates, feed conversion ratios and flesh fat content were measured.

A randomised, replicated, controlled study in Canada (5) found similar growth and survival rates and feed efficiency between groups of fingerling salmon, *Salmo salar*, fed diets containing fish meal compared with diets containing sunflower meal. Growth rates were, on average, 1.39-1.45% per day. Average survival rates were 96.0-99.3% and average feed efficiency was 1.19-1.26. Groups of 50 fingerling salmon were fed one of four experimental diets containing 8.25%, 16.5%, 24.75% or 33% of sunflower meal. A control diet was given to a fifth group of fish containing 68.2% low-temperature dried anchovy (fish) meal. Squid meal (70g per kg) and Finnstim™ (10g per kg) were incorporated into each diet to reduce problems associated with palatability. Salmon were fed for 84 days and were weighed on day 0, 42 and 84.

Between 2002 and 2003, a randomised, replicated study in Scotland (6) found that diets containing maize- and pea-based protein plus carbohydrates (to replace fish oil) achieved similar growth rates in salmon smolts, *Salmo salar*. Over 377 days, fish across all groups grew from an average 52g to between 1.9kg and 2.5kg. Salmon smolts fed low-energy feeds (containing less fish oil and more carbohydrate) had a lower body condition compared with those fed high-energy feeds (containing more fish oil and less carbohydrates). Nine experimental diets were produced containing different levels of vegetable protein, carbohydrate and fish oil. Groups of salmon smolts were fed one of the experimental diets for 377 days during their marine grow-out phase. Fish were fed using automated feeders. Growth rates, weights and body condition were measured.

A replicated, controlled study in Norway (7) found similar levels of weight gain and feed intake in salmon, *Salmo salar*, fed diets containing fish meal, soybean meal or pea protein concentrate mixed with crude protein. Weight gain ranged from 228g to 274g in salmon fed the control and vegetable protein diets. Levels of protein, fat, starch and essential amino acid digestibility were similar between the control and pea protein diets. However, the soybean meal diet had a reduced digestibility in comparison and induced morphological change in the distal intestine. Over twelve weeks, 600 salmon were fed the experimental diets using automated feeders. One group was fed a control diet based on high quality fish meal. The other diets contained either 200g per kg soybean meal or 200g per kg pea protein concentrate mixed with 350 or 500g per kg crude protein. Final body weights and digestibility of feed components were measured.

Between 2007 and 2008, a randomised, replicated and controlled study in Scotland (8) found salmon, *Salmo salar*, fed three plant-based protein diets had lower growth rates and final body weights compared to those fed a high fish meal content diet. Growth rates were reduced by between 5-23% in the plant-based protein diets when compared to the high fish meal diet. After 19 weeks, the overall average weight gain within the plant-protein diets were between 1.67-2.08kg compared to 2.53kg in the high fish meal diet. Differences were attributed to decreased food intake. Over 19 weeks 1,800 salmon were fed a high fish meal diet (55%) or one of three experimental plant protein diets, containing between 50% and 60% plant protein. Growth rates and final body weights were measured.

A replicated, controlled study in Norway (9) found lower growth rates and weight gain in salmon (*Salmo salar*) fed diets containing plant-based protein sources compared to a fish meal diet (control). Salmon fed the maize and pea protein diets showed lower specific growth rates of 0.53 and 0.56, compared to the control diet (0.63). Feed conversion ratio was highest in fish receiving the maize or pea protein diets and final average weight gain was highest in the control group (1.05kg) compared to fish fed with soybean protein (0.96kg), maize gluten (0.85kg), pea protein (0.94kg) and a plant-based combination diet (1.01kg). Fat digestibility was highest in the fish meal diet, however protein digestibility was the same across all diets. High inclusion of pea protein inflamed the distal intestine in a similar manner to soy enteritis. Over eight weeks, five diets were fed to salmon. The control diet was based on fish meal (250g per kg). Three low fish meal diets (100g per kg) contained either 350g per kg pea protein concentrate, 300g per kg soybean protein concentrate or 300g per kg maize gluten. A further low fish meal combination diet comprised of 130g per kg pea protein concentrate, 105g per kg soybean protein concentrate and 105 g per kg maize gluten. Growth rates, final body weight, digestibility and morphological parameters were measured.

A randomised, replicated, controlled study in Norway (10) found salmon, *Salmo salar*, fed soybean meal diets (positive control) had a higher food conversion ratio and lower weight gain than those fed pure fish meal (negative control) or fish meal plus supplements (experimental diets). Average weight gain in the group fed soybean meal was 142kg compared to the negative control diet (237kg) or supplemented diets (180-214kg). The supplemented diets did not interfere with fat or protein digestibility and no morphological changes were recorded in the distal intestine. Over 68 days, groups of salmon were fed one of six diets. These comprised a negative control fish meal diet, a positive control soybean meal diet and one of four diets based on the negative control diet and added supplements (raffinose, stachyose, a combination of raffinose and stachyose and the same combination further supplemented with soya-saponins). Feed conversion ratios, final body weight, fat and protein digestibility and morphological changes were measured.

A controlled study comprising of two trials in the USA (11) found varied results in final body weight when feeding different stage fingerling salmon, *Salmo salar*, plant-based protein diets compared to a fish meal control. Trial one found early stage fingerlings fed a plant protein diet had lower average final body weights (19.23-22.97g) compared to the control (27.29g). Trial two found that late stage fingerlings had similar final average body weights across all diets. Survival rates ranged from 92.4-96.3% and were similar across all treatment groups. In trial one, 50 early stage fingerling salmon were fed six experimental diets prepared using plant protein blends (soybean, maize gluten, wheat gluten). Plant protein was added to five diets in increasing increments (50%, 66% and 84%) to substitute fish meal. The control diet contained fish meal only. Feeding took place over 18 weeks, using automated feeders. In trial two, 112 late stage fingerling salmon were fed diets containing 100% plant protein blend for 12 weeks. All fish were bulk weighed and counted every four weeks during the study.

1) Opstvedt, J., Aksnes, A., Hope, B. and Pike, I. H. (2003). Efficiency of feed utilization in Atlantic salmon (*Salmo salar* L.) fed diets with increasing substitution of fish meal with vegetable proteins. *Aquaculture*, **221**(1-4): 365-379.
2) Refstie, S. and Tiekstra, H. A. J. (2003). Potato protein concentrate with low content of solanidine glycoalkaloids in diets for Atlantic salmon (*Salmo salar*). *Aquaculture*, **216**: 283- 298.
3) Mundheim, H., Aksnes, A.and Hope, B. (2004). Growth, feed efficiency and digestibility in salmon (*Salmo salar* L.) fed different dietary proportions of vegetable protein sources in combination with two fish meal qualities. *Aquaculture*, **237**(1-4): 315-331.
4) Espe, M., Lemme, A., Petri, A. and El-Mowafi, A. (2006). Can Atlantic salmon (*Salmo salar*) grow on diets devoid of fish meal? *Aquaculture*, **255**(1-4): 255-262.
5) Gill, N., Higgs, D.A., Skura, B.J., Rowshandeli, M., Dosanjh, B.S., Mann, J. and Gannam, A.L. (2006). Nutritive value of partially dehulled and extruded sunflower meal for post-smolt Atlantic salmon (*Salmo salar* L.) in sea water. *Aquaculture Research*, **37**(13): 1348-1359.
6) Young, A., Morris, P. C., Huntingford, F. A. and Sinnott, R. (2006). Replacing fish oil with pre-extruded carbohydrate in diets for Atlantic salmon, *Salmo salar*, during their entire marine grow-out phase: Effects on growth, composition and colour. *Aquaculture*, **253**(1-4): 531-546.
7) Øverland, M., Sørensen, M., Storebakken, T., Penn, M., Krogdahl, Å. and Skrede, A. (2009). Pea protein concentrate substituting fish meal or soybean meal in diets for Atlantic salmon (*Salmo salar*)—Effect on growth performance, nutrient digestibility, carcass composition, gut health, and physical feed quality. *Aquaculture*, **288**(3-4): 305-311.
8) Pratoomyot, J., Bendiksen, E. Å., Bell, J. G. and Tocher, D. R. (2010). Effects of increasing replacement of dietary fishmeal with plant protein sources on growth performance and body lipid composition of Atlantic salmon (*Salmo salar* L.). *Aquaculture*, **305**(1-4): 124-132.
9) Penn, M. H., Bendiksen, E. Å., Campbell, P. and Krogdahl, Å. (2011). High level of dietary pea protein concentrate induces enteropathy in Atlantic salmon (*Salmo salar* L.). *Aquaculture*, **310**(3-4): 267-273.

10) Sørensen, M., Penn, M., El-Mowafi, A., Storebakken, T., Chunfang, C., Øverland, M. and Krogdahl, Å. (2011). Effect of stachyose, raffinose and soya-saponins supplementation on nutrient digestibility, digestive enzymes, gut morphology and growth performance in Atlantic salmon (*Salmo salar*, L). *Aquaculture*, **314**(1-4): 145-152.
11) Burr, G. S., Wolters, W. R., Barrows, F. T. and Hardy, R.W. (2012). Replacing fishmeal with blends of alternative proteins on growth performance of rainbow trout (*Oncorhynchus mykiss*), and early or late stage juvenile Atlantic salmon (*Salmo salar*). *Aquaculture*, **334-337**: 110-116.

4.7 Use an alternative oil source: plant-based

- Three replicated studies in Norway[1, 5, 8] found growth rates were similar in salmon that were fed diets containing fish oil and vegetable oil. One replicated Norwegian study found growth rates were higher in fish fed diets containing vegetable oil[10]. Another study[9] found salmon growth rates were both lower and higher in vegetable oil diets compared to fish oil diets, dependant on family genetics.
- Two replicated studies in Norway[5, 6] found similar average final body weights between groups of salmon fed both fish oil and vegetable oil diets.
- Three studies[3, 4, 5] found that the fatty acid profile of salmon flesh reflected oil source within diets.
- A study in Norway[3] found that oil source in diets did not affect salmon broodstock fecundity levels, egg weights, fertility rates, as well as the weights and development of resultant fry.
- One replicated Norwegian study[9] found that salmon fed vegetable oil diets had high liver lipid and low plasma lipoprotein compared to the fish oil diet. Another study[8] found high levels of n-3 highly unsaturated fatty acids compared to diets containing rapeseed oil.
- A Scottish study[2] found salmon fed vegetable oil-based diets had lower concentrations of dioxin and polychlorinated biphenyls within flesh, compared with diets containing fish oil.
- A replicated study in Norway[4] found that fresh, frozen and smoked salmon flesh from fish fed vegetable oil- and fish oil-based diets had similar levels of gaping, texture and liquid holding capacity. Pigment concentration was lower in vegetable oil diets.

Background

Aquaculture feeds were originally based on fish meal and fish oil in order to provide salmon with the protein and oil sources they require. Removing this biomass from marine ecosystems impacts pelagic fisheries biodiversity which has top-down effects on ecosystems. By reducing the fish oil content and replacing it with plant-based oil sources, reliance on over-exploited, high-priced fish stocks to produce fish oil is mitigated. However, practitioners would expect alternative oil sources to produce at least the same quality and quantity of salmon as fish oil. Palm oil, rapeseed oil, linseed oil and soybean oil are examples of possible plant-based (vegetable oil) sources.

In 2002, a randomised, replicated study in Norway (1) found there were similar growth rates and feeding efficiency in salmon, *Salmo salar*, fed one of two experimental diets containing different blends of fish oil, palm oil and rapeseed oil. Both experimental diets contained 50 % fish oil with either 10 % or 25 % palm oil. Rapeseed oil made up the remainder of the oil in the diet. Over 12 weeks, 880 salmon were fed one of the experimental diets. Growth rates and feeding efficiency were measured.

Between 2000 and 2002, a replicated, controlled study in Scotland (2) found salmon, *Salmo salar*, fed diets containing low fish oil, and low-high vegetable oil concentrations had lower levels of dioxin and polychlorinated biphenyls within flesh. This was in comparison to feeds containing high fish oil concentration. The highest dioxin and PCB flesh concentrations in salmon fed the high fish oil diet was 0.53 ng TEQ per kg and 1.48 ng TEQ per kg, respectively. The lowest dioxin and PCB flesh concentrations in salmon fed the high vegetable oil diet was 0.10 ng TEQ per kg and 0.58 ng TEQ per kg, respectively. Over 115 weeks, salmon were fed one of four diets comprised of low fish oil (17%), high fish oil (35%), low vegetable oil (17% linseed and rapeseed oil) and high vegetable oil (35% linseed and rapeseed oil).

Between 2002 and 2003, a study in Norway (3) found that salmon, *Salmo salar*, broodstock fed diets containing pure fish oil and a mix of fish and rapeseed oil had similar levels of adult fecundity, egg weights plus development and body weight in resultant fry. The fatty acid profiles of both the eggs and fry reflected the oil source and were different. Rates of fertilisation, eyeing and hatching plus fry survival to first feeding were similar between diets. Approximately 315 salmon were tagged and distributed across three sea cages. One cage was fed a broodstock diet containing 100 % fish oil. The other two cages were fed a diet containing 50% fish oil and 50% rapeseed oil. Fish were weighed intermittently. Fecundity and egg weights were measured in mature salmon transferred to fresh water. Eggs were fertilised using a pool of milt from three males of the same treatment. Pre-fertilised eggs and fry underwent fatty acid chemical analysis. Rates of fertilisation were recorded, alongside eyeing, hatching and survival rates in the fry.

A randomised, replicated study in Norway (4) found similar growth rates in salmon, *Salmo salar*, fed diets containing either 29% fish oil or 29% soybean oil. Muscle fatty acid profile reflected dietary oil source with malondialdehyde being four times higher in the fish oil diet. Pigment concentration was lower in salmon fed the soybean oil diet. Gaping, texture and liquid holding capacity of fresh, frozen and smoked muscle was similar between diets. A consumer panel detected no differences between dietary treatments and end products. Three groups of 400 salmon were fed one of two experimental diets for 120 days. Diets contained either 29% fish oil or 29% soybean oil and were identical in composition otherwise. Chemical analyses were conducted on fresh muscle. Colour, texture and LHC analyses were performed on fresh, frozen and smoked muscle.

Between 2002 and 2004, a replicated, controlled study comprising two trials in Scotland and Norway (5) found salmon, *Salmo salar*, fed fish oil and vegetable oil diets had different fatty acid compositions within flesh that reflected oil source. However, final body weights were similar (2.5kg on average). Growth rates were similar between diets. It was calculated a 200 g portion of salmon fed 75% vegetable oil would meet 80% of the recommended weekly human intake for very long chain n-3 polyunsaturated fatty acids. Groups of salmon juveniles were fed diets containing 100% fish oil, 75%

vegetable oil or 100% vegetable oil, followed by a finishing diet period when all groups were fed 100% fish oil. The vegetable oil was composed of blended rapeseed, palm and linseed oil. The trials were conducted over 22 months in Norway and 25 months in Scotland.

Between 2002 and 2004, a replicated study in Norway (6) found that liver lipid and plasma lipoprotein levels were affected when salmon, *Salmo salar*, were fed vegetable oil-based diets as a complete replacement for fish oil. Salmon weights were similar and increased from 890g to 2.3kg and 2.7kg in the fish oil and vegetable oil groups, respectively. Lipid liver stores were higher in fish fed the vegetable oil diet after 14 and 22 months of feeding. In contrast, plasma lipid levels were lower. Over 22 months, 2,000 salmon juveniles were fed diets containing either 100% fish oil or 100 % vegetable oil (comprising 55 % rapeseed oil, 30 % palm oil and 15 % linseed oil). Fish meal was used as a protein source. Fish were weighed at 0, 6, 9, 14 and 16 months. Liver and plasma were analysed for lipid and lipoprotein content.

In 2005, a randomised study in Scotland (7) found that salmon, *Salmo salar*, fed diets containing vegetable oil had lower proportions of n-3 highly unsaturated fatty acids than diets containing fish oil. Flesh from salmon fed the fish oil diets contained 26.0% of n-3 highly unsaturated fatty acids compared to 17.7% in vegetable oil fed fish. HUFA is essential for protecting humans from cardiovascular disease. Over 12 weeks, groups of 30 salmon were fed diets containing either 100% fish oil or vegetable oil (comprised of rapeseed, linseed and palm oils at a 2:2:1 ratio). Flesh was analysed for n-3 highly unsaturated fatty acid content.

A replicated, controlled study in Norway (8) found salmon, *Salmo salar*, fed fish oil, decontaminated fish oil and different vegetable oil diets had similar growth rates and final average body weights. In terms of n-3 highly unsaturated fatty acids, essential to humans for protecting against cardiovascular disease, soybean-based vegetable oil produced higher levels in salmon flesh compared to rapeseed oil. One of five experimental diets were fed to groups of 120 salmon for 10 weeks: 100% fish oil, 100% decontaminated fish oil and three different of vegetable/fish oil blends (using soybean or rapeseed oil). Growth rates and n-3 highly unsaturated fatty acid content were measured.

In 2010, a replicated study in Norway (9) found that salmon, Salmo salar, with different breed characteristics (fat and lean flesh) had different growth rates and flesh lipid content from each other and the control group, dependant on whether they were fed fish or vegetable oil diets. Growth rates ranged from 0.89 in the fat group fed the 100% vegetable oil diet to 1.01 in the control group fed the same diet. Flesh lipid levels were in the order fat>control>lean in diets containing 100% fish oil and fat=lean>control in diets containing 100% vegetable oil. It was calculated that a 140g portion of fish oil-fed salmon would provide 63–76% of the recommended weekly human intake of n-3 PUFA, while the vegetable oil-fed salmon would provide 46–61% of this value. Over 55 weeks, three groups of trait-bred salmon smolts were grown on diets with reduced fish meal that contained either 100% fish oil or vegetable oil (comprised of rapeseed, palm and *Camelina* oils in a ratio of 5:3:2). After a 15 week finishing diet, flesh lipid content was analysed. Growth rates were also measured over the course of the study.

A replicated study in Norway (10) found that salmon, *Salmo salar*, fed diets containing rapeseed oil had higher growth rates and average final body weights compared to those fed diets containing fish oil. Growth rates were 0.94 and 0.87, respectively. Average final weights were 3.64kg and 3.34kg, respectively. Protein content did not affect growth parameters. Six experimental diets were fed to salmon over a 10 week period. Three contained high, medium and low protein content and 100% fish oil. Three contained high, medium and low protein content and 100% rapeseed oil. The protein/lipid contents were high: 350g per kg/350g per kg, medium: 330g per kg/360g per kg and low: 290g per kg/380g per kg. Growth rates and final body weights were measured.

1) Ng, W.-K., Sigholt, T. and Gordon Bell, J. (2004). The influence of environmental temperature on the apparent nutrient and fatty acid digestibility in Atlantic salmon (*Salmo salar* L.) fed finishing diets containing different blends of fish oil, rapeseed oil and palm oil. *Aquaculture Research*, **35**(13): 1228-1237.
2) Bell, J.G., McGhee, F., Dick, J.R. and Tocher, D.R. (2005). Dioxin and dioxin-like polychlorinated biphenyls (PCBs) in Scottish farmed salmon (*Salmo salar*): effects of replacement of dietary marine fish oil with vegetable oils. *Aquaculture*, **243**(1-4): 305-314.
3) Rennie, S., Huntingford, F.A., Loeland, A.-L. and Rimbach, M. (2005). Long term partial replacement of dietary fish oil with rapeseed oil; effects on egg quality of Atlantic salmon *Salmo salar*. *Aquaculture*, 248(1-4): 135-146.
4) Rora, A. M. B., Ruyter, B., Skorve, J., Berge, R. K. and Slinning, K.-E. (2005). Influence of high content of dietary soybean oil on quality of large fresh, smoked and frozen Atlantic salmon (*Salmo salar*). *Aquaculture International*, **13**(3): 217-231.
5) Torstensen, B.E., Bell, J. G., Rosenlund, G., Henderson, R. J., Graff, I.E., Tocher, D.R., Lie, O. and Sargent, J. R. (2005). Tailoring of Atlantic Salmon (*Salmo salar* L.) Flesh Lipid Composition and Sensory Quality by Replacing Fish Oil with a Vegetable Oil Blend. *Journal of Agricultural and Food Chemistry*, **53**: 10166- 10178.
6) Jordal, A.-E.O., Lie, O. and Torstensen, B.E. (2007). Complete replacement of dietary fish oil with a vegetable oil blend affect liver lipid and plasma lipoprotein levels in Atlantic salmon (*Salmo salar* L.). *Aquaculture Nutrition*, **13**: 114- 130.
7) Schlechtriem, C., Bron, J.E. and Tocher, D.R. (2007). Inter-individual variation in total fatty acid compositions of flesh of Atlantic salmon smolts-fed diets containing fish oil or vegetable oil. *Aquaculture Research*, **38**(10): 1045-1055.
8) Pratoomyot, J., Bendiksen, E.Å., Bell, J.G. and Tocher, D.R. (2008). Comparison of effects of vegetable oils blended with southern hemisphere fish oil and decontaminated northern hemisphere fish oil on growth performance, composition and gene expression in Atlantic salmon (Salmo salar L.). *Aquaculture*, **280**(1-4): 170-178.
9) Bell, J. G., Pratoomyot, J., Strachan, F., Henderson, R. J., Fontanillas, R., Hebard, A., Guy, D. R., Hunter, D. and Tocher, D. R. (2010). Growth, flesh adiposity and fatty acid composition of Atlantic salmon (*Salmo salar*) families with contrasting flesh adiposity: Effects of replacement of dietary fish oil with vegetable oils. *Aquaculture*, **306**(1-4): 225-232.
10) Karalazos, V., Bendiksen E. Å. and Bell J.G. (2011). Interactive effects of dietary protein/lipid level and oil source on growth, feed utilisation and nutrient and fatty acid digestibility of Atlantic salmon. *Aquaculture*, 311(1-4): 193-200.

4.8 Use genetically modified alternatives

- Three studies in Norway[1, 2, 4] found no difference in growth rate of Atlantic salmon that were fed diets containing either GM or non- GM soybeans. One study in Norway[3] found no differences in fish fed diets containing either GM or non- GM soybeans on the histology of the fish.

Background

Aquaculture feeds were originally based on fish meal and fish oil in order to provide salmon with the protein and oil sources they require. Future demand for feed from the aquaculture industry will require an environmentally and economically sustainable alternative to fishmeal. Soybean, the source for an alternative plant based protein has GM varieties that could be incorporated into feeds. GM feeds are not common in European aquaculture and there is scepticism about GM fed salmon as regards to consumer safety.

A randomised, replicated, controlled experiment in Norway (1) found similar growth rates and final body weights in salmon, *Salmo salar*, fed diets containing non-genetically modified soybean, genetically modified soybean or fish meal diets. Average body weight increased from 135g to 500g over a three month period. A lower condition factor was detected in salmon fed the control fish meal diet (1.35) compared with the genetically modified soybean (1.37). Over 12 weeks, 1,200 smolt salmon were fed one of three diets for 12 weeks using automated feeders: a diet containing non-genetically modified soybean, genetically modified soybean or a standard fish meal diet. Soybean is a replacement protein for fish meal. Growth rates and weights were measured at the start of the experiment then after 6 and 12 weeks.

In 2007, a randomised, replicated, controlled study in Norway (2) found similarities in survivorship, growth rates and histology between salmon, *Salmar salar*, fed non-genetically modified and genetically modified soybean diets to replace fish meal. Histological examination of the stomach, pyloric caeca, mid-intestine, liver, spleen, kidney, thymus, brain and muscle tissue revealed no differences that could be attributed to feed composition. For 3 months, groups of salmon were fed one of three diets containing 172g per kilogram genetically modified full-fat soybean meal, an unmodified soybean meal or a reference (control) diet with fish meal as the protein source. Fish were acclimatised for 6 weeks before being fed the experimental diets using automatic feeders. Seven fish were randomly sampled from each tank after 12 weeks for sampling. Survivorship and growth rates were measured and histology investigated.

In 2007, a randomised, replicated, controlled study in Norway (3) found no effects on the histology of salmon, *Salmo salar*, fed diets containing genetically-modified maize and soybean as a substitute protein source for fish meal. Histological examination of the stomach, diffuse pancreatic tissue adjacent to the pyloric caeca, liver, spleen, kidney or thymus that could be attributed to feed composition. Over eight months, fingerling salmon were fed one of seven diets containing maize (two genetically-modified and two standard varieties), soybean (one genetically-modified and one standard variety) and a standard fish meal diet. Fish were removed from tanks were taken for histological screening. The Atlantic salmon used within the experiment were at the parr- smolt transformation stage.

A controlled, replicated study in Western Norway (4) found similar overall in final weight and growth rate between Atlantic salmon that were fed diets containing genetically modified and non- genetically modified soybeans. However, one of four sampling periods found that growth rate was lower in genetically modified fed fish (0.74 compared to 0.85). Another sampling period found the genetically modified fed fish to be heavier (98.3g) compared to the salmon fed standard soybean meal (93.5g). Over seven months, salmon (average initial weight 40g) going through the parr–smolt transformation, were fed experimental diets: a non-genetically modified soybean diet (control) and two diets with genetically modified soybean meal included at a 25% and 26.2% level. Fish meal was the main source of protein in the diets. Growth rates and weights were measured. The trial began in July with four experimental sampling dates in September, December and the beginning and end of February.

1) Hemre, G.I., Sanden, M., Bakke- McKellop, A.M., Sagstad, A. and Krogdahl, Å. (2005). Growth, feed utilization and health of Atlantic salmon *Salmo salar* L. fed genetically modified compared to non-modified commercial hybrid soybeans. *Aquaculture Nutrition*, **11**: 157- 167.
2) Bakke- McKellop, A. M., Koppang, E. O., Gunnes, G., Sanden, M., Hemre, G. I., Landsverk, T. and Krogdahl, Å. (2007). Histological, digestive, metabolic, hormonal and some immune factor responses in Atlantic salmon, *Salmo salar* L., fed genetically modified soybeans. *Journal of Fish Diseases*, **30**: 65-79.
3) Bakke-McKellep, A. M., Sanden, M., Danieli, A., Acierno, R., Hemre, G. I., Maffia, M. and Krogdahl, Å. (2008). Atlantic salmon (*Salmo salar* L.) parr fed genetically modified soybeans and maize: Histological, digestive, metabolic, and immunological investigations. *Research in Veterinary Science*, **84**(3): 395-408.
4) Sissener, N. H., Sanden, M., Bakke, A. M., Krogdahl, Å. and Hemre, G. I. (2009). A long term trial with Atlantic salmon (*Salmo salar* L.) fed genetically modified soy; focusing general health and performance before, during and after the parr–smolt transformation. *Aquaculture*, **294**(1-2): 108-117.

4.9 Use supplements

- A study in Australia[1] found no difference in weight gain of Atlantic salmon with and without dietary supplementation of phytase and phosphate.
- In another Australian study[2] fish fed diets supplemented with phytase had greater final weights than those given no supplement.
- A study in Norway found no difference in weight gain of salmon that were fed diets with or without taurine supplementation.

Background

Aquaculture feeds were originally based on fish meal and fish oil in order to provide salmon with the protein and oil sources they require. There is concern that fish fed plant based diets as an alternative to fishmeal show reduced performance compared to those fed a marine based diet. Supplements can affect feed intake, digestion and retention of nutrients in fish and can be given as a pre- treatment or included within diets. The addition of supplements to plant based diets can increase the nutritional quality to be more comparable with marine based diets.

A controlled, replicated study in Tasmania, Australia (1) found similar levels of weight gain and feed intake of Atlantic salmon that were fed diets with or without phytase and phosphate supplementation. Weight gain over the experiment was between 192.3 and 220.3 g per fish. Total feed intake was between 3.88 and 4.39 kg per salmon. Four diets were fed to groups of Atlantic salmon for 12 weeks; one diet with no phytase or inorganic phosphorus supplementation, one diet with phytase, one diet with supplemental inorganic phosphorus and one with both phytase and supplemental inorganic phosphorus. The diets were canola meal protein based with reduced fishmeal and were not commercial diets. Twenty fish per tank were fed one of the experimental diets (3 tanks for each diet treatment) and anaesthetised, counted and bulk-weighed every 3 weeks.

A controlled, replicated study in Tasmania, Australia (2) found that Atlantic salmon fed soy protein diets with at least 4000 units per kg of phytase had higher average final body weight (93.49g) than those fed an un-supplemented controlled diet (82.35g). Average final body weights were similar in diets supplemented with 250 and 1,000 units per kg (84.32-89.1g). Percentage survival was not significantly different between treatments (96–100%). Groups of salmon were fed one of four experimental diets and a control diet for a 12 week period. Phytase was added at levels of 250, 500, 1,000 or 4,000 units per kg to salmon diets that had low fish meal content (4.5%) and contained 60% soy protein concentrate. Fish were bulk weighed every three weeks throughout this time.

A controlled, replicated experiment in Norway (3) found that fingerling Atlantic salmon fed low fishmeal diets with and without taurine supplementation had lower average weight gain (12.8 and 13.5g per fish) than fish fed a control fish meal diet (17.5g per fish). Growth in salmon given the low fish meal, supplemented diet was about 75% of the growth in fish fed the control diet. Over 56 days, 2,250 fingerling salmon were fed either plant protein-based low fish meal diets (16.5% fish meal) with or without taurine supplementation (0 or 0.1% taurine) or a control high fish meal diet (65% fishmeal). Both low fishmeal diets were supplemented with 1% krill meal to aid palatability. Salmon were fed by automated feeders and weighed at the start and end of the experiment.

1) Sajjadi, M. and C. G. Carter (2004). Dietary phytase supplementation and the utilisation of phosphorus by Atlantic salmon (*Salmo salar* L.) fed a canola-meal-based diet. *Aquaculture*, 240(1-4), 417-431.
2) Carter, C. G. and Sajjadi, M. (2010). Low fishmeal diets for Atlantic salmon, *Salmo salar* L., using soy protein concentrate treated with graded levels of phytase. *Aquaculture International*, **19**(3), 431-444.
3) Espe, M., Ruohonen, K. and El-Mowafi, A. (2012). Effect of taurine supplementation on the metabolism and body lipid-to-protein ratio in juvenile Atlantic salmon (*Salmo salar*). *Aquaculture Research*, **43**(3): 349-360.

5. THEME: Pollution

Effluents from Atlantic salmon farms (from faeces and uneaten food) are reported to be a source of organic pollution to the surrounding environment (Hall et al., 1992). The excess particulate organic matter released into the marine environment can cause eutrophication around fish cages (Gowen & Bradbury 1987), organic enrichment of sediment (leading to anoxia and hydrogen sulphide accumulation) (Holmer & Kristensen 1992; Angel *et al.* 1995) and changes in the macrofaunal and microbial composition of the sediment under fish cages (Weston 1990). In order to reduce the environmental impact of such pollutants, a number of measures have been proposed.

Angel, D. L., Krost, P., Gordin, H. (1995). Benthic implications of net cage aquaculture in the oligotrophic Gulf of Aqaba. *European Aquaculture Society Special Publication*, 25: 129–173.

Gowen, R. J. & Bradbury, N. B. (1987). The ecological impact of salmonid farming in coastal waters: a review. *Oceanography and Marine Biology - An Annual Review,* 25: 563–575

Hall, P.O.J., Holby, O., Kollberg, S., Samuelsson, M.O., (1992). Chemical fluxes and mass balances in a marine fish cage farm. IV. Nitrogen. *Marine Ecology Progress Series*, 89, 81–91.

Holmer, M. & E. Kristensen, (1992). Impact of marine fish cage farming on metabolism and sulfate reduction of underlying sediments. *Marine Ecology Progress Series*, 80: 191–201.

Weston, D. P., (1990). Quantitative examination of macrobenthic community changes along an organic enrichment gradient. *Marine Ecology Progress Series*, 61: 233–24.

Key messages

Integrated aquaculture systems

Three studies found enhanced growth of bivalves and algae when grown adjacent to salmon farms. One study reported no evidence that oyster and mussels were feeding on fish farm waste.

Construct artificial reefs

One study found no difference in sediment carbon at artificial reef sites adjacent to or away from fish farms. It also reported that the artificial reefs at both sites were colonised with various species with the potential to remove organic compounds from fish farm effluents.

Dry sludge in beds

Two studies found sludge drying beds removed phosphorus from fish farm sludge.

Use exclusion nets

One study found higher levels of sediment carbon at stocked cages with exclusion nets compared to cages without exclusion nets.

Establish fallowing to reduce pollution

One trial in found sediment community structure under Atlantic salmon cages became more similar to non- impacted sites over two fallowing cycles.

5.1 Integrated aquaculture systems

- One study in the U.S.A.[1] reported greater growth of scallops grown next to fish farms.
- Another study in Canada[3] found that blue mussels absorbed waste from a salmon farm.
- A study in Scotland[4] reported enhanced algal growth when placed adjacent to fish farms.
- One study in Spain[2] found no evidence that oyster and mussels were feeding on fish farm waste.

Background

Salmon farms may release large amounts of particulate matter which mainly consists of uneaten feed and excretion products. Polyculture systems have been proposed in order to recycle this particulate matter and enhance productivity. Finfish have been cultured with macroalgae or bivalve species. Polyculture systems are reported to reduce nutrients generated by finfish culture thereby reducing the impact of finfish farms on the environment.

Between 1994 and 1996, a replicated, controlled study at two sites in Maine, USA (1) found that shell height and survival of sea scallops, *Placopecten magellanicus* was greater on drop lines adjacent to salmon cages compared to benthic cages. Percentage survival of the scallops held for one and a half years in the pearl nets (72.7% and 63.9%) was higher than that of those in benthic cages (28% and 32.0%) at both sites and was the case for each sampling date. Mean shell height in the pearl nets (73.0 mm and 69.0 mm) was also higher than that of those in benthic cages (68.5 mm and 52.0 mm) after one and a half years. Pearl nets comprised of drop lines containing ten nets at 3m depth were deployed 4m away from salmon cages at two sites and sampled every four months for eighteen months. Benthic cages of modified lobster traps were deployed 100m away from salmon cages at depth of 10 and 15m at each site. The authors note that growth rates recorded in this trial are comparable with those of scallops grown away from salmon farms.

A study in the surroundings of a marine fish farm located in Águilas, SE Spain in 2008 (2) found evidence to indicate that oysters and mussels were not feeding on waste from fish farms when grown in polyculture systems. Between the beginning and end of the 90 day trial, oysters and mussels showed an increase in shell length of 85±54 mm and 152±45 mm, respectively. Analysis of stable isotopes content from the bivalves indicated no relationship between the trophic behaviour of the bivalves and the main input of organic matter from the fish farm (the feed). Growth of the bivalves was not affected by proximity to the fish farm. Oyster (*Ostrea edulis*) and mussel (*Mytilus galloprovincialis*) were deployed along a distance transect running from 0 to 1800 m from fish cages containing cultured gilthead sea bream (*Sparus aurata*) and European sea bass (*Dicentrarchus labrax*) for 3 months. The bivalves were placed at 15 m depth at 0, 25, 120, 300, 600 and 1800 m from the net cages to assess whether the fish farm influenced their development.

Laboratory and field trial in Canada in 2005 (3) found that organic material in waste from salmon culture can be absorbed by blue mussels (*Mytilus edulis* and *M. trossulus*).

The absorption efficiencies for the spat formula feed, diatom based salmon feed, salmon faeces (laboratory trial) and total particulate matter at salmon cages were 87, 81, 90, 86, and 54% respectively. In the laboratory experiments, four diets were fed to three size classes of mussels; spat formula diet, diatom based formula diet, salmon feed and salmon faeces over a period of one and a half months. In the field trials, mussels were placed individually in chambers on a moored boat and the outflowfrom the salmon farm was used to measure total particulate matter, total organic matter and organic carbon with collection occurring prior to, and mid-way through each 1.5 h trial. The trials occurred on three separate days. Faecal deposits were collected throughout the trial to determine absorption efficiency.

Between 2004 and 2005, a replicated, controlled trial in Scotland between 2004 and 2005 (4) found that growth of two algae species, *Palmaria palmata* and *Saccharina latissima* was enhanced when grown close to fish farm cages. Algae grown on frames adjacent to fish farms had 63% and 27% greater fresh weight biomass compared to algae grown on frames away from fish farms for *P.palmata* and *S.latissima* respectively. A similar pattern was observed for algae grown on longlines. Nitrogen content of the algae grown at reference sites away from the cages was lower than those grown close to the fish cages (Percentage nitrogen in: farm frames- 4.6 and 1.90%, reference frames- 2.3 and 1.23%, farm longlines- 2.7 and 1.65% and reference longlines- 2.0 and 1.29% for *P.palmata* and *S.latissima* respectively). Algae were grown at three sites adjacent to fish farm cages and at seven other sites distant from fish farm cages. Attached to three buoyed frames at each site were stings with *P. palmata* at 1–1.8 m depth and ropes with *S. latissima* at 1.8–2.6 m depth. In addition, three longlines were put in place, two at reference sites away from the cages and one running perpendicular to a group of cages. Seeded string of 2 to 6 m lengths of *P.palmata* was deployed three times throughout the experiment. Three groups of five droppers were attached to each longline. Droppers of *S. latissima* consisted of 7 m lengths of 10mm three-strand polypropylene rope with 10 cm lengths of seeded string inserted into the lay of the rope at depths of 1, 2, 3, 4 and 5 m.

1) Parsons, G.J., Shumway, S.E., Kuenstner, S. and Gryska, A. (2002). Polyculture of sea scallops (*Placopecten magellanicus*) suspended from sea cages. *Aquaculture International*, 10: 65- 77.
2) Navarrete-Mier, F., Sanz-Lázaro, C. and Marín, A. (2010). Does bivalve mollusc polyculture reduce marine fin fish farming environmental impact? *Aquaculture*, **306**(1-4): 101-107.
3) Reid, G. K., Liutkus, M., Bennett, A., Robinson, S. M. C., MacDonald, B. and Page, F. (2010). Absorption efficiency of blue mussels (*Mytilus edulis* and *M. trossulus*) feeding on Atlantic salmon (*Salmo salar*) feed and fecal particulates: Implications for integrated multi-trophic aquaculture. *Aquaculture*, 299(1-4): 165-169.
4) Sanderson, J. C., Dring, M. J., Davidson, K. and Kelly, M. S. (2012). Culture, yield and bioremediation potential of *Palmaria palmata* (Linnaeus) Weber & Mohr and *Saccharina latissima* (Linnaeus) C.E. Lane, C. Mayes, Druehl & G.W. Saunders adjacent to fish farm cages in northwest Scotland. *Aquaculture*, **354-355**: 128-135.

5.2 Construct artificial reefs

- One study in the Red Sea[2] found no difference in sediment carbon at artificial reef sites adjacent to or away from fish farms.
- Another publication from the same study[1] reports that the artificial reefs at both sites were colonised with various species with the potential to remove organic compounds from fish farm effluents.

Background

Salmon farms may release large amounts of particulate matter which mainly consists of uneaten feed and excretion products. Wild fish can be attracted to net cages in order to scavenge food and take shelter. This could potentially lead to increased build-up of organic matter beneath cages. Artificial reefs can be situated near to net cages to provide a large surface area that can be colonised by micro-organisms that could act as a biofilter to reduce pollution in the surrounding area.

Between 1999 and 2000, a controlled study in the Gulf of Aqaba, Red Sea (1) found that an artificial reef structure placed below a fish farm became colonised by a variety of organisms with potential to remove organic matter produced by farmed gilthead sea bream, *Sparus aurata*. Both artificial reefs were rapidly colonised by a range of species; algae, small invertebrates, and macro fauna, compared to the control site. Biomass was greatest on the reef under the fish farm. Fish were seldom observed at the control site but numerous at both artificial reefs (886 and 1,185 below and west of the fish farm, respectively). Chlorophyll a was used as an indicator of filtration efficiency and was most efficient at intermediate current speeds (15 to 35% filtration). Two triangular-shaped artificial reefs, made of porous polyethylene, with a total volume of 8.2 m^3 were deployed at 20m depth: one below a commercial fish farm and the other 500m west of this farm. A control site was established with no artificial reef structure 10m south of the fish farm. Plates were attached to the reef to allow sampling without disturbing the integrity of the reef structure. Three plates were removed from each reef every other month and were photographed, identified, counted, dried and weighed. Every two months, the fish populations were counted by visual diver surveys and video recordings reefs. Chlorophyll a was measured using a fluorometer. The experiment was conducted over one year.

A controlled study in the Gulf of Aqaba, Red Sea between 1999 and 2000 (2) found similar levels of sediment carbon between artificial reef sites below and to the west of cages containing farmed gilthead seabream, *Sparus aurata*. Three months after deployment of the reef, percentage carbon in all sediment tested was similar, inclusive of a four control sites. Below the farm, there was 3.95% of carbon, compared to the control sites (4.06%). West of the farm, there was 2.25% of carbon, compared to the control sites (2.34%). Two triangular-shaped artificial reefs, made of porous polyethylene, with a total volume of 8.2 m^3 were deployed at 20m depth: one below a commercial fish farm and the other 500m west of this farm. Scuba divers sampled sediments every three months for 12 months. Four sampling stations were established

3m from the edge of reefs on either side to act as control sites. Carbon content of sediment samples was measured.

1) Angel, D. (2002). An application of artificial reefs to reduce organic enrichment caused by net-cage fish farming: preliminary results. *ICES Journal of Marine Science*. **59**: 324-329.
2) Angel, D. L., Eden, N., Breitstein, S., Yurman, A., Katz, T. and Spanier, E. (2002). In situ bio filtration: a means to limit the dispersal of effluents from marine finfish cage aquaculture. *Hydrobiologia*, **469**: 1-10.

5.3 Dry sludge in beds

- Two trials in Canada[1] found sludge drying beds removed phosphorus from fish farm sludge.

Background

Freshwater smolt farms may release large amounts of particulate matter which mainly consists of uneaten feed and excretion products. Phosphorous accelerated eutrophication and can be found in high concentrations in the effluent from salmonid farms. Solids from the effluent must be removed in order to reduce the phosphorus discharge into the surrounding environment.

Two replicated experiments in Quebec, Canada in 2009 (1) found that treatment of freshwater fish farm sludge with sludge drying beds removed 95- 99% of total phosphorus (TP). The first experiment showed there was no difference in total phosphorus removed between sludge loading. The second experiment found that phosphorus leaching from sludge drying beds was 5 µg TP released per gram of total phosphorus regardless of sludge loading. For the first experiment, four sludge drying beds were set up at a rainbow trout farm; each consisted of a 1m^2 reservoir filled with different types of river gravel (20cm) and a top layer of sand (20cm). *Typha latifolia* was planted on the sludge drying bed one year before the experiment at a density of 8 plants m^2. During the experiment, the sludge drying beds were fed once a week with sludge from the fish farm at two concentrations (32 or 18 kg of dry matter per m^2 year). The second experiment in a laboratory aimed to determine phosphorus leaching using 2L beakers containing 0.5L of sludge and 1.4 L of filtered pond water. Phosphate concentrations in sludge and pond water were monitored.

1) Puigagut, J., Angles, H., Chazarenc, F. and Comeau, Y. (2011). Decreasing phosphorus discharge in fish farm ponds by treating the sludge generated with sludge drying beds. *Aquaculture*, **318**(1-2): 7-14.

5.4 Use exclusion nets

- A trial in Australia[1] found higher levels of sediment carbon at stocked cages with exclusion nets compared to cages without exclusion nets.

Background

Salmon farms may release large amounts of particulate matter which mainly consists of uneaten feed and excretion products. Wild fish can be attracted to net cages in order to scavenge food and take shelter. This could potentially lead to increased build-up of organic matter beneath cages. There is debate as to whether wild fish contribute to the build-up of organic matter or not. Exclusion nets can keep wild fish away from net cages, which could potentially reduce the pollution impact on the surrounding sediment.

A replicated, controlled study in Fremantle, Western Australia in 2001 (1) found sediment carbon to be greater at cages containing fish and with an exclusion net than cages without fish or an exclusion net. Sediment carbon levels increased at the stocked cages with exclusion nets (to 9.8% and 10.0%) whereas at all other stations, sediment carbon either remained the same or decreased (sediment carbon values ranged from 6.3% to 7.5% C). Organic carbon deposition levels at cages with exclusion nets were measured as 4.5 g C m^{-2} day^{-1} compared to 0.7 to 1.1 g C m^{-2} day^{-1} at control and reference sites. Three treatments in duplicate were set up within a harbour in water 3 to 4m depth; cages without exclusion nets, cages surrounded by a 35mm mesh exclusion net and empty cages surrounded by exclusion nets (control). The first two treatments were stocked with rainbow trout at2.4 kg m^{-3}. Four reference sites without cages were set up 150m from fish cages. Sediment samples and sediment cores were taken one week prior to sampling and immediately after the 62 day trial.

1) Felsing, M., Glencross, B. and Telfer, T. (2005). Preliminary study on the effects of exclusion of wild fauna from aquaculture cages in a shallow marine environment. *Aquaculture*, **243**(1-4): 159-174.

5.5 Establish fallowing to reduce pollution

- A trial in Tasmania[1] found sediment community structure under Atlantic salmon cages became more similar to non- impacted sites over two fallowing cycles.

Background

Husbandry practice on salmon farms is important in reducing the spread of disease within and beyond the farm. Fallowing has been practiced in terrestrial agriculture for centuries to reduce the incidence of disease. Many salmon farms use fallowing as a technique for disease control and some to reduce the build- up of sediments below cages. Chemical and biological remediation of benthos near salmon farms has been proven. A two month fallowing cycle is mandatory to break parasite cycles on salmon farms.

A controlled, replicated trial between 2003 and 2004 at two fish farm sites in southeast Tasmania (1) found sediment community structure under Atlantic salmon cages became more similar to non- impacted sites over two fallowing cycles. Similarity of the community structure of the impact sites to the reference sites increased from 25% to 31% at one site and 11% to 27% at the other after fallowing. The extent and rate of recovery were affected by length of fallow period, farm location and the initial impact of the sediments. An annual stocking regime was employed at both farms where cages were stocked for nine months and then fallowed for three months. Sediment samples were collected from cage positions and reference sites before the cages were stocked, after nine months of stocking and at the end of the three month fallow period. Samples were taken at monthly intervals during the second year. Circular study cages with a circumference of 120 m were used at both farms.

1. Macleod, C. K., Moltschaniwskyj, N. A. & Crawford, C. M. (2006). Evaluation of short-term fallowing as a strategy for the management of recurring organic enrichment under salmon cages. *Marine Pollution Bulletin*, **52**(11): 1458-1466.

6. THEME: Bioinvasive species

Invasive species can pose serious problems to cultured species worldwide (Hodson *et al*. 2000). Biofouling can reduce water quality within cages leading to deterioration in fish health (Kent 1992; Braithwaite & McEvoy 2005), can harbour pathogens (Kent 1992) and can obstruct nets and requires costly and frequent cleaning (Hodson *et al*. 1997). Copper- based antifoulants have conventionally been used to reduce bio invasive species from settling on nets however, they also bring undesirable environmental effects (Lewis 1994; Braithwaite & McEvoy 2005). More environmentally friendly antifouling strategies are required to combat the problem.

Braithwaite RA, McEvoy LA. (2005). Marine biofouling on fish farms and its remediation. *Advances in Marine Biology*, 47: 215–252.

Kent, M.L., (1992). Diseases of seawater netpen-reared salmonid fishes in the Pacific Northwest. *Canadian Special Publication of Fisheries and Aquatic Sciences*, 116: 76.

Hodson, S.L., Lewis, T.E., Burke, C.M., (1997). Biofouling of fish-cage netting: efficacy and problems of in situ cleaning. *Aquaculture*, 152: 77–90.

Hodson, S.L., Burke, C.M.& Bissett, A.P. (2000). Biofouling of fish-cage netting: the efficacy of a silicone coating and the effect of netting colour. *Aquaculture*, 184: 277–290.

Lewis, T., (1994). Impact of biofouling on the aquaculture industry. In: Hodson, S.L., Burke, C.M. & Bissett, A.P. (2000). Biofouling of fish-cage netting: the efficacy of a silicone coating and the effect of netting colour. *Aquaculture*, 184: 277–290.

Key message

Eco friendly biofouling prevention

Two studies found silicon coated nets and those treated at high temperatures accumulated less biofouling organisms than untreated nets.

6.1 Eco friendly biofouling prevention

- A study in Australia[1] found silicon coated nets accumulated less biofouling organisms which could be more easily removed than untreated nets.
- Two trials[2] found that a temperature of 50^{o}C prevented the settlement of actinulae and hydroids on nets.

Background

Bio-fouling on nets can occlude nets requiring frequent cleaning, reduce water and oxygen flow and harbour disease causing micro-organisms. Copper based net treatments are very effective but also have undesirable environmental impacts as a result of metal based toxins. More environmentally friendly solutions are encouraged;

either non- toxic net coatings that release a deterrent or nets with reduced adhesion for fouling organisms.

A replicated, controlled study in Tasmania, Australia in 1995 (1) found that fouling organisms were less abundant and they could be more easily removed from silicon coated nets compared to untreated nets. After 163 days of immersion, there was less fouling on the white silicon coated nets (1.9 kg/m^2) compared to uncoated white (7.8 kg/ m^2) and black (8.5 kg/ m^2) nets. Fouling organisms were also removed more easily from silicon nets compared to untreated nets; 15.3% of the fouling was removed from the silicone coated nets, but only 3.0% and 3.6% was removed from the white and black nets respectively. Three netting types were immersed adjacent to a cage of a salmon farm; a white silicon coated net (coated with Veridian 2000), uncoated white netting and uncoated black netting. Panels were placed on the nets to allow removal without disturbing the integrity of the net structure. After 140 days of immersion, nine panels (three replicates per net type) were removed to quantify ease of fouling removal and fouling composition. Panels were cleaned with a water jet held 30 cm away for 10 seconds to quantify ease of removal of fouling organisms.

Two replicated, controlled experiments in a laboratory and at a fish farm in Norway in 2010 (2) found that a temperature of at least 50°C was effective in preventing the settlement and survival of juvenile hydroids under laboratory conditions. Lab experiments resulted in 100% mortality of juveniles when exposed to 50°C or 60°C. When exposed to 50°C for one or three seconds, low survival rates of adults were observed (12% and 4% respectively) and at 60°C, 100% mortality was observed. Laboratory experiments with 0.2% acetic acid and an immersion time of one minute reduced the survival of juvenile and adult hydroids to between 0 and 35%. There was 100% mortality for juveniles and adults for the five minute immersion. All short term immersion in the 2.0% concentration acetic acid reduced the average settlement of actinulae, and survival of juvenile and adult hydroids to less than 10%. In the field experiments, mean wet weights of biofouling organisms of the heat treatments were significantly lower than the control group. The wet weights of biofouling organisms between the acetic acid treatments were similar. In the laboratory heat experiments, treatment groups were immersed in sand filtered seawater at temperatures of 12 (control), 30, 40, 50 and 60°C for immersion times of 1 and 3 s. In the acetic acid experiments, treatment groups were immersed in acetic acid solutions at concentrations of 0% (control), 0.2% and 2.0% for 1, 3 and 10 seconds, 1 and 5 min. For the fieldwork experiments, net panels were attached to two PVC frames (565 net panels each) and deployed at 2 m depth on the outside of a cage in a fish farm. The net panels were treated with water temperatures of 50 and 60°C and immersion times of 1 and 3 seconds; and an acetic acid concentration of 0.2% with immersion times of 1 and 5 min and a concentration of 2.0% and immersion times of 1 and 3 s. The wet weights (g) and photographs of the net panels with biofouling were taken just before treatment, and two and five days after treatment.

1) Hodson, S. L., Burke, C. M. and Bissett, A. P. (2000). Biofouling of fish- cage netting: the efficacy of a silicone coating and the effect of netting colour. *Aquaculture*, **184**: 277- 290.
2) Guenther, J., Fitridge, I. and Misimi, E. (2011). Potential antifouling strategies for marine finfish aquaculture: the effects of physical and chemical treatments on the settlement and survival of the hydroid *Ectopleura larynx*. *Biofouling*, **27**(9): 1033-1042.

7. THEME: Wild escapes

The effects of escaped farmed salmon on local ecosystems have been of concern for some time (Clifford *et al.* 1998; Skilbrei *et al.* 2009). There is evidence to suggest that interbreeding between wild and farmed salmon may result in decreased fitness of wild stocks (McGinnity *et al.* 2003). Commercially farmed salmon may have been selectively bred for production traits and therefore differ in life history, morphology and physiology compared with wild stocks (Jonsson & Jonsson 2006). Effective escape prevention strategies are currently necessary (Skilbrei *et al.* 2009).

Clifford, S.L., McGinnity, P., Ferguson, A. (1998). Genetic changes in Atlantic salmon *(Salmo salar)* populations of Northwest Irish rivers resulting from escapes of adult farm salmon. *Canadian Journal of Fisheries and Aquatic Sciences*, 55: 358–363.

Jonsson, B. & Jonsson, N. (2006). Cultured Atlantic salmon in nature: a review of their ecology and interaction with wild fish. *ICES Journal of Marine Science*, 63: 1162–1181.

McGinnity P., Prodohl P., Ferguson A., Hynes R., O´ Maoileidigh N., Baker N., Cotter D., O_Hea B., Cooke D., Rogan G., Taggart J.B. & Cross T. (2003). Fitness reduction and potential extinction of wild populations of Atlantic salmon, Salmo salar, as a result of interactions with escaped farm salmon. *Proceedings of the Royal Society of London B*, 270: 2443–2450.

Skilbrei, O.T., Holst, J.C., Asplin, L., Holm, M. (2009). Vertical movements of 'escaped' farmed Atlantic salmon (*Salmo salar* L.)—a simulation study in a western Norwegian fjord. *ICES Journal of Marine Science*, 66: 278–288.

Key message

Domestication: sterility/triploidy

One study found reduced return of stock but similar weight, length and condition of triploid salmon compared with diploid

7.1 Domestication: sterility/triploidy

- A study in Ireland[1] found reduced return of stock but similar weight, length and condition of triploid salmon compared with diploid

Background

Commercial salmon farm breeders can induce triploidy in salmon stocks. If any of these farmed salmon escape, they will be unable to interbreed with the wild salmon population. This will reduce the potential impact of interbreeding between the two groups.

A controlled, replicated experiment in Ireland in 1996 (1) found reduced return of triploid salmon compared to diploid salmon to coast and fresh water sites after release.

The ranched, mixed sex diploid group of salmon showed the highest percentage return to fresh water (2.25%). Across the three release groups, the percentage return of triploid mixed-sex and all female stocks (0.81 and 0.75) was significantly lower than diploid mixed-sex and all female stocks (3.42 and 3.95). Weight, length and condition factor were similar between triploid and diploid coastal return fish. Groups of mixed-sex and all female salmon stocks were produced and triploidy was induced in a proportion of fertilised ova in February. Groups of both diploid and triploid mixed-sex and all female fish were released from two sites on the western coast of Ireland; a tidal lake by a hatchery and next to a commercial aquaculture operation on the coast. Capture location and return data of the groups was gathered as part of an on-going Irish programme. Fifteen major salmon landing ports were monitored between May and June 1996.

1. Cotter, D., O'Donovan, V., O´ Maoileidigh N., Rogan G., Roche, N. and Wilkins, N.P. (2000). An evaluation of the use of triploid Atlantic salmon (Salmo salar L.) in minimising the impact of escaped farmed salmon on wild populations. Aquaculture, 186: 61- 75.

Glossary

Fingerling: A general term for a young or small salmon.

Fry: A newly hatched salmon.

Smolt: A silvery young salmon that will migrate to sea for the first time.

APPENDIX 1
Atlantic salmon- Key terms search list

Pathogens

- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND pathogen
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND cleaner wrasse
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND chemical treatment
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND immunostimulant
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND probiotic
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND stocking density
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND fallowing
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND quarantine
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND vaccination
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND selective breeding
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND location
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND stress
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND husbandry
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND lice

Wild escapes

- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND escapes
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND acclimation

- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND sterility
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND triploidy
- (Atlantic salmon OR *Salmo salar*) AND wild AND gene bank
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND handling
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND biosecurity
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND tagging
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND escape AND closed recirculation

<u>Artificial feed</u>

- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND protein
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND oil
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND fish meal
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND feed
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND soybean
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND linseed
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND rapeseed
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND discard
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND trimmings
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND GM feed
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND sustainable food

<u>Pollutants</u>

- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND water flow
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND organic waste
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND biofilters
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND bioflocs
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND carcass
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND aeration

- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND feed delivery
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND growth
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND breeding
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND on shore
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND polyculture

Bioinvasive species

- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND biodiversity
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND biofouling
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND spat
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND native

Climate change

- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND climate change
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND greenhouse
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND processing

Predators

- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND predator
- (Atlantic salmon OR *Salmo salar*) AND (fish farm OR aquaculture) AND plastic