AN OVERVIEW OF SCIENTIFIC RESEARCH ON ENVIRONMENTAL EFFECTS OF THE SCOTTISH AQUACULTURE INDUSTRY

P A Gillibrand

January 2001
EXECUTIVE SUMMARY

Research investigating the environmental effects of aquaculture in Scotland extends across many scientific disciplines, involving a number of research institutes and university departments. In addition to scientists conducting the research, many government regulators and civil servants are involved in monitoring the impact of the industry on the Scottish environment and seeking to ensure the industry remains sustainable over the longer term. This report summarises current research projects and programs, being conducted at institutes and universities across the country, investigating the effects of marine and freshwater aquaculture on the environment. In addition, the report attempts to look forward at the issues that scientists and regulators anticipate will require investigating and developing in future. The report focuses on effects of fish and shellfish culture on the surrounding aquatic environment. Scenic and landscaping impacts are not considered, nor are disease issues. Marine and freshwater aquaculture are both considered, although the emphasis lies with mariculture.

On-going research projects are grouped into themes on:

- organic waste emissions;
- the effects of nutrient emissions from salmon farms on biological processes within the semi-enclosed environments of Scottish sea lochs;
- other sediment impacts such as trace metal concentrations;
- the impact of aquaculture on local populations of wild salmonids;
- the effects of sea lice treatment medicines;
- the effects of other chemicals;
- assessment and prediction of impacts through monitoring and modelling;
- generic related environmental research.

Individual projects within each theme are briefly described, with participating institutions and principal investigators noted.

The likely requirements for future research projects are also broken into themes. For both marine and freshwater aquaculture, anticipated future research needs vary from improved understanding and prediction of local impacts, to better assessment and management on regional and national scales. Key points in a strategy to address these issues were identified as:

- to improve understanding and prediction, through research, of local site impacts to ensure good husbandry and maximum sustainable production on site;
- to improve regional industry management and assessment, through modelling, of the carrying capacity of management areas, including assessing effects of cumulative nutrient discharges, cumulative medicine usage, interactions between farms and indigenous populations, etc;
- to maintain, and widen, regular discourse and dissemination between all parties involved in the coastal zone environment and aquaculture industry;
- to improve integrated coastal zone management, both internally within the aquaculture industry and in association with other coastal zone stakeholders.
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1. INTRODUCTION

A sustainable future for the finfish and shellfish aquaculture industry is a key social, economic and political issue for Scotland. As the industry has grown in recent years, there has been an intensification of conflict between stakeholders in the marine environment where the industry is based. Development of the scientific principles needed to determine the sustainable level of activity has lagged behind the rate of growth in the industry. As a consequence, the Scottish Executive now faces a situation in which, for certain sites, the operations have the appearance of being unsustainable, but there is no defensible basis for legislating down the level of activity.

Research into the marine environmental impact of aquaculture, and in particular the effects of Atlantic salmon production, encompasses a wide range of scientific activities and disciplines and is currently conducted in various institutes around Scotland. The principal topics being investigated at Scottish laboratories include: a) the effects of medicines on natural benthic and pelagic populations, b) the effects on local benthos of carbon deposition beneath cages, c) other sediment impact studies, d) the quantification of nutrients emitted by farms, e) the hydrography and water exchange of sea lochs, and f) prediction and assessment of effects through monitoring and modelling. These investigations involve combinations of laboratory experiments, field studies and computer modelling.

The diversity of this research, and the numbers of scientists necessarily involved, means that the direction and coordination of the overall programme is diffuse. It is difficult for both scientists and managers to remain aware of the latest research findings in all the various disciplines. Furthermore, research proposals tend to address problems of immediate concern to the industry and management, and there is a lack of strategic research to investigate potential impacts, which may become areas of concern in the future. For example, one area of research that may require particular attention is the impact of aquaculture on biological processes in Scottish waters. Through the discharge of nutrients and chemicals, finfish and shellfish production may have adverse, though currently poorly understood, effects on the plankton and bacterial populations of sea lochs and coastal waters.

This overview will firstly summarise current on-going research projects at publicly funded institutes and universities in Scotland investigating environmental aspects of the aquaculture industry. This summary will document the institutes where major research projects are being conducted, principal investigators and the funding agencies involved. The review will consider the marine finfish and shellfish industries and the freshwater industry. Secondly, the review will seek to highlight perceived areas where environmental concerns may arise, or persist, in future. Finally, the review will consider the Irish and Norwegian industries and briefly highlight environmental concerns in those producing countries to put the Scottish industry into perspective.
This report will not attempt to review in detail the environmental effects of the aquaculture industry as presently understood by the scientific community. For this, the reader is referred to the scientific literature. The aim is to summarise current research projects and to identify issues that scientists and funding agencies might usefully address in the future. Although the focus is principally on research involving government-funded laboratories, some of the projects and research interests at various university departments are included to give a university perspective. Topics discussed focus on impacts in the aquatic environment, so other environmental issues such as visual impact, equipment loss, etc are not discussed. Disease transfer between salmon farms, and between farmed and wild fish, is not considered within this report.

2. CURRENT RESEARCH PROJECTS IN SCOTLAND

Marine and freshwater aquaculture will be considered separately. In this section, current research projects and research interests at universities and research laboratories in Scotland will be described briefly. Projects have been grouped into themes. Only a brief outline of each project is given, but the institutes and principal investigators involved are noted should further details of particular projects be required.

2.1 Marine Aquaculture

The debate in Scotland about the marine environmental aspects of aquaculture is dominated currently by perceived and potential effects of the Atlantic salmon industry. One known impact on the marine environment is that of enhanced carbon deposition on the seabed beneath farms, and the extent of this impact, its effect on benthic processes and prediction and assessment of the impact has been researched for about two decades. Research now focuses on minimising those effects by improved husbandry.

Other potential or perceived impacts from the Atlantic salmon industry have been broken down into the following themes: waste emissions; the effects of nutrient emissions from salmon farms on biological processes within the semi-enclosed environments of Scottish sea lochs; other sediment impacts such as trace metal concentrations; the impact of marine parasites on local populations of wild salmonids; the effects of medicines; and the effects of other chemicals. Research is currently being undertaken to investigate the extent of these effects and those projects are briefly described below. Research is also undertaken to improve the assessment and prediction of the holding capacity of sites through monitoring and modelling. Finally, broader research into the oceanography of Scottish coastal waters provides the canvas on which environmental effects of aquaculture can be assessed.

The present document describes particular research projects and programmes related to environmental effects of aquaculture in Scotland. A broader review is being carried out under the auspices of an EU Concerted Action being coordinated by Napier University, Edinburgh. Under the title ‘Monitoring and Regulation of Marine Aquaculture (MARAQUA)’, the project aims to review existing information on the environmental effects of aquaculture and establish a set of agreed guidelines for the monitoring and regulation of marine aquaculture. The project has established a European Network to bring together scientists, producers, regulators and voluntary organisations, in an effort to coordinate and provide means for the efficient exchange and review of information. An important element of the programme is the preparation of papers on a series of subjects leading to a draft Best Environmental Practice document for mariculture. The subjects include several of the themes discussed in the present paper. More information can be obtained from the web site: http://www.biol.napier.ac.uk/maraqua/
2.1.1 Waste Discharges

(i) Emission of Soluble Nitrogenous Compounds. FRS ML (Dr Ian Davies). Funded by SERAD, Ongoing.

Farmed salmon excrete soluble nitrogen (in the form of ammonia) into the water column as a by-product of metabolism. The quantity emitted by each fish varies due to a number of factors, including food composition, fish age and size, and water temperature. The total quantity of ammonia emitted from a fish farm then depends on the level of production and the stage of the production cycle. In order to estimate correctly the effects of nutrient emissions on the local ecosystem, it is imperative to have an accurate assessment of the quantities of nutrients being released. This work aims to provide improved estimates of the monthly releases of soluble nitrogenous compounds from salmon farms over a production cycle. These results will then provide input to computer models predicting nutrient levels in the water column.

(ii) Quantification and Characterisation of Solid Waste Emissions. IoA (Dr Malcolm Beveridge and Dr Trevor Telfer). Funded by Taiwan Government Studentship, 1996-2000 (Dr Y S Chen, Completed), and Various.

The impact of finfish farms on the local benthic environment and water quality depends fundamentally on the quantity of waste organic material produced by the farm. This research programme aims to improve estimates of the quantity of waste food and faeces emanating from salmon farms. The quantity of solid waste generated by farms depends on many factors, from the feeding regime to feed composition. The developed methods and results then provide a basis for quantifying the benefits of, for example, improved husbandry, the use of automated feeders, etc. The data also provide input to models predicting benthic effects of salmon farms.

The effects of solid waste material on the local environment also depends on the characteristics of that waste. Work is continuing to investigate and quantify parameters such as the settling rates of feed and faecal pellets, and the leaching of nutrients from pellets into the water column during settling. Estimated values of these parameters change as feed composition changes with new brands coming on the market, and good knowledge of appropriate parameter values is essential for accurate modelling of impacts.

(iii) Environmental Benefits of Intelligent Feeding Systems in Cage Culture of Atlantic salmon. IoA and DML (Dr Trevor Telfer, Dr Malcolm Beveridge and Dr Kenny Black), NERC Industrial CASE studentship, 2000-2003 (Mr Richard Corner) with Aquasmart Systems Ltd (Dr Sunil Kadri).

The use of intelligent feeding systems are becoming more widespread in countries such as Scotland and Norway. These systems allow automated feeding of fish using a variety of timed and behavioural responses. These systems have been developed primarily to use food more efficiently for economic reasons but this will have environmental implications for input of solid wastes and, possibly, for control and more effective use of in-feed chemotherapeutants.

This project, to begin in September 2000, will investigate the waste inputs from sites containing intelligent feeding systems with those of similar production biomass and conditions over three years. Sedimentation and in situ manipulation techniques will be used as well as investigating the physico-chemical and biological environments at the trial sites.
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Data collected may be used to improve data sued in modelling of waste material and included into the framework for fish farm regulation.

This project has links with a current EU framework 4 funded study investigating intelligent feeding systems with bass and bream culture in the Mediterranean.

2.1.2 Water Quality/Eutrophication


The objective of this work is to investigate the effects of salmonid cage-culture effluents (metabolic waste products and uneaten food) on planktonic community structure and microplankton ecosystem function in a sea loch. A programme of field observations was undertaken at Loch Fyne over a complete seasonal cycle. Salinity/temperature profiles and water samples were collected from three depths at each of four stations located at different proximity to the fish farm. The water samples are being analysed for inorganic (NH4, NO3, PO4, SiO2) and organic nutrients (nitrogen, phosphorus), chlorophyll concentrations, and the abundance and biomass of phytoplankton, bacteria, ciliates and heterotrophic nanoflagellates. These results will contribute to improved understanding of the effects of aquaculture effluents on semi-enclosed environments.

(ii) *Monitoring Winter Nutrient Levels.* FRS ML (Dr Ian Davies and Dr Phil Gillibrand). Funded by SERAD, Ongoing.

FRS ML has previously undertaken occasional research cruises to measure nutrient levels during winter in a number of Scottish sea lochs. These data provide background data for nutrient models assessing the enhancement of nutrients in these systems due to fish farming. Cruises have previously taken place in December 1992 and December 1998. These and subsequent cruises may contribute to any indication of long-term changes in background nutrient levels in sea lochs.

2.1.3 Sediment Impacts

(i) *Nutrient Cycling within Sediments.* Leeds University (Dr R Mortimer), FRS ML (Dr Ian Davies). Funded by Leverhulme Trust, 2000-2002.

The project is led by researchers from the University of Leeds investigating novel aspects of nutrient cycling within sediments. Results from a preliminary study indicate that understanding and representation of microbial processes occurring in organic rich marine sediments has previously been oversimplified. Evidence from modern, state-of-the-art, geochemical and biochemical techniques have identified previously unknown microbial processes, resulting in rapid recycling of nutrients and trace metals within the sediment. This project aims to characterise these processes and to determine the rate of the major recycling reactions. Results from the project may modify understanding of enriched sediment processes in both natural environments (eg below cage fish farms) and artificial systems such as sewage treatment ponds and aquaculture systems.

(ii) *Physical and Biogeochemical Pathways of Fish Farm Wastes in Scottish Sea Lochs.* DML (Dr Tracy Shimmield and Dr Kenny Black), FRS ML (Dr Phil Gillibrand), UHI Studentship (Rebecca Dean), 1998-2002.
It has recently been noted that sea bed sediments at fish farms can contain high concentrations of some metals, notably copper and zinc. The sources of these metals are suspected to be antifoulants on cage nets, and galvanising on walkways respectively. The objectives of the PhD are to establish the extent of the phenomenon and to investigate the environmental significance of the relatively high concentrations that are found, particularly of copper.

(iii) Benthic Impacts of Shellfish Farming. FRS ML (Dr Ian Davies). FRS Studentship (Jon Chamberlain), 1997-2000.

The aim of the this project is to provide a detailed survey of the benthic impacts of specific mussel farms. These farms were selected such that they were in areas of low energy and the biodeposits exposed to reduced dispersive forces. This allowed us to examine the effects of the biodeposits along gradients of deposition at increasing distances from the farms. Three sites were selected for survey on the coasts of west Scotland and south west Ireland. These farms provided a range of farm sizes (25-150 m) and ages (3-14 years) and were representative of the types of farms found in the areas. The effects of these biodeposits on the biology and physico-chemical structure of the surficial sediment was analysed. The quantity and nature of the sedimenting material was also analysed. A model was then developed to quantify the area over which the flux of biodeposits from the farm sites would settle out onto the benthos. The model was an adaptation and development of the fish farm impact model DEPOMOD, incorporating the results of the surveys and of mussel faeces settling velocity experiments. The potential effects of the increased sedimentation, in the form of faeces and pseudofaeces, on the macrobenthic community, physical structure and biogeochemistry of the surficial sediment around the farms were identified and possible impacts predicted.

(iv) Measuring and Modelling the Resuspension of Solid Wastes Beneath Fish Cages Due to Wind and Wave Events. FRS ML (Dr Phil Gillibrand), UWB. Funded by CEC, SSFA, 2000-2001.

This aim of this project is to measure and model the wind- and wave-driven water currents near aquaculture cages at sites where these effects may play an important role in the resuspension and redistribution of particulate wastes. The ultimate goal is to develop a predictive computer module that will incorporate these processes into the regulatory procedures for discharge consenting by SEPA.

The project consists of two components: a field study of wind and wave conditions and associated near-bed tidal, wind-driven and wave-orbital velocities at selected locations in Shetland; and a modelling study to predict the water currents generated by the observed wind and wave characteristics and to predict the extent of sediment resuspension at the site. By calibrating the model using the measured data, this project should produce a generic model capable of predicting on-site current conditions from local wind data. This will allow improved estimates of waste dispersion and therefore holding capacities of sites and therefore help maximise the sustainable production level of the industry.

2.1.4 Sea Lice

(i) Responses of Sea Lice to Odour Stimuli. AU (Dr Jennifer Mordue) and Others. Funded by SQS, MHM, Landcatch UK Through Link Aquaculture, 1998-2001.

This project seeks to provide a scientific basis and practical knowledge for the use of semiochemicals (behaviour modifying chemicals) in sea lice control. The use of
semiochemicals could, together with disease management control, the use of medicines, and other methods, form an effective, sustainable, Integrated Pest Management Strategy. The present project aims to investigate ways in which semiochemicals could practically be used to help control sea lice infestations on salmon farms. Possible uses of semiochemicals to help control sea lice are: to monitor lice numbers to predict treatment; to employ repellent/attractant strategies to move sea lice from cages to traps with host odours and pheromones outside cages; to disrupt lice mating by causing confusion in mate location. The method is intrinsically environmentally friendly and could help reduce the environmental effects of sea lice control.

(ii) Development of Data Based Models for Effective Treatment and the Environmentally Safe Use of Veterinary Methods in the Control of Sea Lice Infestation of Farmed Salmon. STAMS (Prof George Gettinby and Dr Crawford Revie). Funded by MAFF, SQS, MHM Through Link Aquaculture, 1999-2002.

This project aims to develop mathematical models of sea lice population dynamics and to investigate the effects of control operations on those populations. Initially, industry databases of sea lice numbers will be collated, audited and analysed. Statistical analysis of the data will be carried out to identify suitable parameterisations for mathematical models. The development of sea lice population models will enable processes such as the development of resistance to treatment to be investigated, and help identify key factors in those processes. The project will also investigate how project findings and results can be implemented at policy level and on fish farms.

(iii) The Impact of Salmon Farming on Wild Fish Populations. FRS ML (Dr Phil Gillibrand), FRS FL (Dr David Hay). Funded by SERAD, 2000-2003.

The project aims to examine the incidence of sea lice on wild sea trout populations in Loch Torridon and two other sea lochs, and to investigate the source and transport of infective lice stages. The project will attempt to establish surface plankton tows as a reliable method of sampling for sea lice in the vicinity of river mouths, which can then be used to monitor the effectiveness of lice treatment strategies on local salmon farms for controlling escaping lice numbers. The project will monitor activities on farms and attempt to link those practices with the variable abundance of lice at nearby river mouths, with the aim of identifying solutions and preventing incidence of high lice numbers during the spring sea trout run. Three-dimensional, hydrodynamic computer modelling, combined with lice behavioural models, and hydrographic work will investigate possible transport mechanisms of the infective lice stages between local farms and affected rivers.

2.1.5 Sea Lice Medicines

(i) Post Authorisation Assessment of the Ecological Effects of Sea Lice Treatments. DML (Dr Kenny Black), PML, SEAS, FRS ML, SAMS. Funded by MAFF, DETR, SEPA, SERAD, SNH, SQS, 1999-2002 (Possible Extension to 2004).

The toxic effects of all new sea lice treatments have been examined during the product licensing and discharge consenting processes but these studies have been limited to a few sentinel species and there is currently little information on the wider ecological consequences of the use of these products. This project seeks to address the widely perceived research need in this area by conducting long term, broad scale BACI (Before After Control Impact) studies at a range of low energy fish farm sites and encompassing all the currently available or presently proposed sea lice treatment chemicals. The results of this research will answer commonly asked questions on the ecological significance of these
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chemicals under realistic treatment regimes with respect to macrofauna, zooplankton, meiofauna, benthic diatoms, phytoplankton and macroalgae.

Sites selected for this work are initially in Lochs Fyne, Torridon and Sunart. In the first fieldwork season only the bath treatment cypermethrin will be studied as this is now widely available. This work will be continued in subsequent years but with the inclusion of new medicines especially emamectin and possibly teflubenzuron.

(ii) To Develop Analytical Methods for Sea Lice Medicines Used in Fish Farming. FRS ML (Dr Lynda Webster). Funded by SERAD, Ongoing.

This work aims to maintain analytical capability to measure concentrations in the environment of chemotherapeutants used in the fish farming industry. Methods have been developed to analyse for levels of cypermethrin in sediment. The project will develop analytical methods for emamectin in sediment and biological tissues, cypermethrin in biological tissue and chitinase inhibitors in biological tissue.

(iii) The Biological Effects of Fish Farm Chemicals Used in the Treatment of Sea Lice. FRS ML (Dr Colin Moffat, Dr Ron Stagg and Dr Ian Davies). FRS Studentship (Ben Gowland), 1998-2001.

This project is an FRS research studentship to develop biomarkers of the effects of sea lice treatment chemicals on marine organisms. The aims of the study are to investigate the effect of selected medicines on particular fauna in laboratory studies, to calibrate the laboratory techniques for field conditions, to demonstrate burdens and the availability of medicines to organisms and to incorporate this knowledge into the advisory role and regulation.

(iv) In situ Investigations of the Fate and Environmental Effects of Sea Lice Medicines. IoA (Dr Trevor Telfer and Dr Donald Baird). Various Funding from Industry (Ongoing).

The use of chemotherapeutants to control sea lice infestation is widespread in the Scottish mariculture industry. The medicines employed are potentially toxic to not only sea lice but other crustacea in the local environment following discharge from the farms, whether application is in-feed or by bath treatment. This programme, of commercially funded research, carries out field trials for new sea lice treatment medicines under commercial use conditions, investigating the environmental fate and ecotoxicological effects of the medicine. Recent field trials have involved examining impacts on benthic macrofauna species of emamectin benzoate and teflubenzuron over long time scales (one and two years respectively). Measurements were also made of the levels of active ingredient and primary metabolites in the water column and sediments to identify temporal variations following treatment and their relationships to community composition.

Short term trials (one month) investigating the effects on sentinel species (eg juvenile lobsters and mussels) transplanted around treated and untreated fish cages have also been undertaken. These specifically investigate organisms which may be targeted by sealice medicines and are of commercial importance.

(v) Investigation of the Environmental Effects of Sea Lice Bath Treatment Chemicals on Zooplankton. IoA (Dr Trevor Telfer and Dr Donald Baird). Chilean Government Research Studentship, 1998-2001 (Mr Matias Medina).
A field and laboratory based investigation of the lethal and sublethal effects of sea lice bath treatments on zooplankton species. Laboratory studies on lethal and sub-lethal effects on Acartia and Tisbe are near completion. In situ mesocosms are now under development to investigate the impacts on zooplankton species assemblages. It is expected these will be deployed later this year.

(vi) Impacts of In-feed Chemicals on Sediment Reworker Species. IoA (Dr Donald Baird, Dr Malcolm Beveridge and Dr Trevor Telfer), Malaysian Government Studentship, 1997-2000 (Mr Rosly Bin Hassan) and Industrial Funding.

Sediment reworkers within the vicinity of fish cages are important in bioprocessing sedimented nutrient waste. A laboratory based PhD study to develop ecotoxicological techniques to investigate the impacts of in-feed sea lice chemicals on these reworkers is complete. In addition, these techniques are being developed further through industrial funding.

The investigation concentrates particularly on the polychaete Capitella, using specimens collected from Scottish farms and standard populations. Cultures of Capitella have been set up and exposures performed as lethal and sub-lethal concentrations. The results have significant implications for the effects of in-feed chemotherapeutants on bioprocessing of wastes. In addition, the techniques may be used as a sediment assay for the development of environmental quality standards, which at present employ organisms which may not be found in the sediment near fish cages where any effects of the drugs are present.

2.1.6 Effects of Chemicals

(i) The Effects Copper on Sediment Reworker Species. IoA (Dr Trevor Telfer and Dr Malcolm Beveridge), Privately Funded Studentship, 1997-2000 (Mr Gernot Vonhoegen).

Other chemicals released in general use from fish cages may have impacts on sediment fauna. Of particular interest are sediment reworkers which help bioprocess sedimented waste. One such important reworker in the polychaete Capitella. This project investigated the effects of sediment copper, released as a fish cage net anti-foulant, which may accumulate within sediments for considerable periods of time even after cessation of use.

The study developed techniques to measure various copper species and laboratory tests to look at lethal and sub-lethal impacts on Capitella. This investigation used behavioural and sublethal endpoints in ecotoxicological testing and employed histological and x-ray methods to investigate the mechanisms of copper movement throughout the body tissues.

(ii) Investigation of the Effects of Anti-bacterials on Sediment Bacteria Using Laboratory Microcosms. IoA. (Dr Valerie Inglis, Dr Trevor Telfer and Dr Donald Baird) Korean Government Research Studentship, 1995-2000 (Mr Duk Hyun Yoon)

This work investigated the effects of anti-bacterials used as medicants in Scottish fish farming on bacteria contained in sediments. Laboratory microcosms were set up to simulate nutrient enriched sediments, like those found near to sea cages, and were treated with various applications of anti-bacterial agent.

An important outcome of the research was the formulation of successful microcosms and HPLC techniques for the analysis of anti-bacterials as well data to show the possible effects on bioprocessing bacteria in sediments.
2.1.7 Assessment and Prediction of Impacts (Modelling and Monitoring)


This project takes as a starting point a model (BenOss) developed by DML for predicting benthic community response to varying the treatment level from long sea sewage outfalls. This model, which essentially tracks particles of organic solids in a current field, follows their incorporation and degradation in sediments, and predicts indices of community response, has been validated for long sea outfalls and is now in wide use in the water industry.

A number of modifications have been made to allow this model to be used at fish farms: the level of organic loading on the sediment is approximately two orders of magnitude greater around fish farms compared with long-sea sewage outfalls, consequently the biological communities present are quite different; the gradients of organic input are extremely steep with very large changes occurring in relatively short distances making sampling station selection critical; fish food and faeces have quite different behaviours in sea-water relative to sewage solids and are of different composition with unknown degradation rates; waste food pellets quickly break down into smaller particles of unknown size distribution which are then susceptible to resuspension at varying rates. In addition fish farm sites are generally more stratified than sites for sewage outfalls requiring a greater appreciation of vertical current shear and its effects on particle dispersion. Whereas sewage outfalls can be described in terms of mean flows and concentrations, the output from fish farms varies dramatically over the growing cycle requiring modelling of fish growth and pellet size change. Food wastage is generally believed to be at a lower level than in the past: losses were historically estimated at typically 20%, but are more commonly thought now to range from 5-15%.

The model has been developed as a Windows 95 PC version entitled DEPOMOD. The model has been made user-friendly, allowing its use directly by fish farmers on the basis of a current meter record and site specific input data. The farmer therefore has an inexpensive and rapid method for determining whether or not to proceed with an application and the level of biomass likely to be consented. Using this model as an agreed tool for determining consents, and knowing that this is also freely accessible to the industry, the regulator should have to deal with fewer applications as those likely to fail will not be submitted. The regulator will have an additional validated method for determining consents thus reducing disputes and may use the data requirements of this model as a benchmark for the integration of regulatory requirements across all Scottish regions.

(ii) Modelling the Regional Effects of Fish Farms. FRS ML (Dr Phil Gillibrand). Funded by SERAD, Ongoing.

The potential cumulative effects of fish farms are modelled on the spatial scales of individual sea loch systems. The cumulative effects of nutrient discharges on background nutrient levels are modelled simply, using box models, to assess the relative impacts and potential burden imposed by fish farming on loch systems around Scotland. The development of a sea loch ecosystem model offers the potential to simulate, on a basin-wide scale, the effects of nutrient discharges from salmon farms on plankton communities, rather than simply estimating the enhancement of nutrient concentrations themselves.

Soluble sea lice medicines, administered as bath treatments, disperse within the water column following release from fish cages. It is important for water environmental quality standards (EQS) that the advection and dilution of released medicines can be predicted,
allowing maximum discharge quantities to be specified. Models developed at FRS ML, and under continuing development, predict the dispersion of medicines from individual farms, and also collectively from a number of farms within a single semi-enclosed sea loch. Thus the models allow discharge consents for individual farms to be set, but also examine the potential cumulative effects of multiple treatments.

(iii) GIS-integrated Site Assessment Models. IoA (Dr Lindsay Ross and Dr Trevor Telfer). Various IoA Funded MSc Projects, 1996-1998, and EU Marie Curie Studentship, 1999-2002 (Mr Oscar Perez).

Models for predicting the rate of carbon deposition beneath fish cages have been integrated into a Geographical Information System (GIS) environment as part of several MSc research projects. The GIS model builds on initial calculations made within programmed spreadsheets, and combines the spatial mathematical functions inherent to a GIS with hydrographic and bathymetric data and pertinent information about fish farm practice to produce mapped contours of predicted carbon deposition beneath cages. Validation of the GIS model against sediment carbon data from beneath cages shows improved comparisons compared to the simpler spreadsheet-based models, and the model results exhibit strong correlations with benthic diversity indices and ordination scores.

This work is being investigated further as part of a PhD which incorporates this model into a GIS programme for aquaculture site selection around Tenerife. If successful, the methods may be applicable in Scotland for use with GIS in coastal resource management.

(iv) Modelling Sea Lice Populations and Effects of Medicines. See 2.1.4 Above.

2.1.8 Generic Related Environmental Research

(i) The Restricted Exchange Environment (REEs) Programme. DML (Dr Kenny Black). Funded by NERC, Ongoing.

The Restricted Exchange Environment Programme is a NERC thematic research programme, and has as one of its main themes the concept of sea loch vulnerability. In sea lochs much of the vulnerability arises from the possibility of hypoxia enhanced by nutrient and organic inputs from anthropogenic inputs such as fish farming. One focus will be to understand, on REE-wide scales, how microbial communities within representative REEs respond to nutrient and organic loading, and the influences such responses have on the residence time of inputs within the system and their ultimate fate (burial or export to the coastal zone). Of particular interest in sea-lochs will be the understanding of interactions between hydrodynamics, organic loading (due to increased inputs from, eg aquaculture and sewage) and the development of hypoxia and its effects on mobilization of redox sensitive metals and other contaminants.

Modelling will be used to couple field and experimental studies, test process understanding and ultimately predict the sensitivity of REEs to key variables such as increased organic, nutrient and contaminant inputs. Ecosystem models (eg BenOss) will be further developed and appropriate biogeochemical modules incorporated. Key physical processes affecting biological vulnerability in REEs will be investigated and quantified using high-resolution, temporal measurements from moored and bottom-mounted instrument arrays and airborne remote sensing. These processes will include cross-sill exchange and deep-water renewal in sea lochs, and stratification, mixing and flushing in the range of REE types to be studied.
The fate of external nutrient inputs and the ensuing enhanced primary production is a key concern to the vulnerability of REEs. Coupling between nutrient inputs and ratios, surface production and transport of organic matter and nutrients will be studied seasonally. These studies will include measurements of the rates and relative importance of in situ primary production and imported production. The fate of this production through grazing by mesozooplankton, microheterotrophs and benthic biota, and through bacterioplankton recycling will be followed. The development of hypoxic sediments and basin waters will be investigated, as will mobilisation of redox-sensitive metals and their effects on both the distribution and bioturbatory activity of benthic biota. Measurements of these processes will be put in a seasonal context using data collected from moored instrument arrays incorporating fluorometers, in situ nutrient analysers and ADCPs (for zooplankton migration and enumeration). High resolution, basin-scale measurements of dissolved oxygen, manganese and key physical variables will be measured in sea-lochs using AUTOSUB. Laboratory experiments in mesocosms will be used to assess the response of bioturbating biota to hypoxia under controlled conditions.

(ii) Modelling Water Circulation, Transport and Dispersion on the Scottish West Coast Shelf and Associated Waters. FRS ML (Dr Phil Gillibrand), UWB. FRS Studentship (Marco Pizzamei), 1998-2001.

Present day understanding of the water movements along the Scottish west coast are due only to limited ad hoc current meter deployments and inferred circulation patterns from temperature, salinity and radio-caesium ($^{137}$Cs) distributions. Although three-dimensional circulation models exist of the entire UK continental shelf, the resolution of these models does not allow for great detail of the Minch and Sea of the Hebrides. A three-dimensional circulation model is therefore being developed of the Scottish west coast continental shelf region. The model will allow an investigation into the transport of water and associated contaminants along the Scottish coast. It will also provide a capability for improved coastal management on the west coast of the country, by providing managers with more detailed information on the exchange and flushing of the coastal zone, and better predictions of transport pathways of contaminants and organisms (eg disease pathogens).

Associated work includes computer modelling of water circulation and exchange in sea lochs. The hydrodynamics of sea loch systems is fundamental in determining the impact of many anthropogenic activities on local ecosystems. High energy systems may have greater carrying capacities than low energy lochs. Isolated deep water may exhibit stronger indications (eg dissolved inorganic nutrient levels) than deep water which is regularly exchanged. The exchange of water between semi-enclosed sea lochs and the adjacent coastal zone controls the residence time of contaminants within the former. Complex water circulation models are required to accurately assess the residence time of such systems in varying conditions of tide, wind and river runoff. Circulation models have been used to investigate processes such as deep water renewal in Loch Sunart and water and contaminant exchange in Loch Fyne. Investigations into the Loch Fyne system are continuing.

(iii) The Shieldaig Sea Trout Project. FRS FL (Dr Andy Walker). Funded by SERAD, HIE, CEC, HC, Ongoing.

There is a need for hard information on the performance of sea trout and some salmon populations in West Highland rivers in view of current concerns over their sustainability. Full-scale trapping and tagging of upstream and downstream migrant sea trout is being undertaken in the River Shieldaig, a small river typical of the region, after the construction of a permanent trap. The juvenile population is assessed annually by electro-fishing and
supplementary stocking is carried out to raise potential smolt production to the carrying capacity of the system. Environmental variables in freshwater and in the local sea lochs (Torridon) are monitored in conjunction with estuarine trapping, which allows separate estimation of annual levels of juvenile and post smolt mortality. Factors which contribute to marine mortality, including parasites and predation, are studied in cooperative research. Currently, sea lice are thought to be a contributory factor to the mortality of early post smolts. The sources of the lice (fish farms or wild salmonid fish) and their means of dispersion are studied by population genetics (St Andrews University) and by association with local fish farming practices and by hydrographic modelling (FRS ML). Seasonal levels of louse abundance are investigated by plankton tows. There are prospects of greater control of sea lice by the fish farmers through improved management by therapeutants and by falling. The Sheildaig Project will be able to assess whether these changes bring about large-scale increases in the marine survival of sea trout. It will act as a model for possible restoration efforts in other west coast rivers. Collaboration is currently with the Wester Ross Fisheries Trust, the Association of West Coast Fisheries Trusts, SEPA, SNH, FRS ML, Inverness College, the Gatty Marine Laboratory and Sea Mammals Research Unit (University of St Andrews).


Dissolved inorganic nitrogen (DIN) includes nitrate, nitrite and ammonium, all potentially enhanced in coastal waters by human activities. Enhancement can lead to eutrophication if the extra nutrient results in additional growth of phytoplankton (or benthic algae). For practical purposes the amount of phytoplankton is most easily measured as chlorophyll, and the UK water quality standard relating to eutrophic conditions is defined using chlorophyll concentration. A knowledge of the proportionality between an increase in DIN and a resulting increase in chlorophyll is thus crucial to estimating the likelihood and extent of the eutrophication resulting from given nitrogen loadings. Two week long microcosm enrichment experiments have been undertaken at DML using natural populations of microplankton (<200 µM) collected from the Lynn of Lorne on the west coast of Scotland. Light quality, light quantity, day length and temperature are the same they would be in the natural environment, changing with the season. 12 µM of ammonium or nitrate is added to microcosms using continuous culture techniques, and yield of chlorophyll from DIN has been determined over different seasons. Similar experiments will be undertaken at SEPA during 2000 using microplankton collected from the Firth of Forth, and then comparisons of yield of chlorophyll from DIN from comparatively oligotrophic (Lynn of Lorne) and hypernutrified (Firth of Forth) sites during different seasons will be made.

2.2 Freshwater Aquaculture

Relatively little research is presently being conducted into the environmental effects of freshwater aquaculture. Freshwater farms tend to be of smaller production tonnage (up to about 300 tonnes) than their marine counterparts (up to 3,000 tonnes), and concerns about environmental effects are not so high on political agendas. The legislative framework for freshwater aquaculture was developed in the 1980s, when research into effects of water and sediment quality was carried out and regulatory modelling tools developed. Many farms have therefore been operating for many years with relatively little interference from government. However, concerns about potential impacts of freshwater aquaculture remain, (eg use of chemicals, nutrient discharges), and these are addressed in the next section. Concerns may also increase as the number of freshwater hatcheries required to supply smolts to the expanding marine industry grows.
An Overview of Scientific Research on Environmental Effects of the Scottish Aquaculture Industry

Many of the environmental concerns about freshwater aquaculture are similar to those in the marine sector. Release of nutrients, particularly, in the freshwater case, phosphorous, and the storage and gradual release of those nutrients in the sediments is a major concern of regulators. The use of chemicals such as anti-fungals (eg malachite green and pyceze), the effects of exotic escaped farmed fish on natural populations and ecosystems, and the sediment impacts due to settling waste material are all environmental issues requiring further research.

One current project is an investigation being carried out by the IoA, Heriot-Watt University and industrial partners into the efficiency and cost-effectiveness of waste collection and disposal technologies, funded through the LINK Aquaculture programme.

3. ANTICIPATED REQUIREMENTS FOR FUTURE RESEARCH

The discussion below briefly outlines the issues raised by government, regulators and industry about environmental aspects of marine and freshwater aquaculture that may require scientific investigation in the near- to medium-term future. Again, marine and freshwater aquaculture are discussed separately, and research topics have been grouped into themes each covering a general area of concern.

3.1 Marine Aquaculture

3.1.1 Sea Lice Medicines

The continuing use of medicines for parasite control means that the potential for unwanted impacts on non-target organisms remains a major concern of regulators. As farms increase in capacity, the potential exists for release of increasing quantities of medicines during treatment, with an associated increase in environmental risk. Consents for medicine discharges are very tightly regulated, but it has been hypothesized that low-level concentrations may have sub-lethal impacts on plankton populations, for example inhibiting zooplankton grazing with the subsequent potential for increased rates of phytoplankton growth. In-feed treatment medicines are better targeted at treating fish for lice, but some have long half-lives (up to several months within sediments) and may accumulate in sediments beneath cages or be redistributed over a wider area through sediment resuspension following treatment. The residues may then effect non-target species removed from the immediate environment of the farm. An additional, though presently unquantified, risk with in-feed medicines is the potential for opportunistic feeders to scavenge waste feed pellets beneath cages, with the possibility that the associated medicine may enter the human food chain.

Many of these concerns are being addressed through current projects (see above). However, while sea lice remain a persistent problem for salmon producers, chemotherapeutants are likely to remain in use for the foreseeable future and it will remain necessary to continue research into the impacts of these substances. At present, research into other chemicals used on salmon farms, such as anti-foulants, is deemed as of lesser importance as effects are perceived as being secondary. However that may change in the future.
3.1.2 Husbandry Practices

One of the major consequences of improved farm husbandry is a reduction in waste material released from farms. This has benefits both for the environment, in terms of reduced impact, and the producer, in terms of reduced cost. Research into specific topics such as automated feeders, waste management and recycling, fish appetite, feeding behaviour and social hierarchy will all contribute to improved husbandry and reduced waste entering the environment. It must be emphasised that from an industry perspective, all technology developed for use on farms needs to be cost-effective. Improved husbandry should reduce problems with sediment quality beneath cages. One concern raised about husbandry methods was the potential for underwater cage lighting to affect the migration of wild salmon and sea trout. In addition, the extent of the effect of escaped salmon on local populations through interbreeding remains unknown, but is potentially significant.

Many of these husbandry issues are being investigated with industry collaboration. Reducing waste through cost-effective technology remains a goal for both industry and regulators, and reducing escape numbers is equally important to both parties. Research into the cause of escapes and development and implementation of rapid-response measures to recapture escaped salmon has been suggested.

3.1.3 Predators

Predators of farmed salmon, particularly seals, can cause considerable damage to cage nets and result in lost stock for producers. Protection of caged fish from attacks by seals remains a major goal for industry. The best methods to achieve this, however, are by no means established. Attempts to solve the problem through technological devices generate their own concerns. For example, the effects of acoustic seal scaring devices on local populations of small cetaceans are not known. Cetaceans are the subject of both European and domestic legislation and any move towards more open coastal fish farm sites could potentially increase interactions with these animals. On a broader scale, control of seal populations on a national level remains a difficult issue politically.

Predators also affect the shellfish industry and, despite recent research on predation by eiders at mussel farms, there is likely to remain a requirement for further development of non-destructive anti-predator methods at mussel farms.

3.1.4 Sea Lice/Wild Fish Interactions

Evidence that the large numbers of sea lice found on salmon farms are impacting wild salmonid populations has been accepted as beyond all reasonable doubt by many in the environmental lobby. Recent research in Norway suggests that locating farms away from rivers with significant wild fish populations is the most effective way of solving the problem. This creates problems in Scotland, which has less room for manoeuvre in terms of site relocation than Norway. Strategic, coordinated lice treatment by farmers within single management areas may help reduce the numbers of lice being released from farms, and an on-going project will attempt to monitor lice numbers at river mouths and identify cost-effective management strategies that could reduce the threat to wild stocks.

The mechanisms of the incidence of infective stages of lice at river mouths remain poorly understood, as the behaviour of these stages of the organism is not fully understood. This problem, together with the research projects investigating control of lice numbers on farms, illustrate the need for continued fundamental research into the biology and life cycles of these organisms. Control of lice numbers, both on and remote from farms, in the future is
likely to depend on an integrated approach utilising various methods (eg traps, medicines, etc). The success or failure of strategies will depend on sufficient knowledge of sea lice biology to identify vulnerable periods within the life cycle.

3.1.5 Site Carrying Capacity Assessment

It is essential if the industry is to develop to its maximum, sustainable, level of production that the carrying capacity of every site is assessed as accurately as possible. This involves appropriate monitoring, hydrographic and benthic data collection, and accurate computer modelling. Prediction of benthic impact beneath cages is presently done using the DEPOMOD model (see above). The model is being modified to include prediction of in-feed medicine concentrations in the sediment following treatment. However, a further concern relates to the impact of aquaculture discharges on hard substrate communities, which is of particular relevance to European marine sites (SAC) which contain such substrates. Computer models are also used to predict dispersion of bath treatment medicines for determining discharge consent levels and nutrient emissions from sea farms.

It is essential that development and refinement of these models continues in order to improve predictions of sustainable production and acceptable discharge levels. The best possible prediction benefits industry and regulators alike in maximising production without unacceptable environmental effects. Models can be improved by better parameterisation of the processes simulated by the model. To achieve this requires a quantitative understanding, and accurate measurement, of those processes at the appropriate temporal and spatial resolution. To improve site modelling and assessment, therefore, requires an associated program of field and/or laboratory research investigating the processes to be modelled. Modelling cannot be done in isolation and should not be regarded as a relatively cheap and easy replacement for monitoring and observation. The two approaches are complementary.

It should also be noted that the impact of aquaculture developments on the local landscape will also be a determinant of carrying capacity. New guidance on aquaculture and landscape is due to be published in the near future.

3.1.6 Genetic Interactions Between Escaped Farm and Wild Salmon

Escaped salmon from farms may threaten local wild salmonid populations in a number of ways; by altering their genetic constitution through interbreeding, or by reducing the size and genetic robustness of wild populations through competition for limited habitat or food resources, or through disease transmission. Effects like these are considered by some to be contributing to the decline in wild salmon and sea trout numbers, particularly in western Scottish rivers. In rivers like these, farmed salmon are regularly present among wild fish at spawning, sometimes in large numbers. However, direct evidence of detrimental impacts on wild populations is not available and difficult to obtain. Nevertheless, the precarious state of many wild salmonid populations requires, and the likely effectiveness of restoration programs depends on, a better understanding of natural population structuring and interactions between escapees and indigenous salmonids.

3.1.7 Cumulative Nutrient Emissions

Nutrient emissions from salmon farms are continually being reduced due to changes in food composition and improved husbandry. However, when taken as a whole, the industry still releases substantial quantities of nitrogen and phosphorous based compounds into the environment. Concern centres on areas where a number of farms in relatively close
proximity, discharging into semi-enclosed environments where water exchange may be somewhat inhibited, may cumulatively affect ecosystem processes. Concern has been expressed over potential impacts of the quantity of nutrients and of supposed distortion of ‘natural’ nutrient ratios. One of the hypothesised effects is an increased occurrence of toxic algal blooms. No direct evidence exists to link aquaculture-derived nutrients with toxin production by plankton in coastal waters, but lack of evidence makes clarification of the issue equally difficult.

Projects described above are investigating the effects of marine fish farms on local ecosystems. It is also essential to be able to predict the cumulative effects of several farms on regional ecosystems, and development of appropriate models is also ongoing. However, these are difficult problems to address, given the variability inherent in biological systems, and research to resolve them must be a long-term commitment.

3.1.8 Regional Carrying Capacity Assessment

Unlike the site assessment computer models discussed in 3.1.5 above, where improvement and fine tuning is required, models assessing the cumulative effects of fish farms on a regional scale are in development stages. An ecosystem model developed as part of an intensive study of nitrogen cycling in Loch Linnhe, simulates annual cycles of pelagic phytoplankton, zooplankton and carnivore populations, but does not include microbial processes. Development of the model to include such processes is being pursued but, again, results will only be expected in the medium-term. However, the proportional uptake of nutrients emitted from fish farms, and other sources, by bacteria and plankton is thought to be a key issue in the impact of nutrient effects, and therefore needs to be resolved and incorporated into these models. Ecosystem models of the UK continental shelf exist (eg the European Regional Seas Ecosystem Model or ERSEM) but presently have rather coarse spatial resolution to address the problems outlined above. However, modification of such a model for Scottish coastal waters would contribute to understanding of nutrient and biological cycling in the region. Development of such a modelling tool would, again, require associated field validation and would therefore be at least a medium term goal.

Models addressing the regional assimilative capacity of sediments in, for example, a whole sea loch system, do not presently exist. Prior to accurately assessing regional scale sediment impacts, an accurate assessment of carbon deposition throughout the system is required, which implies that processes such as resuspension and redistribution of settled wastes need to be simulated. That requires high-resolution, three-dimensional hydrodynamic models to reproduce water current patterns throughout systems, and development of such models has only recently begun. The regional modelling of sediment impacts in Scottish coastal waters is therefore as yet some way in the future.

3.1.9 Integrated Coastal Zone Management

The ultimate aim of scientific research into environmental aspects of marine aquaculture is to develop coastal zone management so that the aquaculture industry can expand to its maximum sustainable production level. Interactions between finfish farms, shellfish farms and wild fish populations are likely to remain at the forefront of planning for future aquaculture development. The implementation of Area Management Agreements for the marine aquaculture industry is being considered for parasite control and for disease control following the Infectious Salmon Anaemia (ISA) outbreak. However, the introduction of the concept for disease purposes provides an opportunity for management of environmental effects, and in particular the cumulative aspects discussed above. The segregation of the industry into management areas, and the coordination of activity within those areas, offers
an opportunity to develop ecosystem monitoring and modelling over constrained areas, rather than requiring a single model of the entire Scottish mainland from the Firth of Clyde to Cape Wrath. Development of those ecosystem models should be considered now, so that expansion of the industry can be guided from accurate assessment of susceptible and exploitable areas. Before modelling and coastal zone management on this scale can begin properly, however, the regional impacts of aquaculture, discussed in sections 3.1.7 and 3.1.8 above, have to be investigated, understood and quantified. In addition, expanded and improved knowledge of the distribution of marine habitats and species will be required. At present, detailed information is only available for a relatively small proportion of Scottish coastal waters. However, improved modelling offers the opportunity for a better assessment of how the Scottish aquaculture industry as a whole is assimilated into the wider environment.

3.2 Freshwater Aquaculture

Potential future environmental concerns about the freshwater aquaculture industry share many similarities with the marine industry. Again, concerns have been grouped into themes.

3.2.1 Use of Chemicals

The potentially toxic effects, on local fauna, of chemicals (eg anti-fungals) used on freshwater aquaculture sites raises similar concerns as the chemicals used in the marine industry. The chemical of most concern, malachite green, is due to be phased out and is likely to be replaced by pyceze, a compound which has undergone a risk assessment process. However, modelling of the dispersion of pyceze is still required as a necessary requirement to ensure that unacceptable impacts do not result from its use.

3.2.2 Husbandry

Improved waste management practices, including collection and recycling, are being investigated and development and implementation of these practices is considered important for the future. Clearly, effective collection of waste products from fish farms will greatly reduce local environmental impacts, both on site and regional scales, and will assist in the sustainability and development of the freshwater industry. Effective collection, however, requires efficient disposal or recycling of the collected waste if the problem is not simply to be moved ashore. This issue is currently being investigated by researchers at IoA and Herriot-Watt University in collaboration with industry partners.

3.2.3 Nutrient Budgeting and Assessment

The levels of phosphorus, derived from aquaculture, being stored in sediments and leaching into the water column is a major concern to regulators. With increasing numbers of salmon smolt hatcheries, and new species being farmed, there is concern that the potential for phosphorous nutrification in freshwater systems could be exacerbated. In comparison with agricultural and forestry inputs of nutrients, the input from aquaculture is generally considered to be small. However, development of nutrient budgeting and modelling would be greatly beneficial to the management of these systems.
4. NORWEGIAN AND IRISH PERSPECTIVES

Environmental aspects of the Atlantic salmon industry were discussed with researchers and governmental staff from Ireland and Norway, to ascertain perspectives from those major producing countries. Production of Atlantic salmon in 1999 was about 410,000 tonnes in Norway compared to 126,686 tonnes in Scotland. The Irish industry is smaller, less than 20% of the Scottish figure. However, the industries experience many of the same difficulties as in Scotland.

In Ireland, perceived and anticipated environmental effects are very similar to the Scottish case. The effect of escaped fish on natural populations through genetic contamination is considered to be a potentially major problem. The sea lice issue is also subject to much research and sea lice numbers on farms are carefully monitored and tightly controlled. Similar concerns over benthic impacts and the use of sea lice medicines as described above exist. An additional aspect of potential benthic impacts, which has perhaps not received as much attention in Scotland, is the effect of long-line mussel farming, which could produce considerable quantities of localised solid organic waste deposition.

Due to the limited number of inshore sites in Ireland suitable for aquaculture development, there is considerable interest in the continued development of offshore cage technology for moving farms further away from the coast. As in Scotland, difficulties are anticipated with regard to the cumulative effects of nutrient emissions from multiple farms located in semi-enclosed bays, and also with the accumulation of medicines in non-target benthic fauna.

In Norway, annual production of salmon continues to grow rapidly. Atlantic salmon farming may soon become the largest anthropogenic sources of nutrients in the coastal waters of western Norway. Production levels at individual sites are set using the MOM (Modelling - Ongrowing Fish Farms - Monitoring) concept. The level of monitoring is specified according to the expected degree of impact, with more detailed surveys required as anticipated impact increases. Modelling of predicted impact focuses solely on solid waste deposition beneath cages and its effects. Once a site has been assigned a maximum biomass and production level, based on predicted benthic impacts, the producer is permitted to use whatever quantities of licensed chemotherapeutant are required to prevent lice problems. Economic considerations are assumed to keep medicine usage to the minimum possible. However, the use of wrasse as cleaner fish is more common in Norway than Scotland, with apparent economic and environmental benefits. Previous research has indicated that using wrasse is not a practical or economic option in Scotland. The link between sea trout population collapses, sea lice infestation, and proximity to salmon farms has been strongly indicated in Norway. Standards of data collection for benthic monitoring surveys are more rigorously enforced in Norway, and will be introduced for water quality and hydrographic measurement protocols. Coastal zone management schemes are being adopted through the County Councils who are responsible for planning aquaculture development, subject to national environmental and fisheries directives. Computer modelling of fjord hydrodynamics and water quality, benthic impacts due to aquaculture, and ecosystem dynamics is well advanced. The opportunity exists for collaborative exercises to develop, compare and contrast model performance, to try and establish whether Norwegian ecosystem models can be adapted for Scottish conditions, and vice versa.
5. CONCLUSIONS

Examining the list of research themes presented in section 3.1 above, it becomes apparent that the first five themes, involving large site-specific processes and impacts, are subject to on-going and relatively intensive research at various institutes throughout Scotland. These are centred on local environmental effects and husbandry practices, which have been investigated for many years, and about most of which a good level of understanding has developed. This work needs to be continued to further improve understanding and quantification of these processes, and to identify other, as yet unidentified processes. The emphasis now lies on reducing impacts and on better prediction and assessment of effects.

In contrast, the potential for subtler effects on regional and far-field scales has been relatively neglected, although many of the hypothesized effects have only been raised in recent years. The effects of marine fish farming on benthic and pelagic communities are now being addressed through field studies, the results of which should provide a basis on which to further develop models of local ecosystems and the effects of aquaculture, and other anthropogenic activities, on them. Laboratory experiments have shown that low levels of chemotherapeutants in the water column can affect zooplankton behaviour. However, the effect of those behavioural changes on the wider ecosystem has yet to be measured or incorporated into management models. The effects, or otherwise, of the cumulative effect on plankton and microbial communities of nutrient emissions from multiple farms in semi-enclosed environments has also yet to be demonstrated, and this issue is presently very sensitive due to recent outbreaks of toxicity in shellfish in Scottish waters. Although no hard evidence exists linking the cause of toxic algal blooms with marine fish farming, the link has been made in the media and requires investigation to clarify the issue. However, nutrients from fish farms constitute only a small proportion of the total sources of nitrogen and phosphorus to the coastal zone water column, and the nutrient aspect of aquaculture effects must be examined in the context of the total nutrient budget of Scottish coastal waters. The development of regional effect models and assessment protocols, and the opportunity for integrated coastal zone management, requires that these questions on wider-scale effects be addressed. However, the issues are extremely difficult to resolve and will only be tackled through long-term, multi-disciplinary, collaborative and coordinated scientific investigation and commitment of resources.

The problems for freshwater aquaculture development are perhaps more tractable in that freshwater lochs are essentially closed, clearly bounded, bodies of water. Modelling of nutrient budgets, therefore, does not include open-ended exchange with a variable ocean. The chemical use and husbandry issues are localised problems, which can be addressed through focussed research projects. The goal of assessing carrying capacities of individual freshwater systems will most likely be attained through budget calculations and modelling of nutrient fluxes, in particular phosphorous. The possibility that freshwater sediments are currently acting as a substantial reservoir of phosphorous, with the potential for sustained release into the future, needs to be addressed in any such budget calculations.

In summary, key stages in developing a research strategy to minimise unacceptable environmental impacts, while maximising production of a sustainable aquaculture industry, may be identified as:

- To reduce local impacts through improved husbandry methods, and to improve prediction of those impacts to ensure maximum sustainable production on site. Both these goals require better, quantitative, understanding of production and assimilation processes of aquaculture waste, and advances in technologies, both waste disposal methods for industry or improved predictive modelling capabilities for regulators.
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• To improve regional management and assessment, through modelling, of the carrying capacity of individual management areas. Determining the carrying capacity of a management area, whether marine or freshwater, should ultimately take account of all relevant factors, which may include:

(i) predicted impacts of cumulative aquaculture nutrient discharges, in the context of total nutrient budgets for the area, on regional benthic and pelagic communities;
(ii) interactions between aquaculture farms and indigenous species, such as wild salmonid populations and cetaceans;
(iii) predicted effects of cumulative medicine usage on benthic and pelagic communities;
(iv) landscaping issues.

Computer modelling is likely to play a key role in many aspects of regional assessment. Continued development of computer models to address these questions offers the prospect of an industry operating at peak sustainable capacity over wide areas of the Scottish coast. Regional management offers producers opportunities to improve parasite control, limit disease transmission, and enhance relations with other coastal interest parties.

• To widen discussion and dissemination of results of studies investigating the various environmental aspects of fin-fish culture. The sustainable future of the aquaculture industry in Scotland, of both the marine and freshwater sectors, depends on a focussed scientific research program tackling relevant areas of environmental concern to regulators. A strategy needs to be developed to address some of the scientifically difficult and politically sensitive issues outlined above. This could involve establishing a Scottish steering group of appropriate representatives from relevant institutes, agencies, university departments, producers and local planning departments. The aim of the group would be to identify research priorities and to ensure the most effective deployment of limited resources.

• To pursue development of a strategy for integrated coastal zone management (ICZM), involving not only the aquaculture industry but all coastal zone stakeholders. For the aquaculture industry, ICZM offers improved disease and parasite control, improved environmental management and better public relations through enhanced interaction with other users of the marine environment. For government, ICZM offers an opportunity to address coastal issues, such as eutrophication, with a holistic rather than the current fragmented approach. The coastal zone in Scotland is used for a wide variety of purposes, from fishing and aquaculture, through waste disposal, to recreation. Many of these activities, and their effects, are interlinked, and integrated management will become essential as pressure on this fragile environment increases.

6. ACKNOWLEDGEMENTS

Many scientists, administrators and industry representatives contributed to this report through discussions, meetings and written contributions. They include:

Dr Philip Balls, Scottish Executive Rural Affairs Department
Dr Malcolm Beveridge, Institute of Aquaculture, University of Stirling
Dr Kenneth Black, Centre for Coastal Marine Science, Dunstaffnage Marine Laboratory
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Dr Brian Clelland, Scottish Environment Protection Agency
Dr Ian Davies, Fisheries Research Services Marine Laboratory
Dr David Donnan, Scottish Natural Heritage
Ms Jackie Doyle and colleagues, Fisheries Research Centre, Dublin
Dr Willie Duncan, Scottish Natural Heritage
Dr Lars Golmen and colleagues, Norwegian Water Research Institute, Bergen
Dr Andrew Grant, Marine Harvest McConnell Ltd
Mr George Hamilton, The Highland Council
Ms Anne Henderson, Scottish Environment Protection Agency
Dr Mary Hennessy, Institute of Aquaculture, University of Stirling
Ms Diane McLafferty, Scottish Executive Rural Affairs Department
Dr Jennifer Mordue, Department of Zoology, University of Aberdeen
Mrs Gillian Moynihan, Scottish Executive Rural Affairs Department
Mr Ian Pritchard, The Crown Estate Office
Mr Gordon Rae, Scottish Quality Salmon
Dr Crawford Revie, STAMS, University of Strathclyde
Dr Trevor Telfer, Institute of Aquaculture, University of Stirling
Mr Graeme Thompson, Scottish Executive Rural Affairs Department
Dr Alan Youngson, Fisheries Research Services Freshwater Laboratory
Ms Angela Wiseman, Scottish Executive Rural Affairs Department
**LIST OF ACRONYMS**

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<tr>
<th>Acronym</th>
<th>Description</th>
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<td>AU</td>
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<td>SSFA</td>
<td>Shetland Salmon Farmers Association</td>
</tr>
<tr>
<td>STAMS</td>
<td>Statistics and Modelling Science Department, Strathclyde University</td>
</tr>
<tr>
<td>UHI</td>
<td>University of Highlands and Islands</td>
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<tr>
<td>UWB</td>
<td>University of Wales, Bangor</td>
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