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REVIEW OF THE ENVIRONMENTAL IMPACTS OF SALMON FARMING IN SCOTLAND

Executive Summary and Main Report

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EXECUTIVE SUMMARY

Introduction

The lochs, voes and sheltered coastal waters of the Scottish west coast and Western and Northern islands provide ideal conditions for growing salmon in floating cages. The aquaculture industry creates jobs not only on farms but also in upstream and downstream activities such as producing fish feed, in logistical support, and in processing the fish. Nevertheless, its growth during recent decades has encountered economic, societal and environmental challenges, which are likely to increase as the industry expands from 163,000 tonnes in 2016 to about 200,000 tonnes in 2020, with the intention to produce up to 300,000 tonnes in 2030.

In 2018 the Rural Economy and Connectivity Committee will be conducting an inquiry into salmon farming in Scotland. To feed into that inquiry the Environmental Climate Change and Land Reform Committee will be considering the current report. Briefing by Scottish Parliament Information Centre (SPICe) on salmon farming in Scotland will also inform both Committees work.

This report specifically reviews the scientific evidence relating to the environmental effects of salmon farming. Where the evidence suggests that there are concerns about harm to marine ecosystems or protected species and habitats, possible mitigation measures are suggested.

The aim of the research is to carry out a comprehensive literature review to assess and summarise:

1. The environmental impacts of salmon farming in Scotland;
2. The scale of these impacts, and;
3. Approaches to mitigating impact.

The environmental impacts were split into six main areas for investigation (as outlined in the research specification issued by The Scottish Parliament, Ref: 2017-18/01/REC). Each of these areas represents a specific issue of concern related to the potential impacts of salmon farming:

- a. Disease impacts on wild and farmed stocks, including the impact of sea lice;
- b. The discharge of waste nutrients and their interaction in the wider marine environment, including:
 - i. Solid wastes from cage farms and effects on sediments;
 - ii. Dissolved nutrient inputs and effects on phytoplankton.
- c. Effects of discharges of medicines and chemicals from salmon farming, including:
 - i. Sea lice medicines;

- ii. Antimicrobial compounds;
- iii. Metals.
- d. Escapes from fish farms and potential effects on wild populations;
- e. Sustainability of feed supplies – including research on plant meal substitution;
- f. Emerging environmental impacts, including:
 - i. Impact on wild wrasse;
 - ii. Impact on marine mammals.

This report was prepared for the Scottish Parliament by a group of subject experts from throughout Scotland.

The review focuses on Atlantic salmon, *Salmo salar*. Reference to 'salmonid' is to any fish of the genera *Salmo* and *Oncorhynchus*, i.e. including species of trout and Pacific salmon. The review may be seen as an update of the "*Review and Synthesis of the Environmental Impacts of Aquaculture*" published in 2002, but which focuses on salmon farming only.

Two main sources of evidence were consulted:

- Scientific papers published after peer review;
- Reports that are in the public domain and that the authors have assessed as reliable.

By preference, those studies that were carried out in Scottish waters were used as evidence. However, where these were scarce, evidence has been taken from investigations of salmonid-farming in Norway, Canada, Australia, New Zealand and Chile, and in some cases, from research into the farming of other species of fin-fish in other waters.

Section 1

Section 1 provides background information on salmon, salmon farming, sea lice and the marine environment of north-west Scotland and the islands, where most salmon are farmed. It also explains the conceptual framework employed in the review. The activity of salmon farming is likely to generate pressures on natural ecosystems, which may cause change in these systems with consequences for ecosystem services and biodiversity. The scientific literature has been reviewed for evidence of causal links between the pressures and their potential effects on ecosystem state.

Effects include those on:

- The ecosystem as a whole in which the farm is situated;
- Habitats, such as rocky reefs or sea grass beds, which are protected under law or have intrinsic conservation value;
- Species protected by law or where there is public opinion favouring their conservation, for example seals or wild salmon.

The potential impacts of some of these effects depend on spatial scale. For example, effects on species can range from the local scale of a farm (on which sea-bed effects are often obvious), through the intermediate scales of sea-loch and coastal water-bodies, to the largest (up to global) scales of fisheries and markets for salmon feed.

Criteria for assessing the significance of effects depend on their scale and also on what is changed. Ecosystems are tolerant of pressures such as organic or nutrient inputs, provided these waste inputs do not exceed the assimilative capacity of these systems. In contrast, any evidenced disturbance to a protected species or habitat was counted as significant.

Sections 2 - 7

These sections consider pressures, effects, and mitigations according to the issues identified in the research specifications. The content of each of these reviews are further summarised within this Executive Summary by issue 'Report Cards' (see below, Pages vi - xiv), with contents arranged under three headings:

Diagnosis - the significant environmental effects given the present state of affairs;

Prognosis - the future state of affairs given current management and regulatory practice, and growth in the industry towards 200,000 tonnes production in 2020 and 300,000 tonnes in 2030;

Mitigation - measures, additional to those presently implemented, for which evidence has been reviewed.

Section 8

The final section revisits the criteria used to assess the significance of effects. A comparison between the findings of this review for Scotland is made with a recent risk assessment of the environmental impact of salmon farming in Norway. It also discusses two mitigation measures in further detail that apply to several of the issues considered in Sections 2 - 7. These are Recirculating Aquaculture Systems (RAS) and Adaptive Management.

By isolating fish from the natural environment, RAS provide security from diseases, infestations and predators, in addition to eliminating potential risks to wild salmon. By retaining wastes, they prevent organic and nutrient impacts on the environment. However, capital costs of establishing RAS units are high, the energy costs for pumping and treating large amounts of water must be factored in, and 100% removal of waste from effluent water is infeasible. RAS waste streams will therefore continue to make demands on environmental assimilative capacity, albeit significantly lower per unit production than open pen cage systems. Freshwater RAS are coming into use as hatcheries, and salt-water RAS might be used to on-grow smolts in order to reduce time spent in net-pens, potentially allowing increased output from cage systems. However, the technology required is still being refined and it seems likely that net-pen farming will continue as the dominant mode of production for at least the next decade.

Adaptive Management is recommended by the FAO as part of the Ecosystem Approach to Aquaculture. It is "*the incorporation of a formal learning process into management actions ... [i.e.] the integration of planning, implementation, monitoring and evaluation to provide a framework to systematically test assumptions, promote learning, and provide timely information for management decisions*".

Adaptive Management takes place to some extent already on farms and in interactions between farms and regulators. At the national level, however, Adaptive Management in the salmon farming industry would require farmers, regulators and scientists to work more closely together to co-produce knowledge that can guide operational and planning decisions.

Issue	<i>Sea lice: Potential for lice from salmon farms to infect wild salmon and damage their populations</i>
Diagnosis	<p>Sea lice are naturally occurring marine parasitic crustacea that attach to the skin of salmon, and harm the fish by feeding on skin and blood and by causing wounds. Eggs laid by female lice hatch into free-living young that are transported by water movements to other salmon, either in the same farm, one at a distance, or to the wild salmon population.</p> <p>The presence of large numbers of salmon, living close together in a farm, can provide conditions that promote the proliferation of lice.</p> <p>Increased abundance of lice on farmed salmon may correlate with increased numbers of lice on wild salmon in the same water-body.</p> <p>There is concern therefore that lice from farmed salmon could damage wild populations of salmon or sea-trout as smolts migrate seawards, and as fish return to rivers to spawn. Although conclusive evidence for damage at the population level is hard to find in Scotland, studies in Norway show that increasing sea lice burdens on wild salmonids adds to pressures on the wild populations already impacted by climate change, river modification, and commercial fishing.</p> <p>Farm controls on lice include; preventing their attachment and development using medicines in the salmon feed, treating salmon using dissolved therapeutants in a bath treatment, and biological control with cleaner fish. These controls can help prevent the build-up of lice populations in the cage pens. Nearly all of these treatments are costly, none are fully effective, and most need to be repeated. They are co-ordinated within farm management areas to help increase efficacy and reduce the likelihood of cross-contamination between farms.</p>
Prognosis	<p>More farmed salmon implies more sea lice (and thus more costs for farmers and more impact on wild salmon), unless mitigation improves. In addition, sea lice populations also appear to be developing resistance to many existing treatment medicines and therapeutants. The timescale for the development and licencing of new treatments can be protracted and costly.</p> <p>Research gaps and gaps in publically available data in Scotland make it difficult to assess the efficacy of present management and regulatory regimes and have generated some public distrust in the industry and regulator.</p>
Mitigation	<p>Research into the efficacy of existing lice treatments and their environmental effects. The development of novel lice treatments. Development of lice-resistant salmon through selective breeding.</p> <p>Growing smolts to a larger size in RAS and transferring the fish to net-pens for the final year of production only.</p> <p>Adaptive Management of lice at the farm level, the disease management area level, and the regional level, with monitoring of lice burdens on wild salmon, placing farm lice data in the public domain, and a more integrated marine planning of salmon farming. Modelling can assist area management.</p>
Additional commentary	<p>In addition to the risk of infecting wild populations of salmonids and the negative effects on production, the presence of sea lice on farmed salmon is a fish welfare concern and requires treatment for this reason. There are also concerns about environmental effects of sea lice medicines and therapeutants. These concerns include; the long term accumulation of some compounds or their breakdown products, impacts on non-target crustacean species present on the seafloor beneath fish farm cages and further afield.</p>

Issue	<i>Diseases: Diseases of farmed fish might spread to other animals, especially wild salmon</i>
Diagnosis	<p>Salmon can be infected by a range of pathogens and parasites, some of which may cause significant losses of farmed fish. About a dozen pathogens and parasites are economically important for salmon farming in Scotland.</p> <p>These infections, and their prevention or treatment, have been much studied in cultivated salmon; less is known about their incidence in wild salmon.</p> <p>The presence of large numbers of fish living close together in a farm provides a favourable habitat for the growth and spread of populations of pathogens and parasites. Depending upon the mode of infection, water currents can spread pathogens between farms and potential between wild and farmed salmon populations.</p> <p>Prevention and treatment measures include biosecurity, fish vaccination, and the use of a range of chemotherapeutants and small amounts of antibiotics. Serious fish or shellfish diseases are called 'notifiable' because farmers must immediately report that they suspect or know about the disease to the Fish Health Inspectorate. There are currently eight notifiable diseases of fish in the UK of which six may be found in salmonids. Suspicion of notifiable diseases will result in movement restrictions and may require the eradication of the infected farm stock.</p> <p>There is some evidence that some disease is transmitted between farmed and wild fish by direct infection, by escapees, or by infection from wild to farmed fish. There are few data allowing the risk of disease transfer between wild and farmed populations to be reliably estimated.</p>
Prognosis	<p>Increased numbers and sizes of farms could lead to increased risk of infection of wild fish unless improvements in farm biosecurity and disease prevention outpace the expansion of production.</p>
Mitigation	<p>Technical mitigations include continued development of effective fish medicines, disease resistant salmon strains, fish vaccines and enhanced biosecurity, especially in hatcheries and RAS.</p> <p>Proactive implementation of management zones and controls on movements of fish to contain disease outbreaks and limit or eliminate their spread.</p> <p>Sampling environmental DNA (eDNA) around farms has the potential provide information on the presence of pathogens. Mathematical models can then be used in some circumstances to estimate risk to wild populations as well as farms.</p>
Additional commentary	<p>As an example of a disease, Infectious Salmon Anaemia (ISA), caused losses in Scottish farms in 1998-1999 and 2008-2009 (all fish at ISA confirmed farms were slaughtered under Government order). The virus is spread by contact with infected fish or their secretions, or contact with equipment or people who have handled infected fish, or perhaps by sea lice. This virus can survive in salt-water, and may therefore be transmitted by water movements.</p> <p>As an example of a parasite, the fluke <i>Diplostomum spathaceum</i> has a complex lifecycle, passing through fish-eating seabirds and freshwater snails before infecting fish, especially their eyes, causing cataracts and mortality. Although infected in freshwater, the disease may not manifest itself until smolts have been put to sea.</p>

Issue	<i>Organic waste: Salmon farm organic waste accumulating on the seabed can significantly degrade communities of benthic animals beneath or near farms</i>
Diagnosis	<p>In some fish-farm sites in lochs and voes where water currents are relatively slow and wave action is limited (low dispersion environments), sinking particulate organic matter results in a farm 'footprint' on the seafloor, within which oxygen demand is much increased as the organic matter is degraded. A combination of reduced oxygen levels coupled to the physical smothering effect of the particulates, the diversity of the community of seabed (benthic) animals is much reduced.</p> <p>This footprint has an area of about half a square kilometre beneath a 1,500 tonne farm. Footprint dimensions and the organic carbon load are estimated by predictive models and confirmed by monitoring. This process is formally regulated. Aggregated footprints only exceed 4% of total seabed in a few lochs and voes.</p> <p>Benthic communities recover when sites are left to fallow, but the recovery rate varies with local conditions. Full recovery may take more than the two years typically allowed. Lack of recent research in Scottish lochs, and failure to synthesise monitoring data, gives rise to some concerns about long-term sustainability of some sites affected by organic waste.</p> <p>Farms make a significant, but not overwhelming, contribution to the organic matter supply in lochs.</p> <p>Site licensing procedures aim to avoid the risk of farm organic waste falling on protected habitats, but there is some evidence of impact in the case of maerl beds.</p>
Prognosis	<p>Increased salmon production will lead to increased organic waste, either adding to the intensity of input at existing sites or adding to the number of 'footprints' as new sites are established.</p> <p>Benthic monitoring near farms, and in relation to protected habitats, is not sufficiently synthesised to allow tracking of long-term changes.</p>
Mitigation	<p>Better modelling when selecting sites, and Adaptive Management of site use, could help to prevent the Assimilative Capacity (AC) of the seabed of a loch or voe for organic waste from being exceeded within the footprint of the farm.</p> <p>As predicted by models, increased use of more dispersive sites could reduce the risk of exceeding AC, resulting in a more diffuse input over a larger area. Research is needed to better understand loch-scale waste AC and to understand long term changes in the benthos of lochs and voes.</p> <p>RAS can retain organic waste but the extent to which this material may be discharged and therefore have an impact on the AC of any given water body will be system and site specific. RAS require energy inputs which must also be taken into account as part of assessing their overall environmental footprint.</p>
Additional commentary	<p>Relevant protected habitats include sea-grass beds, maerl beds of slow-growing calcareous red seaweeds, and unusual reefs of serpulid tube-worms.</p>

Issue	<i>Eutrophication: Significant enrichment of lochs and regional seas by salmon farm nutrients could lead to enhanced growth of phytoplankton, and undesirable disturbance to the balance of organisms and to water quality</i>
Diagnosis	<p>Increased (but not harmful) concentrations of ammonium and phosphate can be observed within a few tens of metres from farms.</p> <p>Models predict, and limited observations confirm, increased nutrients in lochs from salmon farming. In some lochs and voes the increase may be substantial during summer. Calculations suggest that this could also be happening in coastal waters such as the Minch. There is, however, no evidence of increased phytoplankton growth or production due to these nutrients.</p> <p>The 'balance of organisms' in the phytoplankton is changing in at least one loch used for farming, but this is likely due to causes other than nutrients from salmon. In most cases, data allowing an assessment in the changes in plankton communities over time are not available.</p> <p>Models suggest that organic waste from farms could add to the risk of deoxygenation in a few lochs with poorly flushed basin water (i.e. water that is trapped behind sills).</p> <p>Enhanced growth of opportunistic green seaweeds can occur near farms, but this is not significant when assessed over lochs as a whole.</p>
Prognosis	<p>Increased salmon production will lead to increased nutrient input and (without mitigation) could result in greater risk of eutrophication or other undesirable change, especially when coupled with effects of other pressures. The greatest risk lies in those lochs and voes where nutrient Assimilative Capacity (AC) becomes overloaded during summer.</p> <p>Although specified harmful algae are currently monitored in Scottish waters because their toxins can cause harm to humans who eat contaminated shellfish, only in two lochs are sufficient observations being made, and interpreted, to track and understand changes in the phytoplankton as a whole.</p>
Mitigation	<p>Better modelling in choice of sites and stocking, and Adaptive Management of site use, could help to prevent the nutrient AC of a loch or voe from being overloaded.</p> <p>Current schemes for monitoring Harmful Algae could be extended to monitor full plankton communities at selected sites, in order to track and understand larger-scale change.</p> <p>RAS remove some, but in most cases not all, fish-excreted nutrients, and are energy expensive. Loch-scale Integrated Multitrophic Aquaculture (IMTA) involving shellfish and seaweed cultivation might beneficially use nutrients excreted by salmon as well as increasing AC. However, there is insufficient evidence about the use of these techniques, and experts differ as to their feasibility and effectiveness.</p>
Additional commentary	<p>Since the early 2000s, monitoring and research have concentrated on Harmful Algae and their blooms (HABs), which can threaten salmon farming by causing fish mortalities and by contaminating cultivated and wild shellfish, rendering these products dangerous for human consumption whilst the contamination persists.</p> <p>Naturally occurring spiny phytoplankton may pose a risk to fish health through damaging gills. Gelatinous plankton such as jelly fish, when present in large numbers, also pose a risk to net-cage farming but little is known about the conditions that give rise to these events.</p>

Issue	<i>Medicines and chemicals: Synthetic chemicals (including antibiotics) used to treat lice infestation or salmon diseases, to prevent fouling of farm structure, or as dietary supplements, might be harming other organisms and, perhaps, ecosystems</i>
Diagnosis	<p>Chemicals used in bath treatments for sea lice include hydrogen peroxide, synthetic pyrethroids, and organophosphates (the latter including the widely used azamethipos). Systemic (in feed) treatments tend to be more efficient; of these, only emamectin benzoate (EMB) is currently used in Scotland. Excepting hydrogen peroxide, both bath and in-feed treatment chemicals can persist in the environment. Lice are becoming resistant to existing medicines treatments.</p> <p>Therapeutants are also used in bath treatments for fungal infections and antibiotics (in diet) are used for several types of bacterial infection.</p> <p>Antifouling compounds based on copper and zinc retard the development of the microbial and micro-algal base layers on maritime structures, which lead to fouling by seaweeds and invertebrates. Derivatives from these compounds can leach into the water column.</p> <p>Use of all these compounds is strictly regulated; Controlled Activity Regulations (CAR) licences are given on the basis of dispersal modelling and Environmental Quality Standards (EQS) are based on laboratory toxicity testing, and updated when necessary.</p> <p>Because these chemicals are designed as biocides, their persistence in the environment can create pressures on populations of non-target organisms. There is a lack of knowledge about diffuse, far-field effects of these chemicals on benthic and pelagic ecosystem components, and this renders uncertain the amount of precaution needed in setting EQS.</p>
Prognosis	<p>Increased production is likely to require additional use of existing or newly developed chemicals</p> <p>There is a lack of ability to adequately predict low-level effects of long-term usage of these chemicals on benthic and pelagic ecosystem components at the scale of lochs. The concept of Assimilative Capacity (AC) may not be applicable.</p>
Mitigation	<p>Replacement of therapeutic treatments for lice which have negative environmental impacts. Development of physical treatments to remove lice, or the use of cleaner-fish (e.g. wrasse and lumpsuckers); development of lice-resistant strains of salmon. Development of vaccines for sea lice has been a long term goal, but there has been no progress in this area despite considerable research effort.</p> <p>An adequate strategy for monitoring and transparently reporting compounds in the environment in relation to benthic and pelagic ecosystem state, and for supporting relevant research using these data.</p> <p>Improved biosecurity (in freshwater hatcheries and in marine farms) to exclude causes of disease (especially untreatable viruses), and increased use of vaccination against bacterial disease, allowing further reduction in antibiotic use.</p>
Additional commentary	<p>Emamectin benzoate (EMB) is the active ingredient in the compound SLICE® that is added into feed, and is used for the control of infestations of all parasitic stages of sea lice.</p>

Issue	<i>Escapes: Salmon escaping from farms could interbreed with wild salmon populations, harming the adaptiveness of the wild fish</i>
Diagnosis	<p>An average of 146,000 cultivated adult salmon are reported to enter the sea from salmon farms each year in Scotland. Causes include holes in nets, human errors and effects of predators. The number is likely to be under-reported.</p> <p>Although the majority of these fish do not survive to mix with wild populations, the number of survivors is estimated to be significant in relation to numbers of wild salmon in Scotland (about a third of a million).</p> <p>Most evidence about the effects of escapes comes from Norway, where flow of genes into wild populations has been documented. There is little information on the extent to which such genetic mixing occurs in Scottish salmon.</p> <p>Although farmed salmon are descended from wild salmon, the genetic makeup of farmed salmon has diverged as a result of artificial selection for survival and growth in farm conditions. Thus, gene flow from escapees to wild salmon, which has been shown to change smolt maturation age and size in Norway, could weaken population adaptiveness to conditions in the wild fishes' natal rivers.</p> <p>There is also the potential for indirect genetic changes to wild populations as a result of changes to the environment experienced by wild populations e.g. increased exposure to sea lice or other pathogens. These could affect the ability of wild populations to deal with natural wild environmental changes e.g. global warming.</p> <p>Additional adverse effects of escapes of cultivated salmon include competition by the escaped fish for food and breeding territory; escaped fish are potential prey and this increased availability of food might attract larger numbers of predators, with greater impacts on the wild populations.</p> <p>There appear to be no studies that quantify these indirect effects.</p>
Prognosis	Increase in numbers of farmed salmon is likely to result in more escapees, unless farming practices are changes.
Mitigation	<p>Changes in farm construction and management practices (e.g. Technical Standard for Scottish Finfish Aquaculture published in 2015) could reduce escapes.</p> <p>Development of salmon strains that are sterile (preventing interbreeding with wild fish).</p> <p>Increased knowledge about the extent of genetic interchange between farmed and wild salmon, and its effects on the latter in Scotland, would benefit assessment of effects and the need for mitigation. Some of this knowledge could be gained by routine genetic monitoring of wild salmon.</p>
Additional commentary	Triploids, strains of cultivated salmon with three sets of chromosomes, cannot cross-breed with wild salmon. However, experiments to develop triploid strains have so far not proven commercially successful.

Issue	<i>Feed sustainability: How to provide enough protein and 'omega-3' rich oil to farmed salmon, without adverse effects on the environment including on stocks of wild fish captured for making feed</i>
Diagnosis	<p>Atlantic salmon require feed with a high protein content to grow well, plus a high content of 'omega-3' lipids if they are to satisfy human dietary needs for these products.</p> <p>During the early years of salmon farming these requirements were met by feed containing about 90% fishmeal (FM) and fish oil (FO), obtained mainly from European and South American catches of small pelagic 'forage fish', such as the Peruvian anchovy.</p> <p>These fisheries are now mostly well-managed and sustainable, but they are finite and their natural productivity varies strongly interannually in response to environmental conditions. Consequently, salmon feeds have been reformulated during the last 25 years, and now contain up to 70% (high-protein) vegetable meal (VM) and an amount of vegetable oil (VO). As a result, salmon farming now produces more marine protein than it consumes.</p> <p>However, FO has proved harder to substitute than fish meal, because VO does not naturally contain 'omega 3'. There are also concerns about using agricultural land to grow oil crops, even if salmon are more efficient than farmed sheep, cattle, pigs or chickens at converting their feed into edible flesh.</p>
Prognosis	<p>Increasing salmon production in Scotland and elsewhere (e.g. Norway) will necessarily increase the demand for the raw materials for feed, and will compete in this with increased production elsewhere (especially, in Norway).</p>
Mitigation	<p>Taking the raw materials for feed from certified sources will aid sustainable management of fisheries.</p> <p>Increased use could be made of directly recycled ingredients such as fish trimmings. Exploring the economic and environmental efficiency of insects grown on waste food, or the products of Integrated Multitrophic Aquaculture (IMTA), could bring additional sources of protein into feed.</p> <p>The required additional, sustainable, source of 'omega-3' could be obtained from transgenic oilseed crops. However, this is not currently possible because of the Scottish ban on Genetically Modified (GM) crops and the widespread European reluctance to allow GM products in diets. An alternative, needing more development and probably more costly, is the use of cultivated micro-organisms.</p>
Additional commentary	<p>The term 'omega-3' refers to a group of <i>long chain polyunsaturated fatty acids</i> (LC-PUFA) that are common in fish oils, and which originate in marine algae before passing up the food chain. Vertebrates (including humans) use them metabolically but have difficulty synthesising them from other foodstuffs. Terrestrial plant (vegetable) oils can contain the related 'omega-6' PUFA and short-chain omega-3, neither of which can substitute for omega-3 LC-PUFA.</p>

Issue	<i>Predators: Deterrence of piscivorous predators by netting, or acoustic methods, or by shooting of seals, might harm populations of protected marine mammals and seabirds</i>
Diagnosis	<p>Salmon-farms are attractive to marine mammals and birds. Reasons include perches (for birds) and sources of food - either the farmed fish, or wild fish (of various species) that are attracted to waste feed, shelter etc. provided by the farms. Birds and mammals, especially seals, may take, injure or frighten farmed fish, or damage nets leading to escapes.</p> <p>Anti-predator nets above net-pens are intended to prevent loss to birds; however, there are few data on the efficiency of this protection. Entanglement in nets above and below water is a potential, although poorly-studied, mortality risk for birds and marine mammals</p> <p>Seals can be shot under Scottish government licence. Based on reported numbers of seals shot, current mortality levels represent a small proportion of Scottish seal populations. There may, however, be potential seal welfare problems (e.g. seals wounded rather than killed, nursing females killed leaving dependent pups).</p> <p>Acoustic Deterrent Devices (ADDs), which produce a loud underwater noise, are widely used as non-lethal seal deterrents. There is, however, little evidence concerning the efficacy of ADD. Their use adds to underwater noise pollution, which is known to cause behavioural changes in acoustically sensitive marine mammals (in particular cetaceans).</p> <p>No publications were found that assessed secondary effects of synthetic therapeutants or antibiotics used at farms on marine mammals and birds, nor any potential effects of plastic waste which may come from farms.</p>
Prognosis	<p>A simple prediction is that effects on predators will increase as salmon production increases, but the outcome may depend on factors such as siting of farms in relation to seal haul-out areas, and on the availability of other food for the mammal and bird populations.</p>
Mitigation	<p>Additional regulation of shooting could improve seal welfare, e.g. through the reintroduction of closed seasons for shooting corresponding to the main nursing periods for seals. Validation of shooting reports, and additional post mortems on shot seals could increase the proportion of 'clean kills'.</p> <p>Better reporting of ADD usage, and improved understanding of ADD function, impact and efficacy, could help to assess and manage the trade-off between seal deterrence and acoustic pollution with its potential effects on cetaceans.</p> <p>Net modifications and good husbandry practices can also reduce depredation risk from seals. Research into entanglement risk to marine mammals and birds might help in designing better and safer gear.</p>
Additional commentary	<p>Only a proportion of seals may predate farmed fish. Others may be attracted by wild fish, or be curious about farm activities.</p>

Issue	<i>Wrasse/lumpsucker fishery: The harvesting of wrasse and lumpsucker for use as lice cleaners, could harm the wild populations of these fish</i>
Diagnosis	<p>There is increasing use of small 'cleaner fish' in salmon farming. Kept in fish cages, where they eat sea lice growing on salmon, they provide an alternative to chemical treatments for lice. The fish used are wrasse (several species), and lumpsuckers.</p> <p>Although most wrasse can be reared in hatcheries, production is at present limited to the species most in demand (ballan wrasse), and is inadequate to meet that demand. An increasing wild fishery bridges the gap.</p> <p>Lumpsuckers are easier and cheaper to rear, and so there is less demand for wild-caught fish. Breeding stock is still obtained from a pre-existing commercial fishery.</p> <p>The (largely unregulated) wrasse fishery may be having direct and indirect effects on wild populations in the coastal waters of Scotland and the SW of England.</p>
Prognosis	<p>There seems to be a growing trend towards rearing lumpsuckers (which are adapted to cold waters) in preference to wrasse (which are fish of temperate and tropical waters). However, it is not clear whether wrasse can, or will, be completely replaced by hatchery-grown lumpsuckers.</p> <p>Increasing unregulated capture of wild wrasse for use as cleaner-fish associated with increasing production of salmon in Scotland, coupled with potential increasing demand for wrasse from Norway, could damage wild wrasse populations.</p>
Mitigation	<p>The industry is moving in the direction of growing cleaner-fish (both wrasse and lumpsucker) in hatcheries. If this can be achieved in Scotland by 2019 (as the industry has stated), the pressure on wild stocks will be reduced.</p> <p>An assessment is required of future demand for cleaner-fish and of the prospects of fully meeting the demand with hatchery reared wrasse or lumpsucker. Such an assessment would be a precursor to identifying whether there is a need to introduce management measures for wild fisheries, especially those for wrasse, if hatchery supply cannot meet industry demand.</p>
Additional commentary	<p>The use of wrasse as cleaner-fish to remove sea lice in salmon farms dates back to the late 1980s. The main species used in Scottish, Irish and Norwegian farms are goldsinny, corkwing, rock cook and juvenile ballan wrasse.</p> <p>In SW England and some Scottish inshore fisheries, the fishing and export of live wild wrasse for use as cleaner fish is of commercial importance.</p>

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Acronyms & Abbreviations

AC	Assimilative Capacity
ADD	Acoustic Deterrent Device
ADI	Acceptable Daily Intake
ADM	Archer Daniels Midland
AGD	Amoebic Gill Disease
AHD	Acoustic Harassment Device
AMBI	AZTI Marine Biotic Index
ASC	Aquaculture Stewardship Council
AZE	Allowable Zone of Effect
BAP	Best Aquaculture Plan
BKD	Bacterial Kidney Disease
CAR	Controlled Activity Regulations
CEFAS	Centre for Environment, Fisheries and Aquaculture Science
CFP	Common Fisheries Policy
CoGP	Code of Good Practice
CoGPSA	Code of Good Practice for Scottish Finfish Aquaculture
CSTT	Comprehensive Studies Task Team
DAIN	Dissolved Available Inorganic Nitrogen
DAIP	Dissolved Available Inorganic Phosphorus
DE	Digestible Energy
Defra	Department for Environment, Food & Rural Affairs
DFO	Fisheries and Oceans Canada
DHA	Docosahexaenoic acid
DNA	Deoxyribonucleic Acid
DIN	Dissolved Inorganic Nitrogen
DIP	Dissolved Inorganic Phosphate
DOM	Dissolved Organic Matter
DON	Dissolved Organic Nitrogen
DP	Digestible Protein
DPSIR	Driver-Pressure-State-Impact-Response
DSD	Dangerous Substance Directive
DSi	Dissolved Silicon
DSP	Diarrhetic Shellfish Poisoning

DZR	Depositional Zone Regulations
ECASA	Ecosystem Approach to Sustainable Aquaculture
ECE	Equilibrium Concentration Enhancement
EC50	Median Effective Concentration
eDNA	Environmental DNA
EFA	Essential Fatty Acids
EMB	Emamectin Benzoate
EPA	Eicosapentaenoic Acid
EPS	European Protected Species
EQS	Environmental Quality Standard
ERSEM	The European Regional Seas Ecosystem Model
EU	European Union
FAO	Feed and Agriculture Organisation
FCR	Feed Conversion Ratio
FFDR	Forage Fish Dependency Ratio
FHI	Fish Health Inspectors
FIFO	Fish in/Fish out Ratio
FM	Fishmeal
FMD	Floating Marine Debris
FO	Fish Oil
FOI	Freedom of Information
GOED	Global Organisation for EPA and DHA Omega -3S
GM	Genetically Modified
GMO	Genetically Modified Organism
HA	Harmful Algae
HABs	Harmful Algal Blooms
HDPE	High Density Polyethylene
HRA	Habitat Regulation Assessment
ICES	International Council for the Exploration of the Sea
IFG	Inshore Fisheries Group
IHN	Infectious Haematopoietic Necrosis
IUU	Illegal, Unreported and Unregulated
IFCA	Inshore Fisheries and Conservation Authorities
IMTA	Integrated Multitrophic Aquaculture

IPN(V)	Infectious Pancreatic Necrosis (Virus)
ISLM	Integrated Sea Lice Management
ISA(V)	Infectious Salmon Anaemia (Virus)
IQI	Infaunal Quality Index
ITI	Infaunal Trophic Index
LAP	Processed Animal Protein (PAP) derived from Land Animal
LCA	Life Cycle Analysis
LC50	Median Lethal Concentration
LC-PUFA	Long Chain Polyunsaturated Fatty Acids
LNA	Linolenic Acid
LOEC	Lowest Observed Effect Concentration
MA	Marketing Authorisation
MASTS	Marine Alliance for Science and Technology for Scotland
MCZ	Marine Conservation Zone
MHC	Major Histocompatibility Complex
MLS	Minimum Landing Sizes
MMAP	Marine Mammal Protection Act
MO	Marine Oil
MODR	Marine Oil Dependency Ratio
MP	Marine Protein
MPA	Marine Protected Areas
MPDR	Marine Protein Dependency Ratio
MRL	Maximum Residue Limit
MSC	Marine Stewardship Council
MSFD	Marine Strategy Framework Directive
MSP	Marine Spatial Planning
MSS	Marine Science Scotland
MTQ	Maximum Treatment Quantity
N	Nitrogen
NGO	Non-Governmental Organisation
NH ₄ ⁺	Ammonium
NO ₃ ⁻	Nitrate
NOEC	No Observed Effect Concentration
P	Phosphorus

PAP	Processed Animal Protein
PBDEs	Polybrominated Diphenyl Ethers
PBR	Potential Biological Removal
PCBs	Polychlorinated Biphenyls
PD	Pancreas Disease
PO ₄ ³⁻	Phosphate
POPs	Persistent Organic Pollutants
PMF	Priority Marine Features
PNEC	Predicted No Effect Concentration
RAS	Recirculating Aquaculture Systems
RIFGs	Regional Inshore Fisheries Groups
RSPCA	The Royal Society for the Prevention of Cruelty to Animals
RTRS	Roundtable on Responsible Soy
SAC	Special Area of Conservation
SAMS	Scottish Association for Marine Science
SARF	Scottish Aquaculture Research Forum
SAV	Salmonid alphavirus
SCOS	Special Committee on Seals
SEPA	Scottish Environment Protection Agency
Si	Silicon
SNH	Scottish Natural Heritage
SPA	Special Protection Areas
SPICe	Scottish Parliament Information Centre
SRSL	SAMS Research Services Ltd.
SSPO	Scottish Salmon Producers Organisation
SSSI	Site of Special Scientific Interest
TAQ	Total Allowable Quantity
TBT	Tributyltin
UFAS	Universal Feed Assurance Scheme
UKBAP	UK Biodiversity Action Plan
V	Volume
VHS(V)	Viral Haemorrhagic Septicaemia (Virus)
VM	Vegetable Meal
VMD	Veterinary Medicines Directorate

VO	Vegetable Oils
WCA	Wildlife and Countryside Act
WCRIFG	West Coast Regional Inshore Fisheries Group
WFD	Water Framework Directive

1 INTRODUCTION

The lochs, voes and sheltered coastal waters of the Scottish west coast and Western and Northern islands provide ideal conditions for growing salmon in floating net-pens. The aquaculture industry creates jobs not only on farms but also in upstream and downstream activities such as producing fish feed and processing fish and supports secondary economic activity in rural coastal communities. Nevertheless, its growth during recent decades has encountered economic, societal and environmental challenges, and these will be intensified during its planned expansion from 163,000 tonnes in 2016 to about 200 thousand tonnes production in 2020, and up to 300 thousand tonnes by 2030.¹

In 2018 the Rural Economy and Connectivity Committee will be conducting an inquiry into salmon farming in Scotland. To feed into that inquiry the Environmental Climate Change and Land Reform Committee will be considering the current report. Briefing by Scottish Parliament Information Centre (SPICe) on salmon farming in Scotland will also inform both Committees work.

This report specifically reviews the environmental effects of salmon farming, and suggests mitigations where there are concerns about harm to marine ecosystems or protected species and habitats.

The aim of the research is to carry out a comprehensive literature review to assess and summarise:

1. The environmental impacts of salmon farming in Scotland;
2. The scale of these impacts, and;
3. Approaches to mitigating impact.

The environmental impacts were split into six main areas for investigation (as outlined in the research specification issued by The Scottish Parliament, Ref: 2017-18/01/REC). Each of these areas represents a specific issue of concern related to the potential impacts of salmon farming:

- a. Disease impacts on wild and farmed stocks, including the impact of sea lice;
- b. The discharge of waste nutrients and their interaction in the wider marine environment, including:
 - i. Solid wastes from cage farms and effects on sediments;
 - ii. Dissolved nutrient inputs and effects on phytoplankton.

¹www.gov.scot/Publications/2017/09/520 gives 2016 production; www.gov.scot/Topics/marine/Fish-Shellfish gives the objective as 210,000 tonnes marine finfish production in 2020; this includes Salmon, Rainbow trout, Halibut, Brown/Sea trout. The last three are unlikely to exceed 10,000 tonnes in total. The industry document, Aquaculture Growth to 2030 (Anonymous, 2016) proposes doubling the value of aquaculture (which includes shellfish) by 2030; www.bbc.co.uk/news/uk-scotland-scotland-business-37781081 interprets this as 350,000 tonnes salmon by 2030.

- c. Effects of discharges of medicines and chemicals from salmon farming, including:
 - i. Sea lice medicines;
 - ii. Antimicrobial compounds;
 - iii. Metals.
- d. Escapes from fish farms and potential effects on wild populations;
- e. Sustainability of feed supplies – including research on plant meal substitution;
- f. Emerging environmental impacts, including:
 - i. Impact on wild wrasse;
 - ii. Impact on marine mammals.

The report was prepared by a group of subject experts from throughout Scotland for the Scottish Parliament.

1.1 Guide to this Document

The present report may be seen as updating, for salmon farming only, the "Review and Synthesis of the Environmental Impacts of Aquaculture" of 2002. The update is based on selected scientific papers and reports published since then. Ideally, these deal with studies carried out in Scottish waters, but, in cases where these were scarce, evidence has been taken from investigations of salmonid-farming effects in Norway, Canada, Australia, New Zealand and Chile, and in some cases from research into the farming of other fin-fish in other waters.

This introductory Section 1 provides background information on salmon, sea lice, and the environment of north-western Scotland and the islands where salmon farming mainly takes place. In addition, it provides a conceptual framework for the identification of environmental effects and their significance.

Sections 2 - 7 address environmental effects in relation to the issues specified in the Scottish Parliament's invitation to tender (2017-18/01/REC) and which are for convenience listed in Box 1.2.

Section 8 revisits the criteria used to assess the significance of effects and compares this review's findings for Scotland with a recent risk assessment of the environmental impact of salmon farming in Norway. It also includes further detail concerning Recirculating Aquaculture Systems (RAS) and Adaptive Management, and how their implementation may be effective mitigations for many of the issues within this review.

A glossary explains the technical terms used in this part of the report; these terms are signalled by appearing in bold on first use.

1.2 Wild and Farmed Salmon

'Salmonid' refers to two genera of cold-water **anadromous** fish, one genus including the Atlantic salmon *Salmo salar* and the sea-trout *Salmo trutta*, and the other, the genus *Oncorhynchus*, containing several species of Pacific salmon and the rainbow trout *Oncorhynchus mykiss*. Anadromous fish hatch in rivers or lakes but spend most of their adult lives in the sea before returning to fresh waters to breed.

Atlantic Salmon breed in rivers discharging to the Arctic, Atlantic and Baltic coasts of Europe, and the Atlantic coasts of Iceland, SW Greenland, and America north of the Hudson river. Eggs hatch in freshwater, the young feeding mainly on the aquatic larvae of insects. After 2 - 3 years they become **smolts**, adapted to salt water, and spend the next 1 to 5 years at sea, with a diet of pelagic crustaceans and small fishes, before returning to rivers to breed, and, in some cases, repeating the cycle. Exactly where Scottish salmon go in the sea is not well known, but it seems likely to be in waters close to southern Greenland or between Iceland and Norway (Curd, 2010; FAO, 2017).

According to **OSPAR** (Curd, 2010), "*The salmon's homing behaviour results in [genetically] distinct groups ['populations'] of individuals returning to reproduce in their natal rivers and streams. ... natural selection acts to adapt the salmon of these groups to the conditions that they will face in the home river and along their migration routes.*" Most wild populations of salmon are in decline, for reasons that include climate change, human alterations of riverine habitats, and commercial fishing in both fresh and salt waters.

While annual commercial catches of Atlantic salmon fell from about 10,000 tonnes between 1950 and 1990, to less than 2,000 tonnes from 2005 (Curd, 2010), global production of farmed Atlantic Salmon rose from 1 tonne in 1964 to more than 2.3 million tonnes in 2014 (FAO, 2017).

During the 19th century freshwater hatcheries were developed to augment reproduction of wild salmon. By the late 1960s, when the first salmon farms were established in Scotland and Norway, breeding methods were well established, and the genetic makeup of farmed salmon was diverging from that of wild salmon (Ellis *et al.*, 2016). Typically, farmed fish are raised in hatcheries for 12 to 18 months, and then transferred as smolts to floating sea cages for 12 to 22 months, before harvesting. In 2014, when Scottish production was about 179 thousand tonnes, about 48 million smolts were 'put to sea' and about 34 million salmon harvested (Ellis *et al.*, 2016). In comparison, the stock of spawning salmon in UK rivers was estimated as about 0.6 million in 2012 (Anonymous, 2013).

Whereas the commercial fishery of salmon is in decline, the sports or recreational fishery of wild salmon in Scottish waters continues to be a significant economic sector (PACEC, 2017). About 47 thousand salmon were taken by rod and line in 2014, most being returned to the river where they were caught.

1.3 Sea Lice and Other Diseases of Salmon

Sea lice are marine crustaceans belonging to the group called **copepods**. Most copepods are free-living, feeding on smaller animals and micro-organisms in the **plankton**. In contrast, adult sea lice of the genera *Caligus* and *Lepeophtheirus* attach to the flesh of salmonids, feeding on host mucus, tissues and blood. They cause wounds that may become infected with pathogens.

Sea lice eggs hatch into free-living young that have a few days to find a host. The keeping of salmon close together in farms increases the probability of a louse completing its life cycle by infecting other farmed fish and, potentially, wild salmon in the vicinity.

What is true of sea lice is also true of viruses, bacteria, protozoa, and fungi that can infect both wild and farmed salmon: the probability of re-infection increases with the number of animals kept in proximity, and there may be an increased risk of cross infection between farmed and wild salmon and other known vectors of these pathogens.

1.4 The Environment for Salmon Farming

Salmon farming is limited to the west coast, and the coasts of the Hebrides and the northern islands, which are characterised by many inlets: the sea-lochs and (in Orkney and Shetland) voes. Most were formed by glaciation and belong to the category called **fjords** by geographers, characterised by their possession of shallow sills at or near their entrances and in some cases between internal basins. These, and island-sheltered straits, are good sites for salmonid farming because they combine shelter with reliable flows of cool, well-oxygenated, sea-water.

Statistics for 110 of the inlets were collected in the 'Sea-lochs Catalogue' (Edwards & Sharples, 1986). Table 1.1 lists some examples, and Figure 1.1 illustrates some of the components of water circulation that mediate the environmental effects of salmon farming (see also Inall & Gillibrand (2010).

The waters into which the sea-lochs and voes open are of several types:

- Larger fjords, such as the Firth of Clyde and the Firth of Lorne; the Clyde differs from others in that it is influenced by the urban, industrial and agricultural wastes of western Scotland;
- Island-sheltered straits, such as the Minch;
- The waters of the Scottish continental shelf beyond the western and northern Isles, open directly to influences from the Atlantic Ocean.

There is a general pattern of clockwise flow around Scotland: water leaving the Firth of Clyde and the Irish Sea, mixes with Atlantic water in the Sea of the Hebrides and then travels northwards up the Minch, and to the west of the Long Island, before passing along the north coast (McKay *et al.*, 1986; Simpson & Hill, 1986; Hill & Simpson, 1988). It can carry contaminants, nutrients, harmful algae, parasites and pathogens.

1.5 Environmental Pressures Due to Salmon Farming

The Driver-Pressure-State-Impact-Response (DPSIR) framework (Luiten, 1999) categorises human-environment interactions in five stages: (1) Drivers in society that determine human activities leading to (2) **pressures** on (3) the **state** of the **ecosystems** that make up the natural environment; (4) the **impacts** on society of effects on State, and (5) society's response to these impacts. Activities associated with salmon farming are listed in Box 1.1; they create pressures, and affect ecosystem state, on several scales:

- On the largest scales, up to that of the planet, there are the effects of the harvesting of wild fish, or the cultivation of crops, to provide feed for farmed salmon;
- On the smallest scale, that of farms themselves, there are the effects on local water quality and biota of farm structures, salmon wastes, chemicals and medicines used to treat fish or prevent fouling of cages;
- In between these scales, organic and nutrient wastes and chemicals can cause changes in ecosystems within sea-loch basins and might aggregate to cause changes over wider areas, such as that of the Minch; sea lice and disease might infect wild salmon on similar scales.

Box 1.1: Activities associated with salmon farming that create pressures on ecosystems or the species and habitats within these:

- The use of water as a medium (including abstraction and interference with flows);
- The construction and deployment of structures (which may damage the seabed) and the use of synthetic chemicals as anti-fouling compounds;
- The deterrence of marine mammals and sea-birds seeking to eat farmed fish, which might harm populations of these animals;
- The feeding of fish and the excretion by the fish of metabolic by-products (i.e. organic waste in food and faeces, and compounds of nitrogen and phosphorus);
- The integrity and maintenance of containment structures, where failure can lead to fish escapes, resulting in a risk of gene flow into wild salmon;
- The containment of fish at comparatively high densities at fixed sites, which can facilitate infections with disease-causing pathogens (viruses, bacteria protozoa, fungi) and parasites (especially, sea lice);
- Treatments for, and prevention of, these diseases, especially chemotherapeutants and antibiotics;
- By-products of farm operation, including plastic waste and diesel spills;
- The acquisition and processing of the raw materials for fish feed.

1.6 Criteria for Assessing Environmental Effects

Mitigation of the environmental effects of salmon farming requires reduction of the pressures generated by the activity. This has costs, at least in the short term, and therefore it is necessary to demonstrate that:

- Effects are caused by pressures caused by salmon farming;
- Effects are significant.

Much of the remainder of this document is concerned with assessing the evidence for causal links from pressures to effects. Notice that 'effect' is used in a value-neutral sense, prior to assessment of the significance of a change.

Judgements about significance will depend on the kind of effect, in two main categories:

- i. Effects on ecosystems that may harm **ecosystem functioning, ecosystem resilience** to other pressures, and the supply of **ecosystem services**;
- ii. Effects on (legally) **protected habitats or species**.

Sea lice nutrient wastes consist mainly of natural materials; persistent harm results only when these overwhelm the Assimilative Capacity of the local environment to disperse, absorb and recycle these wastes. The wastes may cause local changes in ecosystems, but these are treated in this review as tolerable, on anthropocentric and utilitarian grounds, so long as they do not lead to widespread harm to ecosystem health or damage to ecosystem services. In contrast, salmon farming (like most other forms of agriculture) also introduces, into the marine environment, synthetic chemical compounds that ecosystems have never previously experienced. An ecosystem's assimilative capacity for these is likely to be low. Regulators try to find Environmental Quality Standards (EQS), concentrations below which the toxic effects of these chemicals are absent; exceeding EQS will be deemed a significant effect. Some debate centres on the reliability of existing EQS.

In the second case, any detectable effect is to be avoided. Protected organisms include marine mammals and sea-birds, which might be attracted to salmon farms by the prospect of food (either from the farmed fish within the net-pens or from wild fish clustering outside). Protected habitats² include maerl beds of calcareous red seaweed, reefs of tube-worms, and underwater meadows of seagrass, all of which may be damaged by farm structures or wastes. This review includes wild salmon in the protected category, even if it is managed mainly as a fishery.

1.7 Issues

As in the case of the 2002 "Review and Synthesis", this review is organised mainly around the issues identified in its Research Specification. Sections 2 through 8 deal with the effects of salmon farming in relation to the issues listed in Box 1.2.

² Refer to Priority Marine Features (PMF) in the Glossary for the meaning of 'protected' in this context.

Box 1.2: Summary of the issue-based Sections

Lettered headings are taken from the Research Specification and numbered headings refer to Sections in this document

a. Disease Impacts on wild and farmed stocks, including the impact of sea lice

- 2.1. Sea lice: lice from salmon farms might infect wild salmon and damage their populations;
- 2.2. Diseases: diseases of farmed fish might spread to other animals, especially wild salmon;

b. The discharge of waste nutrients and their interaction in the wider marine environment, including (i) solid wastes from cage farms and effects on sediments, (ii) dissolved nutrient inputs and effects on phytoplankton

- 3.1. Organic waste: salmon farm organic waste accumulating on the seabed can significantly degrade communities of benthic animals beneath or near farms;
- 3.2. Eutrophication: significant enrichment of lochs and regional seas by salmon farm nutrients could lead to enhanced growth of phytoplankton and undesirable disturbance to the balance of organisms and to water quality;

c. Effects of discharges of medicines and chemicals from salmon farming, including (i) sea lice medicines, (ii) antimicrobial compounds, (iii) metals

- 4. Medicines and chemicals: synthetic chemicals (including antibiotics) used to treat lice infestation or salmon diseases, to prevent fouling of farm structures, or as dietary supplements, might be harming other organisms and, perhaps, ecosystems;

d. Escapes from farms and potential effects on wild populations

- 5. Escapes: salmon escaping from farms could interbreed with wild salmon populations, potentially harming the adaptiveness of the latter;

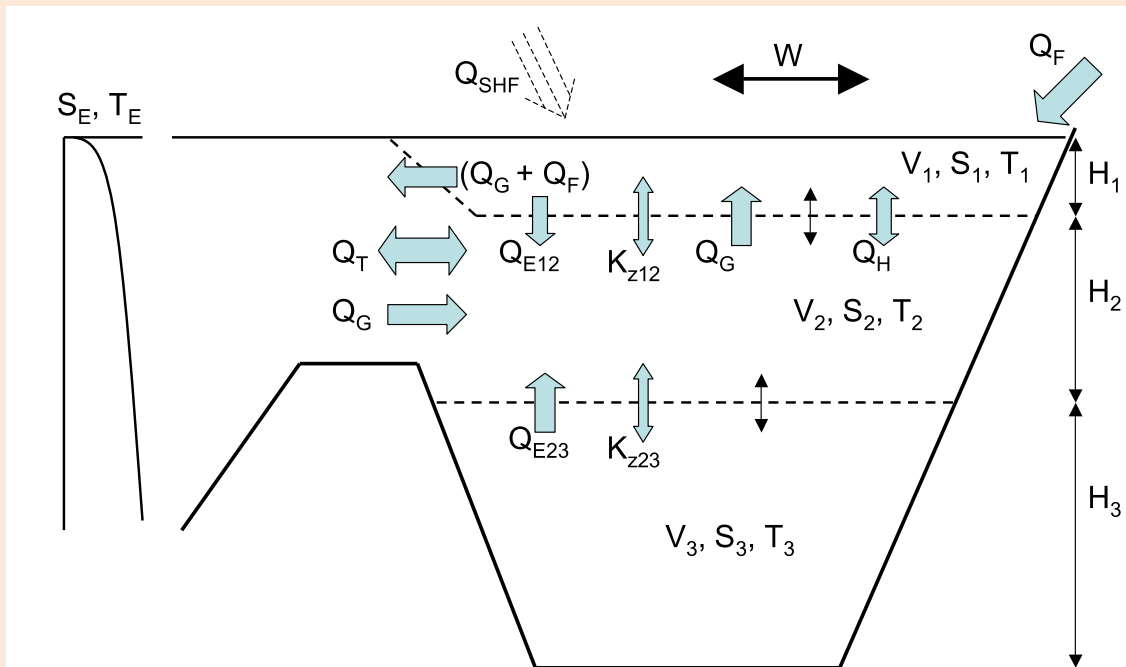
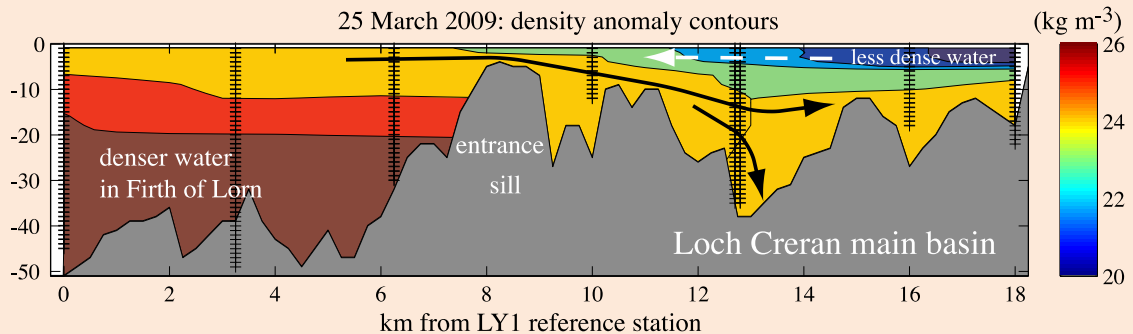
e. Sustainability of feed supplies -- including research on plant meal substitution

- 6. Feed sustainability: ability to provide enough protein and 'omega-3' rich oil to farmed salmon, without adverse effects on the environment including on stocks of wild fish captured for making feed;

f. Emerging environment issues, including (i) impact on wild wrasse and (ii) impact on marine mammals

- 7.1. Predators: deterrence of piscivorous predators by netting, or acoustic methods, or by shooting of seals, might harm populations of protected marine mammals and seabirds;
- 7.2. Wrasse fishery: the harvesting of wrasse and lumpsucker for use as lice-cleaners, could harm the wild populations of these fish.

Figure 1.1: Physical processes in sea-lochs



The upper part (from Tett *et al.*, 2011b) is a vertical longitudinal section through the Firth of Lorn (on the left) and Loch Creran (on the right). It has been contoured to show the main features of the distribution of high-density (cold, salty, more than 24 kg m^{-3} excess over freshwater) water and low-density (warm, fresher, less than 22 kg m^{-3}) water. The latter results from rivers discharging into the loch, and the circulation implied by this input and density distributions is shown by arrows. Tidal flood and ebb are also important.

The lower part shows the processes that contribute to water circulation and mixing in a sea-loch simulated as 3 layers by the ACEXR model of Gillibrand *et al.* (2013). H refers to layer thickness; K are exchanges of water properties by mixing; Q are water flow quantities (except Q_{SHF} , which gives the flow of heat from air to loch, or vice versa); S is salinity; T is temperature; V is layer volume; and W is wind speed. The flow subscripts are as follows: E, entrainment; F, freshwater; G, gravitational (density-driven); H wind-driven entrainment; T, tidal. Diagram from P. Gillibrand.

Table 1.1: A selection of sea-lochs (and one voe)

Name	Title	Where	Length (km)	Volume, million m³	Area, km²	Sills	Max depth (m)	In basin
Ainort	Loch	Skye	3.9	50.6	3.1	1	45	1
Ardbhair	Loch	Assynt	2.2	1.3	0.4	1	12	1
Creran	Loch	Argyll	12.8	177.6	13.3	4	49	2
Etive	Loch	Argyll	29.5	939.8	27.7	6	139	6
Fyne	Loch	Argyll	60.5	9746.7	175.5	2	135	2
Sand-sound	Voe	Shetland	8.6	79.1	6.1	0	42	0
Seaforth	Loch	Lewis/ Harris	22.6	372.4	20.2	3	98	1
Torridon	Loch	Wester Ross	22.2	4029.4	70	3	145	1

2 SEA LICE & DISEASE IMPACTS ON WILD AND FARMED STOCKS

This Section reviews the main diseases and infestations of farmed salmon, and seeks to answer the following questions:

- How are they controlled, and how successful is that control?
- Do parasites, and disease-causing micro-organisms (pathogens), transfer from farmed to wild salmonids?
- If so, do they cause significant harm to populations of wild salmon?

Infestations of the parasitic copepods called sea lice are a threat to fish welfare and farm economics as well as, possibly, to wild salmon populations. In addition, treatments for lice have environmental effects themselves. Thus, the effects of sea lice are given a subsection to themselves. This is followed by a Section dealing with other common diseases. The term 'impact' is retained from the research specification, and is understood to mean an effect of concern, assessed according to the criteria set out in Section 1.

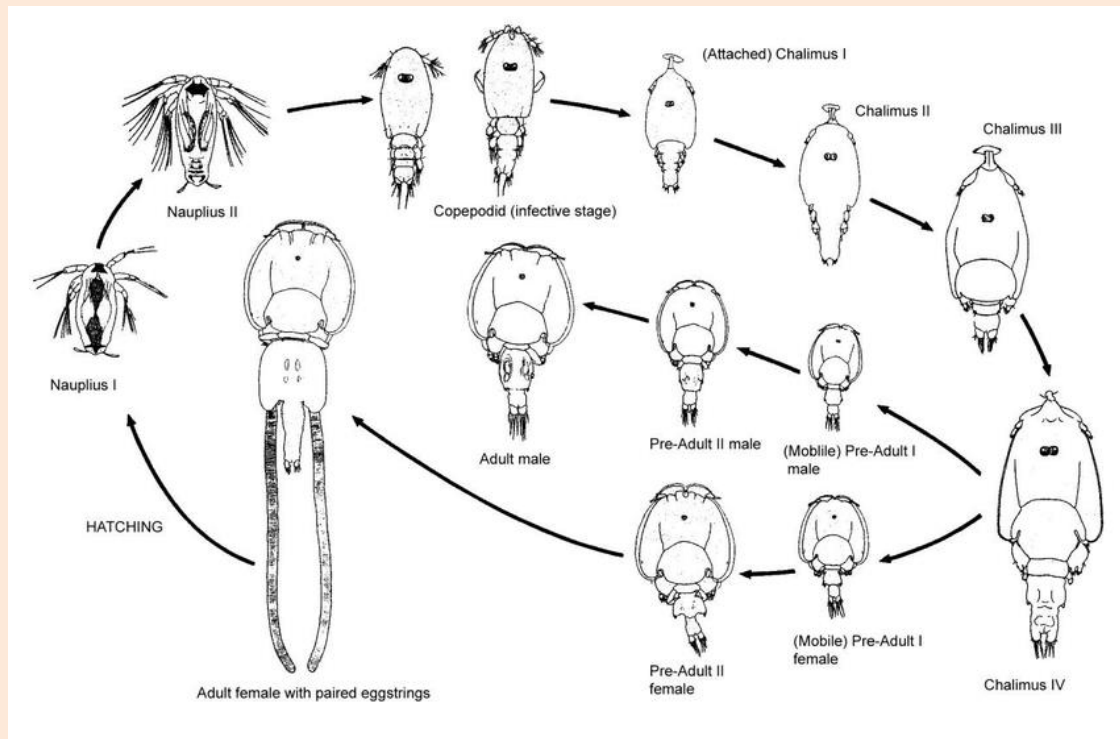
2.1 Sea Lice Impacts

Sea lice such as, *Lepeophtheirus salmonis* and *Caligus elongatus* (amongst others), are **ectoparasites** and a key impediment to the expansion of the Scottish salmon farming industry in the marine environment.

2.1.1 Lice and salmon

Sea lice occur naturally in the marine environment and are commonly found on wild adult salmon (Costello, 2006). Their life cycle lasts about 2 months, and has a free-living stage followed by a parasitic phase (Frazer, 2009) (Figure 2.1). Wild salmon can potentially infect farmed stocks when the former return from the ocean. Larval lice from untreated farmed salmon can increase the infestation levels on other farmed salmon, as well as on wild salmonids as they migrate past the cages to the sea (Bjørn *et al.*, 2011; Middlemas *et al.*, 2013; Serra-Llinares *et al.*, 2014; Helland *et al.*, 2015; Gargan *et al.*, 2017).

Figure 2.1: The stages in the life-cycle of the sea louse *Lepeophtheirus salmonis*. The Nauplius I & II and copepodid are free-living planktonic stages (Whelan, 2010).



Damage to salmon from sea lice

The parasitic phase can cause both **morbidity** and mortality of salmon as the parasite feeds on its host's mucous, blood, and skin (Costello, 2006). The first parasitic stage (**chalmus**) in the sea lice life cycle commonly only inflicts minor damage unless the infestation is excessively high and within the dorsal fin area (Bjørn & Finstad, 1998). The chalmus stage is succeeded by the pre-adult and fixed adult stages, which can inflict severe damage as they feed on the salmonid tissues; high infestation rates can lead to mortality of the host fish (Bjørn & Finstad, 1998; Dawson *et al.*, 1998; Wells *et al.*, 2006; 2007).

In addition to the mechanical tissue damage caused by lice feeding, the host fish also experience increased stress, diminished swimming capability, and imbalances in water and salt levels (Finstad & Bjørn, 2011; Thorstad *et al.*, 2015). Between 0.04 and 0.15 lice per gram of fish weight can elicit these responses in salmonids (Nolan *et al.*, 1999; Wagner *et al.*, 2003; Wagner *et al.*, 2004). For smolts and post-smolts, both laboratory and natural infestations studies indicate that eleven or more pre-adult and adult stage lice per fish will cause mortality (Finstad *et al.*, 2000; Wells *et al.*, 2006).

Lice and farming

Salmon farming provides favourable conditions for the growth of sea lice populations due to the high density of hosts (Torrissen *et al.*, 2013). The available evidence demonstrates that high sea lice abundance has direct negative effects on farmed fish (Jones & Beamish, 2011).

Salmon farming increases sea lice abundance and infects wild salmon

A clear relationship between the increased abundance of sea lice due to salmon farming and presence on wild hosts in the sea has been demonstrated outwith Scotland (Marshall, 2003; Morton *et al.*, 2004; Serra-Llinares *et al.*, 2016). For Scotland, there are no published accounts of systematic counts of sea lice levels on wild salmon and its association with salmon farming. The only reported scientific study relates to wild sea trout monitored over five successive farm cycles (Middlemas *et al.*, 2010; 2013), which found that lice burdens above critical levels (based on laboratory studies of sea trout) were significantly higher in the second year of the production cycle. Preliminary analysis of data from fallowing zones indicated that lice levels in farming areas are also correlated with farmed biomass (ICES, 2016).

Sea lice effects on wild salmon populations

The consequences of increased sea lice levels for wild salmonid populations are unclear. It is reasonable to expect that if levels on wild fish increase, there is potential for a negative impact. However, quantifying wild salmonid population mortality due to sea lice infections is complex, and the magnitude of lice effects depend on environmental, biological and ecological variables that have not been studied in depth (Helland *et al.*, 2015; Vollset *et al.*, 2015). Mortality levels due to sea lice have been predicted to cause a fall of 1% to 20% in adult salmon abundance (Jackson *et al.*, 2013; Krkošek *et al.*, 2013). However, salmon lice may only threaten population viability if high infections persist over a number of years and if populations are already depressed. Average parasite induced mortality in smolts has been estimated as in the range of 0.6% to 39% (across various locations and years) in experiments based on protecting groups of smolts chemically against sea lice (Gargan *et al.*, 2012; Jackson *et al.*, 2013; Krkošek *et al.*, 2013; Skilbrei *et al.*, 2013; Torrissen *et al.*, 2013; Vollset *et al.*, 2016). However, even a small percentage loss of smolts or adults may be significant if it combines with losses due to other causes so that salmon become critically endangered or lost (e.g. Finstad *et al.*, 2007; 2012).

In a recent review of sea lice impacts on wild salmon stocks, (ICES, 2016), it was notable that there were no studies relating specifically to effects in Scotland.

2.1.2 Sea lice management in Scotland

In Scotland, actions to control sea lice levels on fish farms are managed through legislation and a voluntary code of good practice. The three legislative frameworks are:

- The Aquaculture and Fisheries (Scotland) Act 2007;
- The Aquaculture and Fisheries (Scotland) Act 2013;

- The Fish Farming Businesses (Record Keeping) (Scotland) Order 2008.

Salmon farms currently work to control lice using several approaches (Aean *et al.*, 2015). These include: in-feed treatments such as emamectin benzoate (EMB; active ingredient in SLICE®); bath treatments such as hydrogen peroxide; biological controls such as cleaner-fish (e.g. wrasse or lumpfish); and new techniques such as thermal bath treatments.

The legislation is enforced by Fish Health Inspectors (FHI) appointed by Scottish Ministers. Inspectors undertake risk based surveillance assessments of all registered fish farms:

- Making on-site sea lice level assessments;
- Ensuring that satisfactory measures are in place for the prevention, control and reduction of sea lice;
- Ensuring that all farms are party to a farm management agreement or maintain a farm management statement;
- Ensuring that all records pertaining to staff sea lice training, sea lice records, medicinal records and sea lice counts are held and maintained appropriately.

The Scottish Salmon Producers Organisation (SSPO) provides a voluntary Code of Good Practice (CoGP), which includes guidance on a National Treatment Strategy for sea lice and Integrated Sea Lice Management (ISLM), though not all fish farming companies in Scotland are members of the SSPO. Compliance with this Code is also checked by FHI.

Across 30 regions in Scotland the SSPO produces quarterly fish health management reports³. These provide details in an aggregated format regarding farm management in areas, stocking, fallowing, strategic sea lice treatments and average sea lice counts.

Recent changes in management

In 2016, the Scottish Government undertook a review of the 'satisfactory measures' aspect of The Aquaculture and Fisheries (Scotland) Act 2007. In consultation with the aquaculture industry a new policy was developed that focused on two trigger levels. Exceeding the first trigger level, of an average of 3.0 female lice per fish, requires a site-specific action plan to be undertaken to manage lice numbers. If the average numbers of adult female lice continue to rise and exceed 8.0, then enforcement action may be taken by the Scottish Government, including the possible requirement to reduce biomass but is not mandatory.

Trigger levels might be set to ensure welfare of farmed fish or to reduce infections on wild salmon. However, there is no published scientific account of the basis for the setting these levels. Furthermore, it is not clear why these trigger levels are above the recommended CoGP levels requiring treatment, which are 0.5 or 1 lice per fish depending on the time of year. No data have yet been published on the results of this new approach. Therefore, it is unclear how successful it has been in keeping sea lice numbers down. This lack of transparency has led organisations to submit Freedom of

³ <http://scottishsalmon.co.uk/publications/>

Information (FOI) requests to Scottish Ministers. For example, data for the period of week 43 in 2016 (November) through to week 35 in 2017 (end of August) was recently released under an FOI appeal⁴ submitted by Salmon & Trout Conservation Scotland, and showed high lice levels at a number of farms.

Evolution in sea lice of resistance to pesticides and other treatments

Medicinal treatment of farmed fish has, so far, been the most reliable method of sea lice control, and this has led to extensive use of the available compounds (Grant, 2002; Aaen *et al.*, 2015). This has resulted in resistant parasites occurring on farmed, and possibly wild, salmonids: resistance has recently been found to be widespread, albeit variable, in all farming areas (Aaen *et al.*, 2015).

This includes resistance to EMB, known commercially as SLICE® (McEwan *et al.*, 2015; Grøntvedt *et al.*, 2014; Helgesen *et al.*, 2015) and to hydrogen peroxide bath treatments (Treasurer *et al.*, 2000). An epidemiological study found a gradual decline in efficacy of this compound since 2004 (Lees *et al.*, 2008), with further reductions in efficacy of EMB reported during the last decade. For example, in Scotland, a sevenfold reduced sensitivity towards EMB has been reported in an isolated salmon lice population on the West Coast (Heumann *et al.*, 2012). A study in Scotland (Treasurer *et al.*, 2000) found that sea lice were also able to develop resistance to hydrogen peroxide treatment, reducing the effectiveness of this form of treatment. Ironically, it has been argued on theoretical grounds that the transfer of sea lice from wild populations to farm stocks could actually be slowing down the evolution of resistance in farm populations of sea lice (McEwan *et al.*, 2015).

Salmon resistance to lice

A recent Scottish study (Hsin-Yuan *et al.*, 2016) indicates that resistance to sea lice in salmon is variable among individuals and families in farm strains, and thus has a significant genetic component. The same may also, by inference, be the case for wild populations of salmon. Furthermore, individuals with resistance can be predicted with moderate to high accuracy, which suggests that selective breeding of salmon strains with enhanced resistance can contribute to lice control in fish farming (Gharbi *et al.*, 2015).

2.1.3 Data availability

Currently data on certain aspects of Scottish Aquaculture production are published on Scotland's Aquaculture website⁵. However, this website does not present any details for sea lice on the farms. The only publicly available data for sea lice on farms at present for Scotland are those which are published in an aggregated format in the SSPO Health reports. Thus, it is difficult to report with any certainty, and in any detail, on the general or location-specific nature and extent of the problem of sea lice on salmon farms in Scotland.

⁴ <http://www.itspublicknowledge.info/ApplicationsandDecisions/Decisions/2017/201700453.aspx>

⁵ <http://aquaculture.scotland.gov.uk/data/data.aspx>

2.1.4 Diagnosis

The proliferation of sea lice on farms in Scotland is an issue in terms of fish welfare and economic cost as well as potential impacts on wild salmon. Sea lice impacts have been well researched in regards to physical host damage, but significant knowledge gaps remain. These include:

- The extent to which salmon farming practices are increasing the abundance of sea lice in the marine environment, and on wild salmonids, in Scotland;
- What, if any, additional mortality this causes to wild Scottish salmonid populations.

However, there is a gradually emerging body of evidence, from studies elsewhere, that sea lice not only have the *potential* to have a negative effect on wild salmon, but that in many situations this is *likely* to be the case (Gargan, 2000; Finstad *et al.*, 2000; Bjørn *et al.*, 2001; Butler, 2002; Ford & Myers, 2008; Otero *et al.*, 2011; Skaala *et al.*, 2014; Vollset *et al.*, 2014; Taranger *et al.*, 2015; ICES, 2016; Gargan *et al.*, 2017). With the currently high marine mortality rate for wild salmonids, and threatened status of many river stocks, any additional pressure, such as increased sea lice burdens, is undesirable, and could further erode the conservation status of vulnerable wild populations.

The main treatment methods used in Scotland are experiencing reduced efficacy in dealing with sea lice on farms. New techniques are being applied, although the long-term success of these is uncertain. The legislative and voluntary frameworks that underpin the management of lice levels on farms are not transparent. They appear neither to be succeeding in controlling sea lice, nor capable of addressing the environmental effects of the lice.

Additionally, the use of such treatments involving existing chemicals or therapeutants has the potential to have direct negative impacts on local ecosystems (as considered in Section 4).

2.1.5 Prognosis and mitigation

What is known indicates that current practices for treating sea lice on farms in Scotland have experienced reduced efficacy, and thus increased numbers of lice are occurring in the wild, in turn increasing the risk to wild salmonid populations. Even without an increase in Scottish production of salmon, this risk can be expected to increase in the future, unless the decreased efficacy due to increased resistance to treatments is addressed. Alternative methods and technologies to manage lice on farms including biological and mechanical controls are one option, but these also present additional farming and environmental challenges (as discussed in the case of wrasse and lumpfish in Section 7.1 of this report).

Sea lice abundance on farms

Management measures could continue to be improved and developed to reduce sea lice numbers on fish farms, and measures to support such activities encouraged, promoted and required.

Existing sea lice farm management and treatment approaches

Measures could be put in place to ensure all historical and current information on sea lice levels is accessible for independent analysis and scrutiny, thus providing the basis for the assessment of the long-term efficacy and sustainability of existing approaches to sea lice control.

New approaches to sea lice management

Measures could be implemented that promote the development of alternative, longer-term solutions to the reduction of sea lice levels in respect of rearing approaches, fish husbandry methods, cleaner fish, new eco-friendly therapeutants, and selective breeding and strain development.

The further development of novel husbandry approaches (such as fallowing and reducing time spent in marine cages) potentially offer more sustainable solutions. The same is true of including selective breeding for sea lice resistance in farm strains, or the development of new, more resistant strains from wild strains known to have a naturally higher resistance.

There is current uncertainty regarding the levels at which sea lice pose a threat to wild salmon; a co-ordinated programme that links sea lice levels on farms with those on wild fish would help reduce this uncertainty. This could provide a transparent and objective basis for defining actions and making decisions regarding the need to change management practices, or reduce farming biomass in some areas, or to allow increases in farm production if sea lice levels are within acceptable limits.

It has been demonstrated in Scotland that biophysical modelling offers an approach that could improve the control of infection risks between farms for sea lice and other diseases (Adams *et al.*, 2012a; Adams *et al.*, 2015; Adams *et al.*, 2016). Similar sea lice modelling approaches have been developed and are currently implemented by the Norwegian government (Nilsen *et al.* 2017). For such models to be fully developed and productive in Scotland there is a requirement to make real time farm sea lice data available.

2.2 Diseases and Other Parasites

In addition to sea lice, wild and farmed salmon are susceptible to a range of infections and parasites and Kilburn *et al.* (2012) estimated that approximately 33% of marine fish mortalities within a major salmon farming company in Scotland were attributed to infectious diseases. A number of these have proved of great economic and fish welfare consequence to salmon farms, but the main issue here is the extent to which pathogens and parasites from farmed fish affect wild populations.

2.2.1 Notifiable diseases

The Scottish Government lists a number of 'notifiable' diseases of wild and farmed fish, including sea lice.⁶ Causes of disease include viruses, bacteria, the water mould *Saprolegnia* (which is related to algae and protozoa, not fungi), and several animal

⁶ <http://www.gov.scot/Topics/marine/Fish-Shellfish/aquaculture/diseases>

parasites: flukes, nematodes and an obscure myxozoan (related to jellyfish). Animal parasites typically have a complex life cycle, requiring intermediate hosts before infecting salmon; the others spread infection directly. Some are primarily freshwater, others salt-water. Some are kept out of Scotland by biosecurity measures. New diseases continue to be described, sometimes without easily ascertainable causes.

About a dozen diseases (in addition to sea lice) are economically important in Scotland. For example, outbreaks of Infectious Salmon Anaemia (ISA), a disease caused by a virus related to influenza, caused major losses in 1998-1999 and 2008-2009. There was no cure, and the epidemics were ended by total elimination of all stock on affected farms. The virus is spread by contact with infected fish or their secretions, or contact with equipment or people who have handled infected fish, or perhaps by sea lice. It can survive in salt-water, so may be transmitted by water movements.

2.2.2 Infection routes and diseases of farmed salmon

Salmon farming is young, and so it is probably safe to assume that all its diseases originated in wild populations of salmonid (in contrast with diseases that have co-evolved in humans and domesticated animals: Dazsak *et al.*, 2000). New infections of farmed salmon can occur in hatcheries, acquired by transmission in freshwater, or can be brought in infected broodstock, eggs, or young.

Parasites might be acquired in the same way. For example, the fluke *Diplostomum spathaceum* has a complex lifecycle, passing through fish-eating seabirds and freshwater snails before infecting fish, especially their eyes, causing cataracts and mortality that might not occur until smolts have been put to sea (Menzies *et al.*, 2002; Voutilainen *et al.*, 2009).

Fish do not directly infect other fish with parasites like this. In cases of viral or bacterial pathogens, which can be directly transmitted between fish hosts, proliferation is favoured by the high density of fish in farms. In these circumstances, normally benign pathogens from wild populations can develop into serious diseases for farmed fish (Harvell *et al.*, 1999; Johansen *et al.*, 2011; Murray & Peeler, 2005; Krkošek, 2017). These can then infect wild populations.

The consequences of disease and other parasites for stocks of farmed fish in Scotland are clear. They include suppressed growth, increased mortality (either as persistent endemic losses and/or occasional large epidemics) and increased costs associated with control/treatments. However, none of these aspects are very well recorded (Murray *et al.*, 2016).

Finally, conditions in the sea help infectious diseases spread more quickly than on land (McCallum *et al.*, 2003). There are fewer barriers to the movement of hosts and pathogens, tides and currents aid the transport of pathogens, and many fish, including salmon, undertake large migrations.

2.2.3 Disease transmission to wild salmon

There is a substantial amount of research available on the diseases of salmonid fishes in respect of their general characteristics and impacts on fish, though largely in cultured

stock (Eiras, 2008). Although a naturally occurring part of aquatic ecosystems, the incidence of diseases in wild fish is poorly understood in most cases, as diseased fish tend to die and are not detected. However, when there are increased levels or outbreaks, either due to natural causes or outbreaks on fish farms, they can be demonstrated to negatively impact wild salmonids.

Very little research has been conducted on diseases of wild fish at the population level, and on the interactions between wild and farmed populations in terms of exchange of pathogens. A number of reviews have been carried out including Bergh (2007), Raynard *et al.* (2007) and Johansen *et al.* (2011). From these studies, several major common conclusions emerge. The first is that most of what little understanding has been gained on the aspects of farmed and wild disease interactions has come through opportunistic studies of outbreaks affecting large numbers of fish. Sampling wild fish in their natal environment for most types of studies poses a major logistic challenge, but this challenge is compounded when trying to quantify the level of disease and presence of pathogens in individuals from a population. This is particularly problematic as diseased fish are likely to die and be excluded from samples, either from the disease itself or due to an increased susceptibility to predators.

Wallace *et al.* (2017) recently undertook a systematic review of published and unpublished data on six key pathogens including *Renibacterium salmoninarum*, *Aeromonas salmonicida*, infectious pancreatic necrosis virus (IPNV), infectious salmon anaemia virus (ISAV), salmonid alphavirus (SAV) and viral haemorrhagic septicaemia virus (VHSV) (See Box 2.1).

Their findings indicated that while there were numerous identifiable cases in farmed fish, few cases were found in Scottish wild fish, something that potentially reflects the challenges of sampling diseased fish in the wild. However, they did conclude that overall the available information provides evidence for disease interactions between farmed salmon and wild populations. In Norway there has been found to be a limited infection of wild fish with most viral and bacterial pathogens experienced on farms, and as such have assessed this aspect to be of low risk to wild fish (Johansen *et al.*, 2011; Taranger *et al.*, 2015). In contrast, Madhun *et al.* (2017) reported that escaped salmon did carry infection into a Norwegian river, although they did not track this through to wild salmon.

Box 2.1: Infectious diseases of production salmonids (adapted from Wallace *et al.*, 2017)

- Bacterial kidney disease (BKD)
Caused by *Renibacterium salmoninarum*. The disease was first reported in Scottish farmed rainbow trout in 1979 and Atlantic salmon in 1980.
- *Aeromonas salmonicida*
Causative bacterial agent for furunculosis. First described on German fish farms in the late 1800s, furunculosis had a large impact on the growing Scottish farmed Atlantic salmon industry in the late 1980s.
- Infectious pancreatic necrosis virus (IPNV)
Primarily a viral disease of salmonids held under intensive rearing conditions. First reported outbreak in Scotland was at a rainbow trout hatchery in 1971.
- Infectious salmon anaemia virus (ISAV)
First reported in Norwegian farmed Atlantic salmon in 1984. The first outbreak of ISA in Scottish farmed salmon was in 1998, and was geographically widespread
- Salmonid alphavirus (SAV)
Pathogens to farmed salmonids that cause pancreas disease (PD) in marine Atlantic salmon, and sleeping disease in freshwater rainbow trout. Six subtypes are recognised, five of which are distributed in Scotland and Ireland. The first report of PD in Scottish salmon was in 1976.
- Viral haemorrhagic septicaemia virus (VHSV).
First described from Europe in 1938, VHSV is geographically widespread and a number of different fish species are susceptible (The World Organisation for Animal Health lists over 70 species). To date, there have been two outbreaks of VHSV in Scottish farmed fish: 1994 in farmed turbot, and 2013 on cleaner wrasse at Atlantic salmon farms.

2.2.4 Legislative framework for farm disease management

The Aquatic Animal Health (Scotland) Regulations 2009 manages the occurrence of the more serious, notifiable diseases of fish, molluscs and crustaceans by setting out requirements for persons with an occupational relationship with any of these species. One such requirement stipulates that the Fish Health Inspectors (FHI) should be notified in the event of certain symptoms arising within the farmed stock. Such notifiable diseases are listed in Part II, Annex IV of Council Directive 2006/88/EC, as amended, or Schedule 1 of the Aquatic Animal Health (Scotland) Regulations 2009. FHI has powers under The Aquaculture and Fisheries (Scotland) Act 2007 to authorise early harvesting of farmed fish if a situation arises where there is unacceptable damage being caused to the farmed fish, causing either commercial losses or animal welfare issues for the farmed fish.

2.2.5 Control and treatment

In some cases of disease outbreak, where diseases have not been detected early, management measures have had to be appropriate e.g. ISA (Hastings *et al.*, 1999) with the killing and removal of all fish in the farm. However, current measures for the control and treatment of the known serious, notifiable disease and pathogens are aimed at proactive prevention and containment. In some cases, such as ISA, the disease/pathogen can be eliminated by decisive action and appropriate changes to farm management. In other cases e.g. Amoebic Gill Disease (AGD), bacterial kidney disease (BKD) and pancreas disease (PD), the problem relates more to minimizing its extent, where causal pathogens are hosted by one or more wild species in the local marine environment e.g. AGD.

Pathogen and disease control in relation to such parasites and infectious agents can be achieved variously by the following methods:

- Biosecurity, both in hatcheries and in open freshwater and marine cases to prevent infection and movements of pathogens or parasites and to maintain exclusion of diseases and parasites not currently found in Britain. For example, fallowing of production sites is advocated to eliminate disease transmission from one generation to the next (Stagg & Allan, 2001), and controlled management zones (Hall *et al.*, 2014);
- Vaccines e.g. furunculosis (Munro & Gauld, 1995; 1996) have been a key contributor to salmon farming in Scotland;
- Chemical treatments e.g. AGD with hydrogen peroxide (Adams *et al.*, 2012b);
- Breeding of resistant strains of salmon e.g. PD (Gonen *et al.*, 2015).

2.2.6 Diagnosis

Farmed salmon suffer from a variety of diseases and parasites, the management of these issues is of great economic importance to the aquaculture industry (Lafferty *et al.*, 2015) and are monitored in Scotland by FHI. There is a risk that the infectious diseases can be transferred to wild salmon, increasing the pressures on threatened natural populations (Krkošek, 2017). There are two known disease transmission avenues between farmed stock and wild populations. The first is known as spill-over where transmission is from wild to farmed animals and the second is spill-back transmission which goes from farmed to wild (Daszak *et al.*, 2000; Krkošek, 2017). However, there is little evidence of the effects of such transmission on wild salmon populations, either in Scotland or elsewhere. It is this lack of knowledge that is of especial concern.

2.2.7 Prognosis and mitigations

As discussed in relation to other issues, increased numbers and sizes of farms is likely to lead to increased risk of infection of wild fish unless increases in farm biosecurity and disease prevention outpace the expansion of production.

Technical mitigations

Mitigations include continued development of resistant strains and vaccines, and enhanced biosecurity, especially in hatcheries and RAS. It can take a significant amount of time – decades in some cases -- to develop and ultimately to be able to use effective treatments. The scale of the salmon aquaculture industry and the market for these treatments is also not sufficiently attractive to many large pharma and agrochemical companies to make the necessary investments in the development of new treatments. This has been documented as a barrier in the past and remains so.

As argued elsewhere, RAS are unlikely to provide a complete solution, but may reduce the length of time that fish are exposed to infection at sea through the production of larger smolts and the associated shorter grow out period.

Research needs

New approaches to gathering information that can help to monitor disease risk need to be developed, as existing methods cannot provide the information required to meet this challenge. One area with the potential to provide useful information is eDNA (environmental DNA), as highlighted by work undertaken in Scotland (Peters *et al.*, 2017) and elsewhere (Fong *et al.*, 2016; Gomes *et al.*, 2017; Polinski *et al.*, 2017). Using such methods as eDNA allow for samples of sea water to be taken around fish farms to detect the extent to which disease vectors are released into the environment, and their temporal and spatial pervasiveness.

While these techniques will not be able to address concerns related to impacts on wild populations, they will be able to provide information about the degree to which pathogens are dispersed into the environment from farms, and provide a basis for monitoring the risk of exposure for wild fish and for modelling potential disease impacts. It may also provide the basis for identifying situations of risk, which can then be explored with more traditional methods.

3 THE DISCHARGE OF WASTE NUTRIENTS AND THEIR INTERACTION IN THE WIDER MARINE ENVIRONMENT

Two types of waste generated by salmon aquaculture are considered within this Section:

- i. Solid organic matter, which can smother seabed organisms or kill them by creating **hypoxic** or **anoxic** conditions whilst decaying,
- ii. Compounds of the elements Nitrogen (N) and Phosphorus (P), either in the solid waste or dissolved form. Both elements are **nutrients** that are essential for plant growth, but excess concentrations can bring about eutrophication.

Each of these wastes and effects is examined in turn, including a diagnosis of the current state of affairs. The third subsection takes the two kinds of waste together to consider effects on protected species and habitats and on the oxygen content of **basin** water in certain lochs. The fourth subsection considers prognosis and mitigations.

An early study of Norwegian salmon farming (Seymour & Bergheim, 1991) estimated that in 1989 the organic waste input into fjords from the production of 150,000 tonnes of fish was equivalent to 60% of the waste emissions generated by Norway's total human population (4.7 million people). Thirty years later, salmon farming is more efficient, but Scotland's target of producing 200,000 tonnes salmon in 2020 will likely emit organic waste equivalent to that of about half of Scotland's human population of 5.3 million. Perhaps a better comparison is with Scotland's 6.8 million sheep, which in 2016 excreted about twice the nitrogenous waste of farmed salmon whilst producing only a quarter as much food (43,000 tonnes of lamb compared to 163,000 tonnes of salmon).

Human, sheep and fish wastes are in themselves natural products. The problem lies in the concentrated quantity of excreta produced when people live in permanent settlements, or fish are housed in large numbers in net pens. This can lead to a local accumulation of pathogenic micro-organisms, and it can overload the capacity of local ecosystems to recycle the waste. Thus, the core issue is that of the waste **assimilative capacity** of marine ecosystems on a range of spatial scales.

3.1 Solid Wastes

The solid waste that emanates from cage farms consists of fish faeces and uneaten feed. These sink through the water column and settle onto the seafloor, where they can alter the chemistry and microbiology of the sediment, and harm the community of **benthic** animals that live there (Mente *et al.*, 2010; Keeley *et al.*, 2014). The impacted zone is referred to as the farm's 'footprint'.

There are four key questions concerning the fate of solid waste from fish farms:

- What happens within a farm's footprint?
- Does the environment recover when farm operation ceases and if so how quickly?
- How big is the footprint?
- What is the contribution of salmon waste to marine ecosystems on scales larger than that of a farm?

3.1.1 What happens within a farm's footprint?

Typically, the local flux of solid waste generated by fish farms much exceeds natural inputs to the seabed, as exemplified in Box 3.1 for Loch Creran. This may disrupt the normal balance between oxygen demand and supply, creating conditions inimical to many of the soft-sediment biota.

Box 3.1: Loch Creran case study

Deposition of organic matter through the water column to the seafloor is a naturally occurring process, and is responsible for providing the food to the bacteria, protozoa and animals that inhabit the benthos. The role that the sinking material plays in the food web is why ecologists quantify it in terms of carbon.

Ansell (1974) used underwater traps in Loch Creran to collect sinking material, and resulted in an estimation of the flux of carbon to the seafloor as 106 grams of carbon per square metre per year ($\text{g C m}^{-2} \text{ yr}^{-1}$).

Ansell's study was undertaken before salmon farming was established in the loch, but at the time there was a factory discharging seaweed waste into the loch. Ansell's figure was subsequently revised downwards, to $50 \text{ g C m}^{-2} \text{ yr}^{-1}$, by Cronin & Tyler (1980) on the grounds that Ansell's traps were also catching re-suspended material, and so counting some inputs twice (see also Loh *et al.*, 2010).

Nevertheless, Ansell's figure provides an upper limit to natural deposition in Loch Creran. A flux of 106 g C is equivalent to about a kilogram wet weight of organic matter. If this were spread evenly over a square metre, it would make a layer 1 mm thick.

Three decades later, the EU Ecosystem Approach to Sustainable Aquaculture (ECASA) project estimated the effects in Loch Creran of a salmon farm with a consented maximum biomass of 1,500 tonnes of fish (Wilson *et al.*, 2007)

During its 22 month production cycle the operation was expected to harvest 2,300 tonnes and consume 2,875 tonnes of feed. Using the model of Black (2001) this should have resulted in 443 tonnes of organic carbon depositing to the seabed.

In the case of Loch Creran, a typical sea-loch, where tidal and wind currents are not large, most of the deposited organic carbon remained within a footprint not much bigger than the cage 'shadow'.

The cages at this farm were 75-80 metre diameter circular net-pens, arranged in two rows of eight. With spacing they occupied about 1/4 square kilometre in total. If the sinking material were spread uniformly over the shadow, it would constitute a flux of about $880 \text{ g C m}^{-2} \text{ yr}^{-1}$, 10-20 times the natural flux.

Effects on oxygen

Whether generated through natural production (e.g. phytoplankton bloom) or artificially (fish farm waste), a flux of carbon to the seabed can affect the dissolved oxygen concentration in the sediments (Brigolin *et al.*, 2009; Keeley *et al.*, 2014). The degree of effect depends on the amount of carbon flux, the hydrodynamics and bathymetry of the site, and the type of sediment. Highest impact is likely to be seen in areas that have low current speeds, soft sediment and a high flux of carbon to the seabed. Accumulation of organic matter on the seabed under these conditions could reduce oxygen concentration in the sediment. Oxygen is required for aerobic processes, such as respiration, or is mopped up during the re-oxidation of the end products created by anaerobic microbial

processes that occur deeper within the sediment. A high rate of organic matter flux can deplete the oxygen quicker than it is being supplied. In cohesive muddy sediments the supply of oxygen is much slower than in permeable sandy sediments, where oxygen can flow more easily through the sediment.

In the muddy sediments typical of sea-lochs, the action of animals pumping seawater through their burrows creates a flow of water that speeds up oxygen resupply in the sediment. The introduction of an excess of organic matter onto the seabed not only increases oxygen demand, it can also block the tubes and smother the burrowing animals, thus reducing oxygen supply.

Oxygen penetration depth in the sediment can provide an indicator of the 'health' of the sediments, based on sediment type (Hargrave, 2010). Intense carbon flux will lead to a depletion in oxygen concentration, which in turn will have an impact on the chemical processes in the sediment. This can result in a switch from an **oxic** system, with animals present at different feeding (trophic) levels, to a **hypoxic** or **anoxic** system dominated by bacteria (Keeley *et al.*, 2013). If the sediment oxygen is depleted so that **anaerobic** processes dominate close to the sediment surface, then the establishment of sulphide oxidising bacteria may be promoted. These bacteria include species such as *Beggiatoa*, which forms white microbial mats at the sediment surface. In the early days of fish-farming it was common to see bubbles of gas rising to the sea-surface around farms: these were often of marsh-gas, methane, also the result of anaerobic biochemical processes in the seabed. This not a feature of modern farms; despite their much larger size, they are typically in more dynamic environments which increase oxygen supply and spread the organic waste over a bigger area.

Effects on benthic fauna

The normal benthic fauna found in the (typically) soft (muddy) sediments of sea lochs includes a variety of species of worm, bivalve, brittle-star and sea-urchin. These communities are supported by the natural flux of particulate organic matter from phytoplankton, seaweed, and other sources, falling onto the seabed. Pearson & Rosenberg (1976; 1978) investigated how this fauna changed in response to increasing amounts of organic matter arriving at the seabed. The conceptual model they devised is illustrated in Figure 3.1. It forms the basis for a variety of indicators of the extent of benthic disturbance, including the widely used AZTI Marine Biotic Index (AMBI) (Borja *et al.*, 2000) and the Infaunal Trophic Index (ITI), and the ITI replacement Infaunal Quality Index (IQI) used for regulation in Scotland, and explained in Box 3.2.

Box 3.2 The Infaunal Trophic Index (ITI)

The ITI was developed in California, USA (Word, 1979). Since then it has been adapted for use in UK waters (WRc, 1992) but the principles remain the same. Invertebrates have been divided into four groups based on what type of food is eaten, where it is obtained and how it is obtained. ITI trophic group 1 are suspension feeders (e.g. *Mya arenaria*), group 2 are surface detritus feeders, group 3 are surface deposit feeders and group 4 are sub-surface deposit feeders (e.g. *Capitella capitata*).

ITI can have values between 0 (a sample containing nothing but group 4) and 100 (a sample containing entirely group 1). Biodiverse samples containing a normal mixture of groups 1, 2 and 3 would score about 70. In the case of samples from soft sediments in sea-lochs, values more than 50 are deemed to show little disturbance, values between 20 and 50 are considered as (organically) 'enriched', and values below 20 are 'degraded'.

The Scottish Environment Protection Agency (SEPA) require ITI values to be 30 or above at the edge of the Allowable Zone of Effect (AZE). Currently ITI is being phased out and replaced with IQI.

The Infaunal Quality Index (IQI)

Combines the number of infaunal taxa, the **AZTI Marine Biotic Index** (AMBI) (Borja *et al.*, 2000; Muxika *et al.*, 2005) and **Simpson's Evenness** (Simpson, 1949) to assess the observed values to those expected for undisturbed conditions. IQI values close to one indicate that the observed benthic invertebrate communities are close to their expected natural state. Values near to zero indicate a high level of divergence from the natural state, and therefore indicate a high level of pollution or disturbance. SEPA will move to the IQI for future consents under the new regulations.

During their survey in Loch Creran in 2006 (see Box 3.1), Wilson *et al.* (2007) also collected sediment cores at the edge of the farm cage shadow (i.e. the projection of the cage area onto the seabed). The fauna within these cores contained large numbers of the resistant worms that thrive in such environments, but few other animals. At between 25 and 50 m outside the shadow, there was a more diverse benthic faunal community, which nevertheless still included species characteristic of enriched conditions. An earlier research survey (Nickell *et al.*, 2003) had shown an influence of farm waste at 60 m from the edge of the shadow, but no with evidence found at 1,000 m distant. Thus, under the conditions in Loch Creran (which are similar to those in many lochs used for salmon farming), the footprint of a 1,500 tonne farm would seem to occupy about half a square kilometre.

3.1.2 Recovery

Recovery of the seabed following the cessation of fish farming starts with micro-organisms, both anaerobic and aerobic. As the flux of organic matter decreases, oxygen-

driven metabolism becomes more important. Hypoxia-tolerant worms continue to consume the waste around the edges of the footprint, joined by an increasing variety of benthic animals as oxygen begins to penetrate into the sediment. The Peason-Rosenberg succession goes into reverse, with the community composition moving from the right to the left of Figure 3.1.

Nickell *et al.* (1995) and Nickell *et al.* (1998) studied the recovery process at three Scottish sites and found that roughly normal biological community structure was restored over 2 years. Pereira *et al.* (2004) took samples from Loch Creran over 15 months of fallowing. They reported that the **macrobenthic** community "*at the two stations furthest from the fish cage site showed signs of recovery with time*" but were "*still moderately to slightly disturbed at the end of this study*". Although recovery was also evident close to the farm site, "*this station was still highly impacted 15 months after fish production ceased, with opportunistic species dominant*." Black *et al.* (2012) sampled 5 salmon sites on the west coast of Scotland at known times after the cessation of farming. Some sites exhibited high initial disturbance "*but recovered substantially within one year*". Others "*had lower initial impacts but were further from recovery after 2 years*."

Recovery has also been studied at sites in Canada, where Brooks and Mahnken (2003) and Brooks *et al.* (2004) reported recovery times varying from a few weeks to more than 6 years. Keeley *et al.* (2014) studied the recovery process at a highly impacted salmon farm site in New Zealand, fallowed after seven years of operation. They reported that "*Substantial recovery occurred in the first 2 years, and was assessed to be complete after about 5 years*." However, defining an endpoint for recovery "...*proved challenging due to: lack of a widely accepted definition, inherent variability in recovering sediments, differing trajectories of impact and reference sites, and statistical challenges*".

Benthic recovery from anthropogenic impact is a much discussed topic (e.g. Borja *et al.*, 2010), as is the question of what indicators should be used to show the presence/absence of benthic disturbance by aquaculture (Borja *et al.*, 2009). Clearly there are differences between sites, and it may be that sites which have been intermittently disturbed for some time, have the fastest recovery rates, having built up a more resilient community.

Given these issues, it would seem that the length of the fallowing period is not based on robust scientific knowledge of how long the period should be, and how this may vary for different sediment types. However, there is no doubt that, so long as the cage footprint is small compared with the total area of the loch floor, the sediment fauna will recover eventually.

3.1.3 How big is the footprint?

In the case of Loch Creran, the footprint of the consented 1,500 tonne farm is about half a square kilometre, which is less than 4% of the loch's area of 13.3 square kilometres at low water (Edwards & Sharples, 1986).

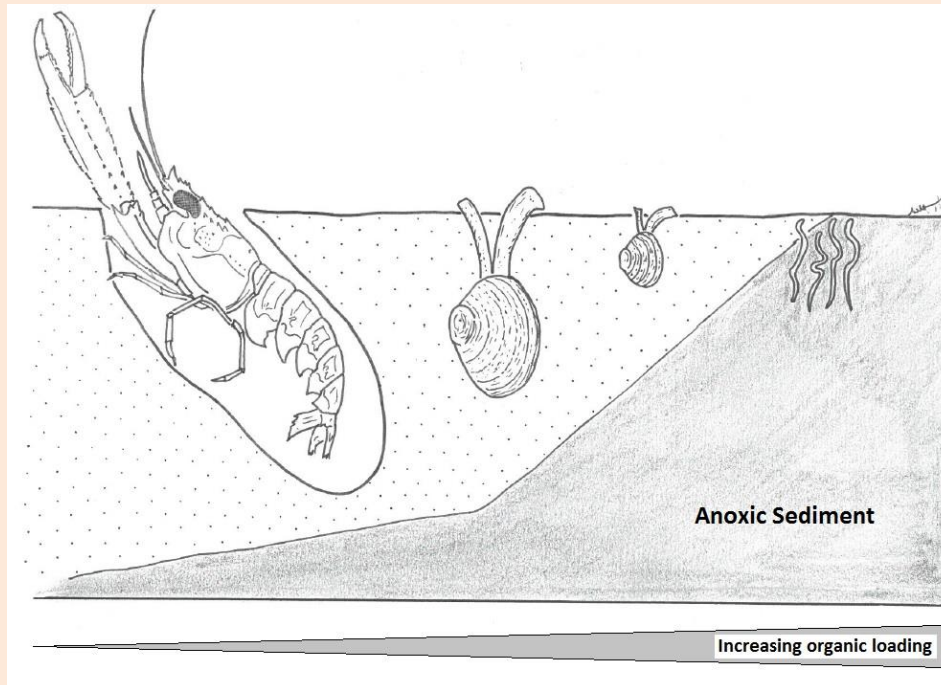
As already mentioned, the footprint of sinking particles on the seabed depends on currents and water depth at a farm. The numerical model, DEPOMOD enables a prediction of how the waste from a fish farm will be distributed as it reaches the seabed,

taking into account dispersion and re-suspension from the seabed when near-bed currents increase. DEPOMOD's simulations are driven by current profiles measured at the farm site. Figure 3.2 shows example images of DEPOMOD predictions.

As this figure shows, a farm in a high-dispersion site will have a larger footprint. However, the rate at which organic matter accumulates on each square metre will be less compared to a low-dispersion site. If the rate of accumulation at the high-dispersion site is within the capacity of the sediment to assimilate the organic material, there should be no ill-effects on the sediment biota (perhaps even beneficially increasing benthic production). Whilst being able to accurately model the seabed distribution of particulates (for well-described current regimes) is an important step in understanding the potential impacts of the organic flux to the seafloor, being able to determine this assimilative capacity (which will vary between sediment types) is also crucial. In principle, new DEPOMOD will make possible the former, but there seems to be some doubt about the latter. This is due in part to lack of scientific knowledge and in part to lack of agreement about where to place the 'acceptable disturbance' threshold in the Pearson-Rosenberg model, or in each of the variety of indicators based on it.

In the extreme case of a very highly dispersive environment and a farm in deep water, there would be no detectable farm footprint. Faeces and waste food would simply join the suspended particulate material in the water column, and either be metabolised there, or else drift and sink elsewhere.

Figure 3.1: Pearson-Rosenberg model for the effects of increased organic input on benthic communities in soft sediment



Organic input increases from left to right, with associated changes in the community composition (Image © SAMS after Tett 2008, simplified from Pearson & Rosenberg 1976).

The diagram shows, on its left, the typical seabed condition in sea-lochs and fjords. Comparatively large animals (e.g. the Dublin bay prawn ('scampi'), *Nephrops norvegicus*) make and irrigate burrows, and oxygen penetrates far (up to 10 cm) into the sediment. Sinking organic matter is taken into burrows or directly into the sediment by benthic animals; its initial breakdown is largely due to micro-organisms, which are fed on by larger (but still small) animals that in turn provide the food for the large burrowers.

Next to the prawn are sketched bivalves, acting as 'surface deposit feeders', sucking in food particles through an inhalant siphon and exhaling water through their second siphon. Although benefitting from small increases in sinking matter, these animals experience difficulties as sediment anoxic conditions approach the sediment surface, or if the sinking flux begins to smother their siphons.

At greater fluxes, only a few kinds of specially-adapted worm can survive, albeit in great abundance. On the right of the diagram is the condition in which the sinking flux is so great that no oxygen-requiring multicellular animals can survive, organic matter builds up faster than it is being decomposed, and *Beggiatoa* becomes the most visible organism.

Model developed from observations of the effects of pulp mill waste in Loch Linnhe/Eil and the Swedish Gulmar's fjord.

3.1.4 Regulation

Although about to change its policies, the SEPA has hitherto regulated benthic effects in terms of an AZE. This is the area within which the Agency permits some degradation of seabed conditions. It was originally set at 25 m from cage edge. Conditions here and within 5 m of the cage group are checked by sampling the seabed along a line running through the major axis of a cage group.⁷

SEPA has required that, even at the cage-edge some kinds of invertebrates continue to be found even in samples: typically, these will be polychaetes such as *Capitella capitata*, present in large numbers *and* responsible for much of a site's assimilation of waste. The AZE boundary should have an ITI of at least 30 (see Box 3.2). As sketched in Figure 3.1, all sediments are anoxic in their interiors; what is critical is the distance from the sediment surface to the start of the anoxic zone. SEPA regulations intend that bioturbation (mixing of sediments by the action of animals) is maintained in sediments across the whole AZE. Under the new regime (DZR = Depositional Zone Regulations) biodiversity must approach background conditions at the edge of the AZE. Existing consents allow somewhat degraded conditions (ITI = 30) at the AZE boundary. In many cases the size of the AZE will be larger under the new regulations (especially for energetic sites) which may compensate for the stricter standard. The use of models such as DEPOMOD has allowed stocking consents to be set (through Controlled Activity Regulations (CAR) licences) to avoid potential breaches of these requirements.

This regulatory approach has evolved in relation to the conditions in the sheltered, low-current, environments in which salmon farming developed. In these conditions a farm's footprint is little bigger than its shadow. Where currents and turbulence are stronger, the waste deposition footprint will be larger but, for a given size of farm, less intense, as illustrated by the DEPOMOD simulation shown in Figure 3.2. Expansion of the industry into such conditions offers new sites and the possibility of larger farms, but requires rethinking of the AZE concept and the requirement to sample seabed conditions along a single line only. SEPA's new approach will give a farm (defined as a group of cages) a patch of 0.5 km² within which the ITI value may fall below 30, so long as this does not exceed 5% of the water-body area.

3.1.5 Effects of farm particulate waste on larger scales

The cumulative effect of farms on the benthos of a sea-loch is taken into account in the Locational Guidelines, and the changes to SEPA policy take account of this. In addition to the 'zone A' (farm-scale) effects that have been the main issue until now, consideration also has to take in 'zone B' (loch-basin-scale) effects. The scales are those defined by Comprehensive Studies Task Team (CSTT), 1994, and the matter of different effects on different scales is further discussed in Section 3.2. The larger-scale effects are likely to be less obvious than those on the farm-scale, but are of greater concern, because degradation of benthic communities throughout a water-body will decrease the ability of a farm site to recover during fallowing, as well as interfering with the ecosystem

⁷ <https://www.sepa.org.uk/regulations/water/aquaculture/fish-farm-manual/>; section H provides details of current regulation

services provided by the benthos. Scottish transposition of the EU **Water Framework Directive (WFD)** (2000/60/EC) may also require 'measures' to correct the situation.

To give a sense of the relative contribution of salmon farming on the water-body scale, Table 3.1 summarises attempts at an organic carbon budget for Loch Creran.

Making such a budget poses many challenges, and the figures shown in Box 3.2 should be regarded as the roughest of estimates. Nevertheless, they suggest that the fish farm in Loch Creran contributes substantially to both inputs to the seabed (representing a third of inputs on a loch-wide scale), and to the overall turnover of organic matter in the basin.

The procedures used for devising and updating the Scottish Government's Locational Guidelines (Gillibrand *et al.*, 2002) include an assessment of benthic disturbance using the model by Gowen (Gowen & Bradbury, 1987; Gowen, 1994) that became the basis of DEPOMOD. Gillibrand *et al.* estimated "*the total percentage area of the seabed of a loch impacted by a level of enhanced organic carbon deposition greater than 0.70 kgC m⁻² y⁻¹. Above this critical value, it has been shown that the infaunal diversity of sediments is reduced, and the seabed can be considered 'degraded'.*"

The model results showed that in 2002 the great majority of Scottish lochs had 3% or less of their seabed area degraded by farm waste. Only 6% of 111 lochs had between 3-10% degraded, and none had greater than 10%. Whereas the 'critical value' of 700 gC m⁻² y⁻¹ used by Gillibrand *et al.* (2002) may have been too high, this is unlikely to have biased findings very much, because the gradient of impact around a farm in a low-dispersion water body is steep.

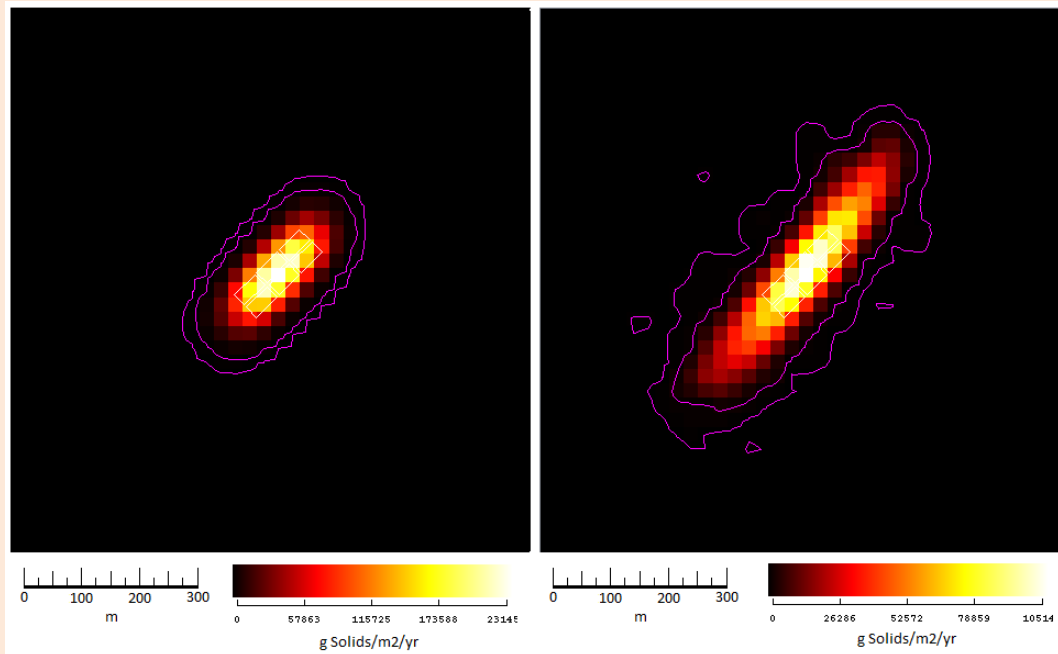
Turning to the regional scale, the data and modelling carried out by Heath *et al.* (2005), (discussed in more detail in Section 3.2), implied that in 2001 the fish-farms contributed between 3- 4% to the total land-derived organic load on Scotland's seas (Table 3.2).

3.1.6 Other issues

Effects on hard substrate communities

Most research has considered effects of farm waste on soft-sediment chemistry and biota. Siting of fish farms in more energetic waters might lead to an organic flux on hard substrates, i.e. seabeds made of rock, boulders or cobbles. A recent review (Roberts *et al.*, 2014) concluded that "*[s]iltation and subsequent smothering effects, organic enrichment and deoxygenation will only occur where particulate waste (i.e. uneaten food and faeces) accumulates or becomes trapped. This was judged less likely to occur in higher energy more dynamic environments*" although it was thought that particulate matter in suspension might enrich food available to the biota.

Figure 3.2: Example DEPOMOD simulations



DEPOMOD simulations of seabed loading from farm sites in low-dispersion (left panel) and high-dispersion (right panel) regimes. The farms were simulated with 6,750 tonnes fish, constant over a year. The loading is given in g solid per model pixel, not in g/m^2 as shown.

High dispersion regimes are characterised by strong tidal flows and currents, and deeper waters; low dispersion sites will have weak flow, and shallow depths beneath fish farms.

Figure created by Trevor Carpenter (SAMS) using the 'new' (2017) version of DEPOMOD.

Other pressures on the benthos

Benthic communities naturally vary from year to year, and in addition can change systematically over decades, as shown in a study of the benthos in the Kattegat (Pearson *et al.*, 1985). Possible causes of change were "*changed fish predation pressure, direct effects of trawling, climate change, and eutrophication*". All these might bring about change in the soft-sediment communities of the sea-lochs and inner coastal waters where fish-farms are located. Eutrophication (discussed in Section 3.2) adds to organic input. Climate change might select for or against certain species of invertebrate, and in addition, oxygen is less soluble in warmer waters. The physical disturbance caused by trawling and dredging selects for fast-growing, short-lived, species (Kaiser and Spencer, 1996; Kaiser, 1998), an effect that mimics that of increased organic load. Thus, it is possible that changes observed at reference stations in lochs are the results of these other pressures and not effects of farms. However, the physical disturbance would select

for short-lived species, but it is not clear that the species selected would be the same as those responding to organic enrichment.

The Pearson-Rosenberg model was the result of decades of seabed sampling in a Scottish loch and a Swedish fjord, aimed to study the effects of wood-pulp effluent (Pearson and Rosenberg, 1976). Current schemes for research funding seldom support such long-term study. Although there is much SEPA and industry monitoring of benthic conditions in Scottish waters for fish-farm regulation, including sampling at reference stations, there is little synthesis of the resulting data in relation to other pressures, as discussed by Wilding *et al.* (2017).

3.1.7 Diagnosis

Salmon farmed in floating net-pens produce large quantities of organic waste that sinks to the seabed in sheltered waters. This gives rise to a 'footprint' of effect, which is a bit bigger than the farm 'shadow'. Within this footprint the biodiversity of the seabed community of invertebrates (the benthos) is reduced, and oxygen demand is increased.

This was of much concern during the first decades of fish-farming. However, the effect is now strictly regulated by predictive modelling and by sampling around farm sites. Regulation aims to preserve a minimum biodiversity and prevent surface anoxia at the footprint edge.

This footprint is typically half a square kilometre beneath a 1500 tonne farm, with aggregated footprints only exceeding 4% of total seabed in a few lochs and voes; footprint dimensions can be reliably estimated by predictive models. Once a farm site is 'fallowed' by removal of cages, the benthos recovers over the next few years. Factors determining recovery rates, however, seem not to be well understood.

In more energetic waters, the waste will be dispersed, so having less impact on the seabed, and enriching the supply of organic matter to the marine food web in a sea-loch.

Taken over Scotland as a whole, salmon farming organic waste is less than 5% of the organic matter reaching the sea from the land, and has been estimated (for 2001) as about a third of that discharged in urban and industrial waste.

Scottish agencies regularly monitor seabed conditions near farms; however, there is no recent synthesis of the data, or recent research into acceptable sediment loadings for different sediment types, following periods, or long-term changes in the benthos of lochs with anthropogenic organic inputs.

Table 3.1: Estimated organic carbon budgets for Loch Creran

	1970s		2000s		2006
	Input	Output	Input	Output	Input
From rivers	1,100		1,440		
From phytoplankton	800		890		
From 'other sources' (farm, seaweed)			670		
From seaweed	300				
Alginate waste	800				
From 1,500 tonne fish farm					443
To sediment		700		1,280	
To sea		1,200		580	
Water-column respiration		1,100		1,140	
Total	3,000	3,000	3,000	3,000	

Values are tonnes of organic carbon per year.

Sources: Cronin & Tyler (1980) drawing on observations in 1970s and including dissolved as well as particulate organic carbon; Loh *et al.* (2010) drawing on observations, mainly of POC, in 2001-2002 and scientific literature. The fish-farm value in 2006 is that derived above, based on Wilson *et al.* (2007).

The alginate factory, which was located at Barcaldine and discharged seaweed-derived waste into Loch Creran until the 1990s, may have contributed more organic matter than the present salmon farm. It is perhaps this long history of elevated organic flux (back into the 1930s) that may explain the report by Wilson *et al.* (2007) that their reference benthic station showed a fauna with some species characteristic of enriched conditions.

Table 3.2: Contribution of fish-farming to Scotland's land-derived carbon sources

	Thousand tonne/yr	Percentage
Rivers (agriculture & erosion) 1984, -87, -90	518	82%
Urban waste water 1999	83.4	13%
Industry 1999	8.2	1%
Fish farming 2001 (Heath)	18.5	3%
Total	628	
Fish farming 2001 (Black)	25.6	4%
Total	635	

From Heath *et al.* (2005), given a salmon production of 138,185 tonnes in 2001;

The alternative figure for salmon waste is the result of applying the model of Black (2001).

3.2 Nutrients and Eutrophication

Eutrophication was defined by the Urban Waste Water Treatment Directive (91/271/EEC, article 2) as:

"...the enrichment of water by nutrients, especially compounds of nitrogen and/or phosphorus, causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned".

Subsequent judgements by the European Court (Box 3.3) interpreted this as a chain of steps. A diagnosis of eutrophication may only be made if all steps are evidenced and causally linked. In relation to salmon farming, the steps can be restated as a sequence of questions:

- Does salmon farming increase nutrient concentrations in seawater?
- Do such increases lead to increased growth, production and biomass of seaweeds or **phytoplankton**?
- Do increases in production and biomass lead to undesirable disturbance of the **'balance of organisms'** and the **'quality of water'**?

This subsection aims to answer those questions for three spatial scales: local (close to fish farms); sea-loch basins; and larger areas of coastal waters such as the Minch. It focuses on two main concerns: those related to eutrophication, as it affects ecosystem function, and those related to changes in the balance of organisms which might affect shellfish as well as finfish farming.

Box 3.3 Eutrophication, nutrients, and undesirable disturbance

Eutrophication was defined by the Urban Waste Water Treatment Directive (91/271/EEC, article 2) as: *"...the enrichment of water by nutrients, especially compounds of nitrogen and/or phosphorus, causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned"*.

An expanded definition was drafted by a European expert group in 2009 (Ferreira *et al.*, 2011): *"Eutrophication is a process driven by enrichment of water by nutrients, especially compounds of nitrogen and/or phosphorus, leading to: increased growth, primary production and biomass of algae; changes in the balance of organisms; and water quality degradation. The consequences of eutrophication are undesirable if they appreciably degrade ecosystem health and/or the sustainable provision of goods and services."*

This drew on two judgements in the European Court of Justice (Case C-280/02 Commission v France [2004] ECLI:EU:C:2004:548; Case C-390/07 Commission v UK [2009] ECLI:EU:C:2009:765) and a developing understanding of undesirable disturbance (Tett *et al.*, 2007).

Ferreira *et al.* (2011) clarified 'changes in the balance of organisms' as: *"...likely to take place initially in the phytoplankton and phytobenthos, and then propagate through marine food webs [i.e. through the remainder of the plankton or benthos]. The primary producer changes, which may in part result from perturbations of natural ratios of nutrient elements, include shifts from diatoms to cyanobacteria or flagellates, and the suppression of furoid seaweeds, or sea grasses, by an overgrowth of opportunistic (green or brown) algae."*

The nutrient elements mentioned in the definition are: nitrogen (N) and phosphorus (P). These occur in seawater mainly in the form of ions, especially of ammonium (chemical formula NH_4^+), nitrate (NO_3^-) and phosphate (PO_4^{3-}), usually in low concentrations. Nitrogen and phosphorus are essential for the synthesis of living matter, and are naturally present in the sea, as a result of decay of organic matter, erosion of rocks containing phosphorus, and the activities of nitrogen fixing bacteria. However, these nutrients are also added by human activities such as the discharge of urban waste water, run-off from fertilised farmland, and by the farming of salmon.

A third element, silicon (Si), is also important for the growth of certain kinds of phytoplankton, especially by the micro-algae called diatoms which use it to strengthen their cell walls. Fish farm waste is not enriched with Silicon, and thus increases in ambient ratios of N:Si are of concern, as they may result in a tilt in the phytoplanktonic 'balance of organisms' away from diatoms, with consequences for marine food webs as well as possibly increasing the risk of Harmful Algal Blooms (HABs). Disturbance of the natural ratios of N:P may also be important: although the evidence is more conflicted for Scottish seas, a relative increase in P could also favour HABs.

3.2.1 Introduction

Concerns about the potentially eutrophying effects of salmon nutrients began in the late 1980s (Gowen & Bradbury, 1987; Gowen, 1994). The topic was controversial in the 1990s (Folke *et al.*, 1994; Black *et al.*, 1997; Folke *et al.*, 1997; Asche *et al.*, 1999) and led to the development of a simple model to quantify likely enrichment of sea-lochs (Gillibrand & Turrell, 1997). The model was subsequently used to inform the Scottish authorities (i.e. Marine Scotland as is) in its 'Locational Guidelines for fish farming' (Gillibrand *et al.*, 2002). A petition (PR 96) to the Scottish Parliament in 2000, requesting '*an Inquiry into Sea cage Fish Farming and the Environment*' led not only to the 2002 'Review and Synthesis' but also to three specialist reviews (Tett & Edwards, 2003; Rydberg *et al.*, 2003; Smayda, 2006) of the risk that salmon farm nutrients were disturbing the balance of organisms and causing more Harmful Algal Blooms (HABs).

Subsequently, the issue moved to the back-burner as problems due to disease and sea lice and their treatment gained prominence. A recent risk assessment of Norwegian salmon farming (Taranger *et al.*, 2015) stated that the "...risk of eutrophication and organic load beyond the production area of the farm is considered low." However, Scotland's hydrography differs from that of Norway. Sea-lochs tend to be smaller and less deep than Norwegian fjords, hence more liable to nutrient enrichment. Even if eutrophication is not a high risk (except in a few poorly-flushed water bodies), it is necessary to review the potential for salmon aquaculture to cause changes in the balance of organisms in the plankton, which may have a knock-on effect on both shellfish and finfish farming.

3.2.2 Effects near farms

Salmon are carnivores, adapted to a diet rich in protein and to metabolising much of this protein as a source of energy. Consequently, much of the nitrogen in a salmon's diet is converted to ammonia (mainly in the form of the ammonium ion), and excreted by way of its gills. Ammonia/ammonium concentrations in pristine sea-water are usually low, and several studies have observed increased ammonium concentrations within a few hundred metres of Scottish net pens (Navarro *et al.*, 2008; Sanderson *et al.*, 2008).

Additional farm-derived ammonia and nitrate (hereafter referred to collectively as Dissolved Available Inorganic Nitrogen-**DAIN**) enters the water-column from the seabed, resulting from the decay of fish faeces and uneaten feed that have sunk to the seafloor. Pitta *et al.* (2005) observed significant increases in these nutrients and also in Dissolved Organic Nitrogen (DON) in bottom waters near fish-farms in the low-nutrient eastern Mediterranean. Although the fish concerned were sea-bream and sea-bass, the effect is likely to be similar to that for salmon.

Navarro *et al.* (2008) found increased bacterial biomass near farms, but no increase in phytoplankton. Microcosm experiments, in which seawater is incubated in illuminated transparent vessels in the laboratory, help understand where the nutrients are going. Olsen *et al.* (2014) carried out such an experiment with water from a Chilean fjord used for salmon farming. Like earlier studies using water from the Firth of Lorne and Loch Creran (Edwards *et al.*, 2003; Jones *et al.*, 1978a; 1978b), **zooplankton** were screened

out at the start. In all these cases, phytoplankton, provided with nutrients and light, start to grow. In the absence of planktonic animals to eat the micro-algae, the result is a bloom of phytoplankton, usually apparent as a big increase in amounts of the green pigment, **chlorophyll**. An ingenious experiment by Pitta *et al.* (2009) confirms these findings for nutrients from fish-farms in Greece (Box 3.4).

In these experiments, water and phytoplankton were contained. Fish farms provide a continuous source of enrichment, but for the majority of Scottish lochs, the turbulent flow of water past farms removes and disperses the locally enriched nutrients. Whereas a bacterium can gain nourishment from Dissolved Organic Matter (DOM), and divide within an hour, an algal cell requires a few days (depending on illumination) to use N and P in its metabolism and reproduce. Thus, it is unlikely that increases in phytoplankton will be seen close to farms.

Box 3.4 Experiments in bags or bottles

Pitta *et al.* (2009) studied the assimilation of nutrients near net-pen farms of sea-bass and sea-bream in the eastern Mediterranean. They tried to explain why earlier studies had failed to detect increases in phytoplankton, despite injections of nutrients into oligotrophic waters. Hypothesizing that phytoplankton growth was stimulated but almost immediately consumed, they experimented with dialysis bags.

The fabric of these bags was permeable to light and small molecules, including nutrients, retained phytoplankton and micro-organisms of similar size, and excluded zooplankton that might have preyed on the phytoplankton.

They filled the bags in three ways, before suspending them in the sea at several distances from a fish farm.

The first option involved laboratory grown suspensions of a green micro-alga. This grew strongly in bags close to the farm, demonstrating the availability of growth-promoting nutrients.

The second option involved seawater. In this case, the natural phytoplankton did not grow, even in the absence of mesozooplanktonic animals.

The third option involved seawater passed through a very fine screen that removed all animals and most of the protozoa - the unicellular animals that eat the micro-algae of the phytoplankton. This third case showed substantial phytoplanktonic growth near farms (and not when distant from farms). Pitta *et al.* concluded that the micro-algae, naturally present at low abundances in these oligotrophic Mediterranean waters, utilised the nutrients excreted by the farmed fish. However, as they did so, the phytoplankton were consumed by the protozoa also naturally present in these waters, so that the nutrients were rapidly passed up the food web.

3.2.3 Effects on the scale of sea-lochs

OSPAR

The multinational treaty organization **OSPAR** has a strategy to combat eutrophication and a procedure for identifying members' sea-areas at risk of eutrophication (OSPAR, 2003). OSPAR (2009) reports that Scotland, as part of the United Kingdom, "*undertook an extensive programme of monitoring and assessment between 2002 and 2006 covering some 38 water bodies supporting fish farms*". All the water bodies surveyed had been identified as 'hot-spots' of enrichment using an **Equilibrium Concentration Enhancement (ECE)** model, but were nevertheless all "*assessed as 'Non Problem Areas' with respect to the effects of nutrients from fish farms by applying the OSPAR Comprehensive Procedure for eutrophication assessment.*" Box 3.5 gives more details.

Box 3.5: Summary of results of UK monitoring (2002-2006) of 'hot-spot' water bodies with Fish Farms

Nutrient concentrations:	Winter nutrient (DAIN) concentrations did not exceed the criteria of 50% above background concentrations of coastal waters for any lochs
Nutrient ratios:	Winter N/P ratios did not exceed 50% above background values for any sea lochs.
Chlorophyll a concentrations:	The 90th percentile of measured values did not exceed 50% above background values for coastal waters at any of the sea lochs surveyed.
Phytoplankton indicator species:	Potentially toxic and nuisance species were recorded at several lochs at densities typical for Scottish waters. The occurrence of these species is not thought to be related to nutrient inputs from aquaculture.

Hot-spots were identified using "simple [ECE] models relating nitrogen discharge from fish farms to flushing rates of sea-lochs". In 2002 the annual salmon harvest "exceeded 145,000 tonnes" (Greathead *et al.*, 2006).

From OSPAR (2009).

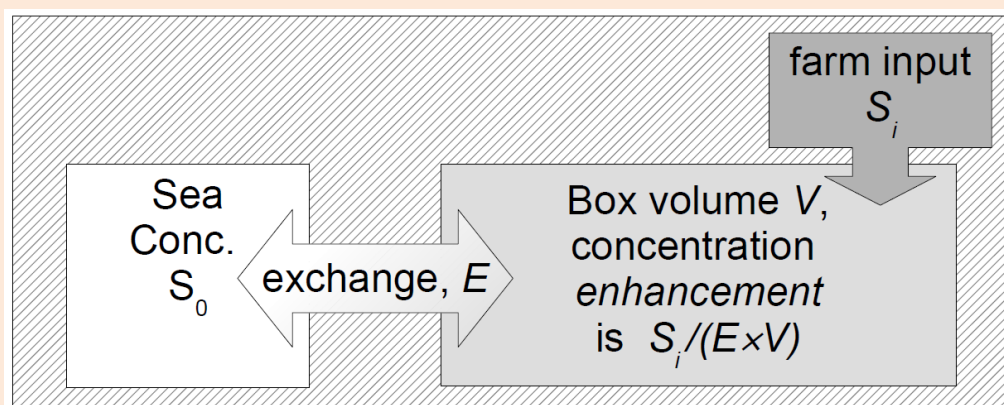
ECE model

In Marine Scotland Science's 'ECE' model (Figure 3.3), an estimate of farms' annual discharge of nitrogen is divided by an estimate of the rate at which a loch exchanges water with the sea (Gillibrand & Turrell, 1997; Gillibrand *et al.*, 2002). The model is routinely used, as part of the 'Locational Guidelines', to predict the aggregate effect of fish-farms within a loch (or voe) and to advise where new farms can be sited without

overloading nutrient assimilative capacity.⁸ It was used to identify the hotspots for the study reported by OSPAR.

Figure 3.3: Principles of Equilibrium Concentration Enhancement (ECE) model

Image © SAMS



The standard ECE model employs annual values, and the OSPAR assessment uses nutrient concentrations measured in winter, when natural concentrations are at their greatest and phytoplankton does not grow because of shortage of light. However, sea-lochs and voes receive seasonally changing inputs of nutrients from coastal waters and in river discharges, as well as from aquaculture. Farm inputs typically reflect a two year cycle, with young fish introduced into cages in the winter of the first year, and removed towards the end of the second year. Salmon are cold-blooded, which means that their metabolism is proportional to water temperature. Thus, the greatest inputs of nutrients occur in summer, when the sea is at its warmest. Furthermore, this is the time when natural concentrations of nutrients are low.

Appreciating this, Greathead *et al.* (2006) applied an ECE model seasonally, to examine the relative share of each input to 104 lochs/voes. Table 3.3 summarises some of their findings, which show that exchange with the sea is the main process controlling nutrient levels in most lochs and voes. However, in one in ten, salmon farming contributed more than a third of DAIN during the summer of the second year of the production cycle.

ACExR-LESV model

The ECE model has proven a useful screening tool and is still in use for the 'Locational Guidelines'. However, as pointed out in an international review of fish-farming effects on phytoplankton in Scottish waters (Rydberg *et al.*, 2003), it greatly simplifies the physical processes renewing water in lochs. Although not in operational use, a more sophisticated

⁸ The Locational Guidelines provide guidance to developers and SEPA and are regularly updated.
<http://www.gov.scot/Topics/marine/Publications/publicationslatest/farmedfish/locationalfishfarms>

model has been developed to better predict fish-farm nutrient impact (Portilla *et al.*, 2009; Tett *et al.*, 2011a; Gillibrand *et al.*, 2013). Part of this model (ACExR) describes physical processes and estimates daily water exchange rates for a loch or voe simulated as up to three vertically stacked layers. The biological part of the model (LESV) computes nutrient enrichment and the conversion of nutrients into several kinds of phytoplankton, enabling assessment of impact on 'the balance of organisms'. It has an 'ECE mode', which allows the 'phytoplankton equations' to be switched off and thus the effect of salmon-farm nutrient enrichment to be seen without the complication of nutrient assimilation by phytoplankton or the grazing of the micro-algae by zooplankton.

Table 3.3: Seasonal contributions to the nutrient-nitrogen budgets of 104 lochs/voes, calculated by an ECE model

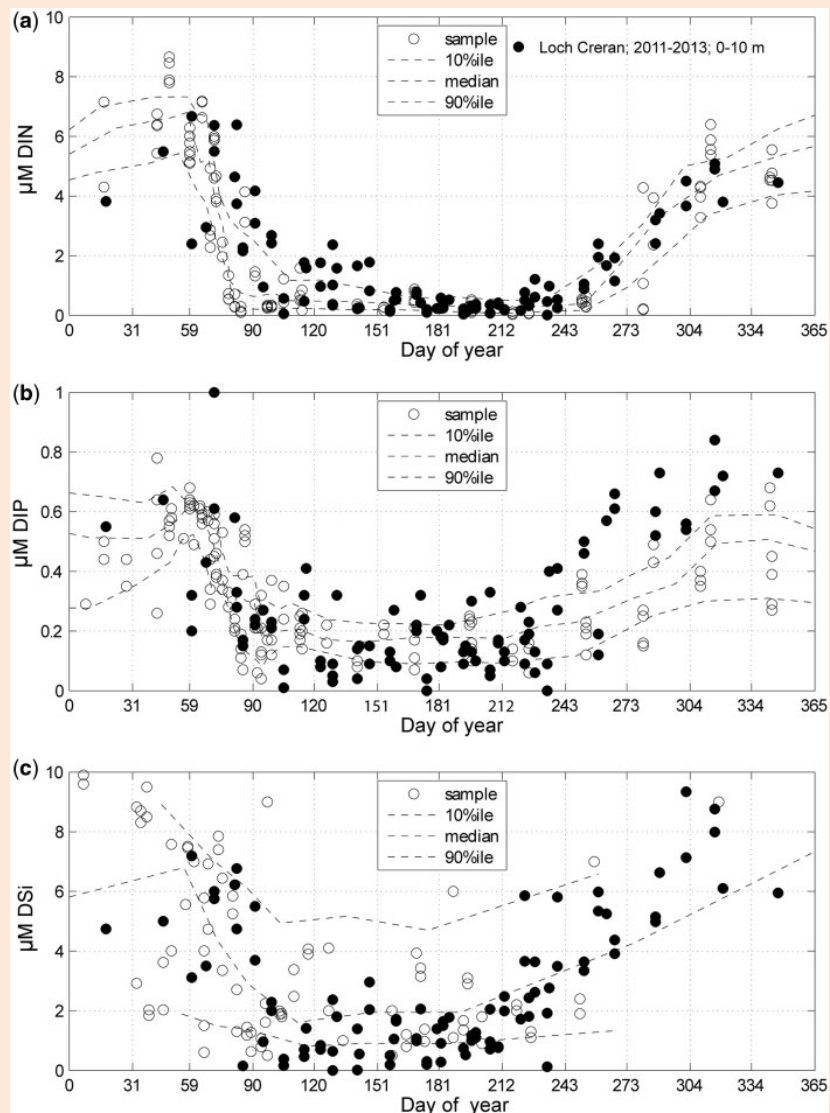
Season	Yr 1/ Winter	Yr 2/ Winter	Yr 1/ Summer	Yr 2/ Summer
'Tidal exchange' (from sea) median	93%	91%	94%	88%
Freshwater median	6%	6%	2%	2%
Aquaculture median	0%	2%	2%	8%
90%-ile	1%	10%	10%	34%

From Greathead *et al.* (2006). Contributions to the nutrient-nitrogen budgets of 104 lochs/voes, rounded to the nearest 1%: Even without rounding, the contributions do not add exactly to 100%, because the medians refer to each category of input.

Table 3.4 reports the simulated summer situation in several sea-lochs and voes. The main part of the table shows that the 'standard farm' (1,500 tonnes) could have markedly different effects in different lochs. Sandsound Voe, the smallest water body, shows the greatest percentage increase in simulated summer nutrient. Loch Fyne and Loch Torridon show the smallest increases because they have the greatest volumes. However, all differ in their flushing. Finally, the background or natural summer nutrient levels differ between water bodies, depending on both local conditions and the state of the water entering the loch or voe.

According to these simulations, the absolute amount of nutrients contributed by fish farms in summer is not particularly large: in the worst case it is about 40% of winter levels of DAIN, and less than this for Dissolved Available Inorganic Phosphorus (DAIP). Nevertheless, there are cases in which the summer input exceeds that from sea. Thus, there is potential to significantly increase summer amounts of phytoplankton.

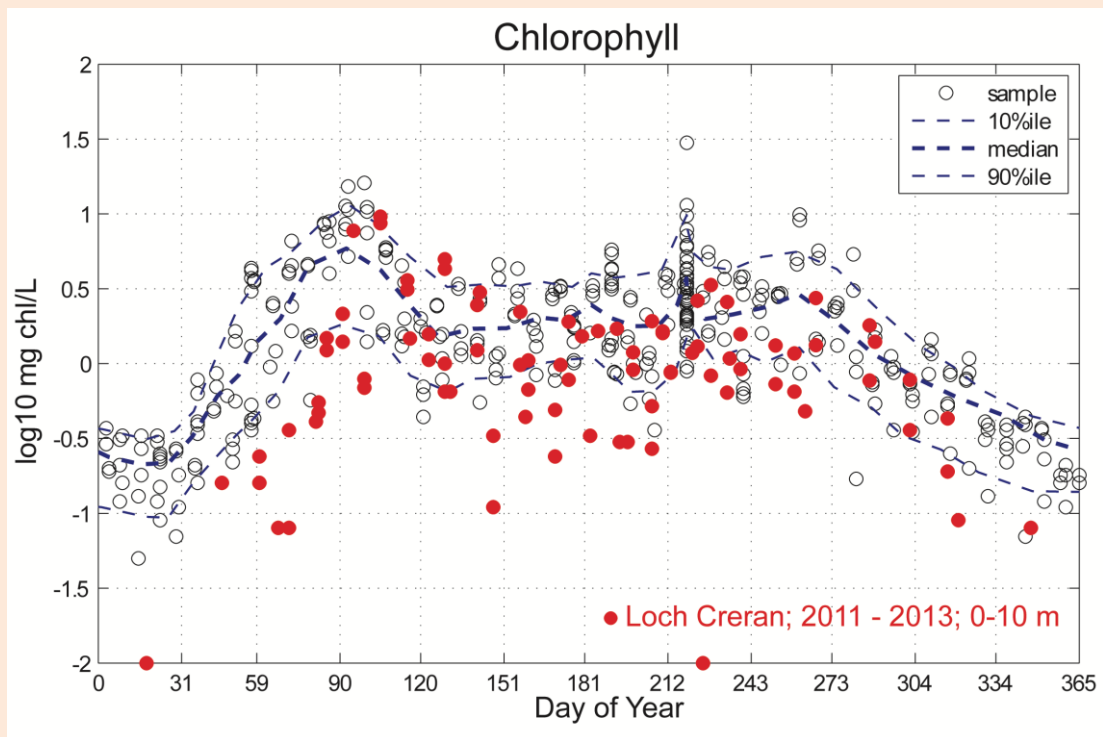
Figure 3.4: Nutrient seasonal cycles observed in Loch Creran



White circles are from 1971-1976 (reference period; no fish farm); Black circles are from 2011-2013 (1,500 tonne fish farm present). The envelope includes 80% of the reference period observations (i.e. excludes the upper and lower 10%). The median line divides the reference period points into two equal sets. The extent of change between the two periods is estimated by counting new (black) points above and below the median line. In the case of Dissolved Inorganic Nitrogen (DIN) (=DAIN) there were significantly more points above the median line, showing a detectable increase in nutrient concentrations; in the case of Dissolved Silicon (DSi) there were significantly more points below the median line. No change for Dissolved Inorganic Phosphate (DIP) (=DAIP).

Figure from Whyte *et al.* (2017).

Figure 3.5: Chlorophyll seasonal cycles observed in Loch Creran



Seasonal cycles of the amount of phytoplankton (measured as chlorophyll). White circles are from 1979-1981 (reference period; no fish farm). Red circles are from 2011-2013 (1,500 tonne fish farm present).

Note that the vertical axis is logarithmic: for example, a chlorophyll concentration of +1 is 100 times a chlorophyll concentration of -1. The envelope includes 80% of the reference period observations (i.e. excludes the upper and lower 10%). The median line divides the reference points into two equal sets. The extent of change between the two periods is estimated by counting new (red) points above and below the median line.

There were significantly more points below the median line in 2011-2013: this means that the typical amount of chlorophyll has substantially decreased. In addition, the productive season (when chlorophyll is high) was shorter in 2011-2013.

Figure from Whyte *et al.* (2017) (Supplementary material).

Table 3.4: Enhancements in summer nutrient simulated by ACExR-LESV

Loch/Voe		Creran*	Fyne	Sandsound Voe	Spelve	Torridon
Volume (million cubic metres)		214	10,246	86	177	4,287
Thickness of surficial layer (m)		6 to 7	18	14	5	12
Flushing Time (days)		4 to 8	91	9	3	24
N, µg/L	farm	10	7	54	11	5
	background	9	42	19	9	36
	% increase	110%	16%	286%	123%	15%
P, µg/L	farm	2	1	10	2	1
	background	8	12	8	8	10
	% increase	24%	8%	115%	32%	6%
Location Guidelines	Nutrient Loading Index	2	1	4	1	1

Enhancements in Summer DAIN and DAIP by a 1,500 tonne farm, simulated for the year 2003 by ACExR-LESV. Nutrient concentrations converted from molar values to micrograms of the nutrient element per Litre of sea-water. Background N and P are concentrations in seawater outside the water body of DAIN and DAIP in summer.

Also shown are values of the Locational Guidelines 'nutrient loading' index (from 0 [low] to 5 [high]) taken from the September 2017 of the MSS 'Locational Guidelines'.⁹ These reflect current (2017) stocking of lochs, and in the case of the larger lochs, are several times greater than the 'standard farm' of 1,500 tonnes used for the ACExR-LESV model.

Volume (in millions of cubic metres, at low water) from the 'Sea-lochs Catalogue' (Edwards & Sharples, 1986, as updated by Marine Science Scotland-MSS). The thickness (h, in metres) of the superficial (sea-wards flowing) layer is the average of daily values calculated by the physical model ACExR, which also calculated daily values of the layer exchange rate. The annual mean of these rates was used to calculate the layer's flushing time (T), which is the number of days required to replace 63% of the layer's contents from deeper water, itself imported from the sea. The Loch Creran* values show the range observed in simulating several years.

From Tett *et al.* (2012).

⁹ <http://www.gov.scot/Resource/0052/00526096.pdf>

Nutrient ratios

Whereas increase in amounts of any nutrient in short supply will tend to enhance growth of some sort of phytoplankton, whether this creates a 'disturbance to the balance of organisms' may depend on the effect on ratios of nutrient elements. Briefly, a ratio of 16 atoms of (available) nitrogen to one atom of (available) phosphorus, seems optimal for a naturally balanced phytoplankton, with about as much silicon as nitrogen required by **diatoms**. Deviations from the optimum may result in shifts in the balance: for example, a decrease in the relative amount of silicon will favour flagellated micro-algae over diatoms and thus perhaps increase the risk of HABs (Tett *et al.*, 2003).

Furthermore, there is some evidence, albeit disputed (Davidson *et al.*, 2012), that shifts in nutrient ratios can increase the toxicity of some harmful algae. MacGarvin (2000) claimed that salmon farming might have such an effect because it increases DAIP more than DAIN.

The OSPAR assessment in Box 3.5 reports no disturbance in winter nutrient ratios. However, it is also important to assess summer ratios. Results from ACExR-LESV simulations in Table 3.5 show that, in some cases, the effect of farm nutrients is to return N:P and N:Si ratios to optimum values. In other cases, enrichment might perturb N:Si ratios to an undesirable extent.

Observations of nutrients & phytoplankton

Two Scottish sea-lochs have been the focus of long-term research studies: Loch Ewe and Loch Creran. Bresnan *et al.* (2015) reported 10 years of weekly plankton observations in Loch Ewe, starting in 2003, subsequent to the use of the loch for salmon farming. Loch Creran was sampled from 1972-1984, before salmon farming started in 1988, and sampled again since 2000, during which period a 1,500 tonne farm has been operated. Since the sampling was irregular (carried out as part of research, rather than monitoring, programmes) it has been necessary to devise new statistical procedures for data analysis. They entail the grouping of several years of data into 'climates' defined by envelopes drawn on graphs (Tett & Wallis, 1978).

Some results from this procedure are shown for Loch Creran in Figures 3.4 for nutrients, and 3.5, for chlorophyll as a measure of amount of phytoplankton. Both illustrate the messy nature of 'real' (as opposed to simulated) data: many natural processes influence the observed concentrations of the variables.

The most obvious feature in Figure 3.4 is that of the seasonal changes in all the nutrients. By counting points on either side of the median line, a significant increase in DAIN, a significant decrease in DSi, and no change in DAIP, can be seen.

Figure 3.5 shows that there has been a significant decrease in chlorophyll. The latter is contrary to expectation, which would be for a moderate increase in the amount of phytoplankton as a result of additional nutrients from the salmon farm (Tett, 2016). Not only are many of the recent chlorophyll values lower than those in the 1970s, they also indicate a shorter growth season, with the implication that the loch has grown less productive. Whyte *et al.* (2017) suggest that this is a consequence of decadal changes in rainfall. In any case, it does not contribute to a diagnosis of eutrophication.

Changes in phytoplankton floristic composition

Whyte *et al.* (2017) examined the 'balance of organisms' in the phytoplankton community within Loch Creran. Comparing samples gathered from 2011-2013 with a reference period 1979-1981, there has been "... a substantial drop in the numbers of observed [centric] diatoms accompanied by a rise in the number of autotrophic/mixotrophic dinoflagellates as well as an increase in the potentially toxin producing [raphid diatom] genus *Pseudo-nitzschia*".

This is the sort of shift in the plankton community composition that would be expected to follow enrichment with N and P without Si, so could be interpreted as linked to salmon farming. However, it may also be explained as a consequence of decreased water transparency, which favours dinoflagellates. Lower light penetration means that growth of all phytoplankton will be inhibited. Whilst diatoms have little ability to move within the water column, dinoflagellates have an element of mobility that allows them to move and exploit estuarine circulation patterns. This enables dinoflagellates to more easily maintain themselves at favourable light levels towards the surface of a water body, and hence continuing to thrive despite poor light penetration.

The observations made in Loch Ewe during 2003-2012, and reported by Bresnan *et al.* (2015), show a seasonal pattern in chlorophyll, and summer dinoflagellate dominance, similar to that in Creran during these years. This is despite the fact that Loch Ewe is larger and more open to the sea than Loch Creran. Bresnan *et al.* (2015) concluded that the plankton community in Loch Ewe was likely "...responding to broader scale environmental influences such as warming sea surface temperatures and changing wind speed and direction".

Conclusions

The observations in Loch Creran, allowing comparison over time, those in Loch Ewe, and the OSPAR (2009) summary, point to the conclusion that Scottish sea-lochs have not been rendered eutrophic by fish-farming. Indeed, there has been a decrease in phytoplankton biomass in Creran during recent decades. However, there are changes in the balance of (phytoplanktonic) organisms in Loch Creran that are hard to explain but might be influenced by farm-derived nutrients.

The results from simulations with ECE and ACExR-LESV models show, first, that it is important to assess summer as well as winter conditions; and, second, that lochs differ and need to be individually assessed.

3.2.4 Effects on larger scales

Larger sea areas (a) aggregate the nutrient outputs from a substantial part of the salmon farming industry, and (b) provide the boundary conditions for inshore water bodies such as the lochs and voes considered in the previous Sections. The Minch is an example of such a larger area. It channels a mainly northwards flow of water (Inall *et al.*, 2009). The nutrient content within the water body is mainly determined by the source of the flow and the biogeochemical processes taking place in it. Tett & Edwards (2003) constructed a budget for N and P for the Minch (Table 3.6). Depending on the estimate for the volume of water within the flow of the Minch, nutrients derived from fish farming were estimated

to represent between 5-10% of the total N within the Minch in summer, and between 3.5-6% of the total P. It was thought unlikely that such changes, would lead to a detectable change in amounts of phytoplankton, or that nutrient ratio changes would be large enough to appreciably perturb the balance of organisms

Heath *et al.* (2002) reported on simulations for a range of eutrophication assessment criteria in Scottish shelf seas using a complex numerical model. This was the European Regional Seas Ecosystem Model (ERSEM) which combines descriptions of any ecosystem processes with estimates of water flows taken from a physical model. They concluded that *"salmon farming contributed approximately 6% of Scotland's nitrogen-nutrient input to coastal waters, and 13% of phosphorus (based on 2001 production figures)." However, farm inputs might represent more than 80% of the land-derived inputs "in some areas of the west of Scotland with small freshwater catchment areas and low levels of human habitation."*

Even in the cases in which farm inputs are a large part of the local supply, they might not be significant, because most nutrients come from the sea. Heath *et al.* (2002) explored this by examining the variability simulated by the model. The 2001 aquaculture input data were used as model input under three different annual weather patterns (those measured for 1984, 1987 and 1990, for which data had been assembled during the original European-funded ERSEM project). Then they simulated halving the aquaculture input, and found that this *"... would have only a small impact on water quality [as indicated by nutrients, chlorophyll and 'balance of organisms'] which would be undetectable against the background of natural variability due to climate variations."*

Heath *et al.* (2005) revisited this work with improved data for salmon production and nutrient release. Their values for the total Scottish input of nutrients to the sea are repeated here in Table 3.7. They reached the same conclusion as their previous study: *"[a] scenario of 50% reduction in salmon production produced regional changes in water quality which were less than 25% of the natural variability due to climate."*

Table 3.5: Summer nutrient ratios simulated by ACExR-LESV

Loch/Voe	Redfield Ratio	N:Si Background	+FF	Redfield Ratio	N:P Background	+FF
Creran	1.0	0.3	0.5-0.7	16	3	5-6
Fyne	1.0	1.4	1.7	16	7	11
Sandsound Voe	1.0	1.0	2.4 †	16	5	11
Spelve	1.0	0.3	0.6	16	3	5
Torridon	1.0	1.3	1.3	16	8	9

The ratios are given in terms of atoms of the elements together with the corresponding values of the 'Redfield ratios' towards which the composition of plankton is said to tend (Tett *et al.*, 2003). 'Background' is the observed summer ratio in seawater outside the water-body, FF is the ratio with one simulated fish farm.

This table differs from others, in that it shows the (simulated) actual ratios rather than the (simulated) changes in the ratios.

These ratios are most often observed in undisturbed seas in winter, and natural processes cause deviations in summer. The idea that a ratio of N:Si atoms of 1:1 is 'optimum' comes not from Redfield (1934, 1958) but from later work, reviewed in Tett *et al.* (2003). It seems that the ratio has to rise above about 3 before there are serious implications for the 'balance of organisms' (i.e. before potentially harmful flagellates began to replace mainly benign diatoms).

The Creran values show the range observed in simulating several years. † marks the case (Sandsound Voe) in which the N:Si ratio shifts towards values that could be of concern. In all model simulated cases, the background ratios (based on observations) fell well below the Redfield Ratio. The model simulated salmon farming simply pushed the summer N:P ratio back towards the optimum of 16:1.

From Tett *et al.* (2012).

3.2.5 Harmful algae and harmful algal blooms

Although the international reviewers (Rydberg *et al.*, 2003; Smayda, 2006) supported the home-grown conclusion that nutrients from salmon farming were not potentiating HABs, research on harmful algae (HA) and HABs has continued, motivated by their threat to shellfish cultivation and associated human health implications.

Rydberg *et al.* (2003) carried out similar calculations to Heath *et al.* (2002) and Tett & Edwards (2003) and concluded that *"it is very unlikely that fish farming should have a large-scale impact on the occurrence of harmful algal blooms, particularly on toxic algae, which are related to shellfish poisoning. Occurrence of such blooms, in general, appears to indicate that they are more common in pristine than in enriched waters and that they appear independently of fish farming activities."*

Smayda (2006) examined the risk that certain harmful algal species could bloom more intensely, or become more toxic, as a result of fish farm nutrients. He concluded that this was unlikely to be the case in Scottish water bodies; because these were 'open' to events driven by weather and/or occurring further out at sea. He noted that the natural variability of HABs, and climate-change induced trends, would make it difficult to detect a small 'signal' due to aquaculture derived nutrients. He added that: *"using the year 1985, when fish farming accelerated, as a branch point, differences in regional bloom patterns and frequencies during the pre- and post-1985 period are not evident. Similarly, the patterns and trends in harmful species of Alexandrium, Dinophysis, Pseudo-nitzschia, phytoflagellates, diatoms and ichthyotoxic Karenia mikimotoi do not show a detectable relationship with increasing delivery of fish farm nutrients."*

Research on HA and HABs has continued, motivated by their threat to shellfish cultivation and associated human health implications. Some of the research draws on the data gathered through the routine monitoring of certain HA for purposes of the Shellfish Hygiene Directive: these are organisms that sometimes contain toxins and which, concentrated by filter-feeding shellfish such as mussels or oysters, can induce a variety of illnesses in human consumers of the shellfish. Other research has looked at the circumstances of 'Red Tides' of phytoplankters such as *Karenia mikimotoi*, which intermittently kill farmed fish and wildlife.

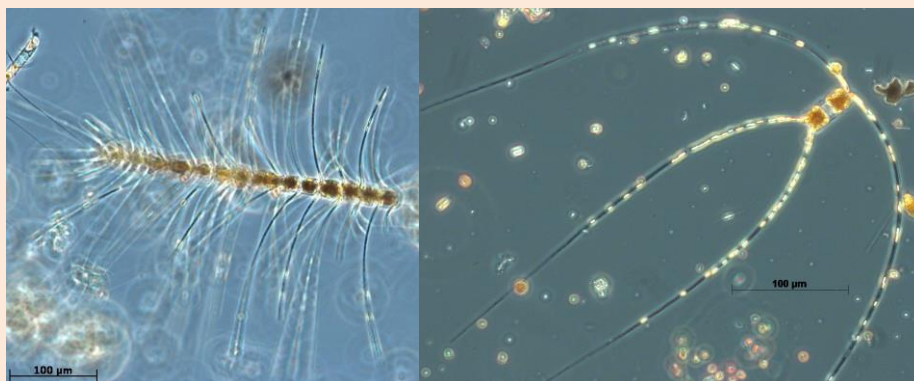
Numerous recent publications dealing with the main HA problematic in Scotland were reviewed for this report. Causality was discussed in most cases, with conclusions similar to those reached by Smayda (2006) - that primary cause of HABs lay in natural processes, often further out on the continental shelf, and those processes are susceptible to climate change. It is possible that nutrient enrichment close to shore could cause enhanced population growth of some HA. This has been considered by some authors, but not supported by scientific evidence due to a lack of relevant nutrient data for statistical analysis.¹⁰

Diatoms are normally considered benign as members of the plankton. However, in some species, the silicified cell wall forms large spiny protuberances (Figure 3.6). Blooms of these diatoms, and of unrelated silicoflagellates, have been reported as causing sometimes fatal gill damage to farmed salmon (Bruno *et al.*, 1989; Treasurer *et al.*, 2003). Soares *et al.* (2011) examined the (comparatively small) contribution of 'environmental' causes to the deaths of farmed salmon recorded within one company's data-base. There seems no reason to consider the causal blooms as anything other than

¹⁰ The list of papers and conclusions, in the form of a table running to several pages, has not been included here; it can however be obtained on request to SRSL. See also reviews by Gowen *et al.* (2009) and Davidson *et al.* (2012) provide an overview.

natural events, part of the normal seasonal cycle in western Scottish waters, but it is possible that farm nutrients could have stimulated increased numbers of the relevant phytoplankton, so long as sufficient dissolved silica were present. However, there are insufficient data to evaluate this possibility.

Figure 3.6: Spiny diatoms, *Chaetoceros phaeoceros* group



Images © SAMS

The long spines of these diatoms can damage the gills of farmed salmonids, when the diatoms are present in large numbers during a bloom, and perhaps especially when the fish are weakened by anti-lice treatments.

3.2.6 Diagnosis

Salmon farming results in the addition of large quantities of nutrient-nitrogen and nutrient-phosphorus to water-columns. Increased (but not harmful) concentrations of some of these nutrients, and of heterotrophic micro-organisms, can be observed close to farms. However, this is not of concern so long as there is adequate dispersion

Models predict, and limited observations confirm, that current levels of salmon farming add to nutrient concentrations, and change ratios of N:P and N:Si, in sea-lochs and voes in summer, to an extent that is of concern only in a few cases of high loadings and weak exchange of water with the sea.

In the only sea-loch where observations have been made before and after the introduction of salmon farming, amounts of phytoplankton have decreased, despite expectation of an increase. In the same case, there has been a shift in the 'balance of organisms', with relatively more dinoflagellates and fewer diatoms. It is not clear what has caused these changes.

On the larger scale, the salmon farming industry is sited mainly in waters that otherwise receive only small amounts of anthropogenic nutrients, the main source being the wider sea and natural cycles. In some cases (such as that of the Minch) nutrient inputs from salmon farming may contribute significantly in summer. There are insufficient data to assess whether phytoplankton biomass has changed on these scales

Evidence regarding change in the balance of organisms is scarce except in relation to harmful algae and their blooms. In these cases, the consensus is that HABs are generated by large-scale processes in waters on the continental shelf, rather than by local stimulation by farms.

Although there are some concerns about lack of understanding of long term change in phytoplankton, and although regulatory modelling does not currently take account of summer conditions, there is no diagnosis of eutrophication on the scale of lochs or wider sea-areas.

Table 3.6: Estimated contributions of Salmon farming to the nutrient content of the flow in the Minch c. 1999

		Nitrogen	Phosphorus
Winter		0.7%	0.9%
Summer Flow 1	–	5.3%	3.5%
Summer Flow 2	–	10%	6%

Calculations were based on the assumption that the Minch flow contained all of the nutrients contributed by 64,000 tonnes of salmon production undertaken in all connected lochs in 1999.

Two estimates of flow of sea-water through the Minch are included

Flow 1 = 90,000 m³ per second

Flow 2 = 50,000 m³ per second

From Tett & Edwards (2003). The flow estimates were taken from work published prior to 2000; there seems to be no published update of these flows.

Conclusion: as estimated here, the contribution of farm nutrients, and any consequent change in phytoplankton, is likely to be undetectable in most cases. However, the estimate of 10% nitrogen contribution for low-flow summer conditions might be detectable and suggests that there is some cause for concern if farm nutrient loadings increase.

Table 3.7: Budget for land-derived discharges of nutrient to the sea

	N (kT/yr)		P (kT/yr)		Si (kT/yr)	
Rivers (incl. agriculture), average 1984-1990	114	81%	6.2	45%	417	100%
Urban & Industry, 1999	19	14%	5.9	43%	0	0%
Aquaculture, 2001	7	5%	1.7	12%	0	0%
Total	140		13.8		417	

Aquaculture production in 2001 was 138,000 tonnes

Nutrient values expressed in kilotonne/yr, and as a percentage of the total value for each category. Values are rounded to nearest whole number (or 1 decimal place for P)

From Heath *et al.* (2005).

Conclusion: 'Aquaculture' - i.e. salmonid farming - contributed only a small fraction of land-derived and anthropogenic nutrient inputs to Scottish coastal waters, around the run of the millennium.

3.3 Effects of Waste Organics and Nutrients on Protected Features and Basin Waters

This subsection considers the direct and indirect effects of farm wastes and nutrients in some special cases. These are **basin water deoxygenation**, effects of nutrient enrichment on seaweeds, and impacts on selected examples of species and habitats, such as **seagrass**, protected by legislation as part of the UK's Biodiversity Action Plan (UKBAP).

3.3.1 Effects on oxygen in basin water

Most sea-lochs are fjords, containing one or more glacially-deepened basins in which the **basin water** is separated by shallow sills from each other and the sea. Decay of organic matter in this basin water consumes oxygen, which is replaced only when the water is exposed to light, allowing photosynthesis, or brought into contact with the atmosphere, allowing gas exchange. If the basin water remains isolated for some time, oxygen concentrations can fall towards a level of oxygen too low to support normal animal activity - i.e. **hypoxia**.

De-oxygenation of basin water is a natural process, but might be intensified directly, by sinking organic waste from fish farms or indirectly, by sedimenting primary production stimulated by farm nutrients. Gillibrand *et al.* (2006) developed a method to assess the risk of hypoxia as a result of slow flushing of the basin water and the augmentation of oxygen consumption by farm organic waste.

Deep water flushing depends on two processes:

- Mixing of water between the superficial and deep waters, which slowly decreases the density of the deeper water; the rate of mixing depends on the energy supply from upper layer water movements and the vertical density gradient, the result of the contrast between deep salty water and low-salinity surface water;
- The replacement of the basin water by dense seawater flowing into the basin over its seawards sill; the replacement depends both on the availability of dense external water and the extent to which the vertical density gradient has been eroded.

Gillibrand *et al.* drew on the FjordEnv mathematical model developed by a Swedish oceanographer (Stigebrandt, 2001) to calculate average replacement intervals for deep water in all Scottish sea-lochs. They also calculated the time taken for fully-oxygenated deep water to become hypoxic, which depends on oxygen demand from decaying organic matter in the water column and in the seabed, offset by oxygen mixed in from superficial water. Finally, they added the effect of sinking waste from salmon farms consented in 2006.

They concluded that between 5 and 38 of 138 sea-loch basins might be at risk of developing hypoxia from time to time, mainly as a result of natural processes. One of them, Loch Etive, has been much studied (Edwards & Edelsten, 1977; Edwards & Grantham, 1986; Edwards & Truesdale, 1997; Austin *et al.*, 2002; Overnell *et al.*, 2002;

Aleynik *et al.*, 2012), and Figure 3.7 shows a longitudinal section through Loch Etive at a time when the basin water had become hypoxic. In the case of this loch, hypoxia means that the scientifically interesting populations of copepods that live here have their living space squeezed between low-salinity surficial waters and the hypoxic deep waters.

Fluxes of organic waste from salmon farming might add significantly to the risk in a few cases. The findings by Gillibrand *et al.* (2006) should be seen as provisional; they pointed out the need for a better understanding of the physical and biological processes. In addition, no estimates were made of the potential indirect effects of salmon farming, i.e. the sinking into deep water of increased primary production. There are likely only a few lochs in which deoxygenation of sea-water might offer a significant risk both to native organisms and also to farmed fish, but expansion of farming in these will need special consideration of this risk.

3.3.2 Seaweeds

Nutrient enrichment can, on the one hand, stimulate growth of seaweeds, and, on the other hand, restrict available illumination because enhanced phytoplankton biomass decreases water transparency.

At one time, a familiar sight on sandy beaches was that of green sea-lettuce growing on leaking sewage pipes. Excess of such green algae is a sign of eutrophication, especially when green species grow as **epiphytes** on the brown and red seaweeds that make up the more usual rocky-shore or sublittoral community.

Oh *et al.* (2015) reported a study in Tasmania that compared seaweed communities on shallow rocky reefs at 100, 400 and 1000 metres from salmonid farms, with those at reference sites at 5000 metres. Greatest disturbance was found close to farms, where various sorts of green epiphytic seaweed grew. The cover of canopy-forming perennial (brown and red) algae appeared unaffected.

There have been experimental studies in Scotland that have investigated whether salmon-farm nutrients can enhance the growth of cultivated seaweeds (Sanderson *et al.*, 2012). However, the only publically available evidence on loch-scale effects comes from a summary of UK reports to the international body, OSPAR, concerning 'hot-spot' lochs with the highest scores for nutrient enrichment (OSPAR, 2009): "*Percentage area coverage of 'nuisance' green macroalgae in the intertidal zone did not exceed the assessment level of 15% at any of the sea lochs surveyed*" (in 2002-2006). OSPAR interprets this, along with the other indicators of eutrophication discussed in Section 3.2., as signifying a non-problem area.

Eutrophication in the Baltic Sea has been causally linked to decreases in water transparency (because of increases in phytoplankton light-absorbing biomass) (Fleming-Lehtinen & Laamanen, 2012), and thus to decreases in the maximum depth to which the perennial seaweeds can grow (Kautsky *et al.*, 1986; Rohde *et al.*, 2008). Burrows (2012) compared remotely sensed marine chlorophyll and macroalgae around Scotland, and found an inverse correlation, implying that the Baltic effect might apply here. However, although water transparency seems to be decreasing in Loch Creran (Tett, 2014; Tett, 2016), this is not associated with increased chlorophyll, and there appear to be no

publications that deal with perennial seaweed growth and transparency in Scottish lochs, either without or with fish-farms.

3.3.3 Seagrass

In the case of the Mediterranean Sea, one of the main concerns about waste from fish-farming is that of the impact on sea-grass meadows formed by plants of the genus *Posidonia* (Apostalaki *et al.*, 2007; Holmer *et al.*, 2008). Particulate organic waste can fall onto these meadows, smothering the grasses. In addition, decreases in water transparency associated with eutrophication can reduce the penetration of light into the sea and thus the maximum depth to which these plants can grow.

Beds of sea-grass of the genus *Zostera* (also known as eel-grass) are priority habitats for conservation under the UK Biodiversity Action Plan (Anonymous 2016). They are included by OSPAR in its list of declining and threatened species and habitats (Tullrot, 2009). They are in decline in England, Wales, Ireland and the Isle of Man (Jones & Unsworth, 2016), and are classified as a Priority Marine Feature in Scottish Waters (Tyler-Walters *et al.*, 2016). According to Scotland's Marine Atlas (Baxter *et al.*, 2011; p. 98)

"Subtidal seagrass beds of the eelgrass *Zostera marina* are considered nationally scarce and found on the west coast of Scotland extending up to the Northern Isles with a few records from the east coast in more sheltered bays and firths. The eelgrass stabilises the underlying sediment and absorbs a proportion of the wave energy as well as being a nursery area for many commercially important species of fish. Scotland holds about 20% of the seagrass beds in north-west Europe with many being considered degraded following significant declines."

Many of the reported sites for *Z. marina* are in the semi-sheltered waters of lochs and bays, and so there is potential for salmon-farm waste to fall on them, with harmful effects (Wilding & Hughes, 2010). In addition, seagrass are negatively affected by high levels of ammonia, such as might be associated with salmon farms. However, such local and direct effects are likely to be minor, because the seagrass beds occur in shallow waters (down to 5-10 m) and net-pens are typically anchored in deeper waters (more than 20 m). There has been little recent research on sea-grasses in Scottish waters, and hence little knowledge of how distributions are changing or whether water transparency is a critical factor.

3.3.4 Other UKBAP features

The topic of seagrass has been dealt with at some length, both because of the intrinsic importance of their habitats, and also as an example of concerns about impacts of salmon farming on protected species and habitats. In principle, such impacts are avoided at the planning stage by Scottish Natural Heritage (SNH) as a statutory consultee. Loch Creran again provides an example.

Reefs of tube-dwelling serpulid worms are a protected habitat, and are a designated feature of the Loch Creran Special Area of Conservation (SAC). The best-developed reefs form a narrow band around the loch in depths of between 6-10 m below chart datum. According to the Loch Creran Marine SAC Management Plan (Buchan &

McConnell, 2006), "[T]he potential impact of finfish aquaculture on serpulid reefs has been recognised and mitigation efforts have already been adopted by moving salmon cages into deeper water away from serpulid reef areas. "

A second example concerns beds of the coralline red seaweed, maerl. The seaweed grows slowly, forming deposits of carbonate-rich gravel, which is a UKBAP Priority Habitat.¹¹ Hall-Spencer *et al.* (2006) reports that, in 2003, 16 of 346 operating farms in Scotland were sited above maerl beds. Even in strongly tidal areas, expected to be of high dispersion, their study of 3 farms showed build-up of organic waste up 100 metres from the cage edge, reductions in live maerl cover, and changes in associated fauna. Hall-Spencer *et al.* argued that, because maerl are slow-growing, fallowing a site for 2 years would not allow recovery because the open structure of maerl decreases the suspension of POM.

3.3.5 Diagnosis

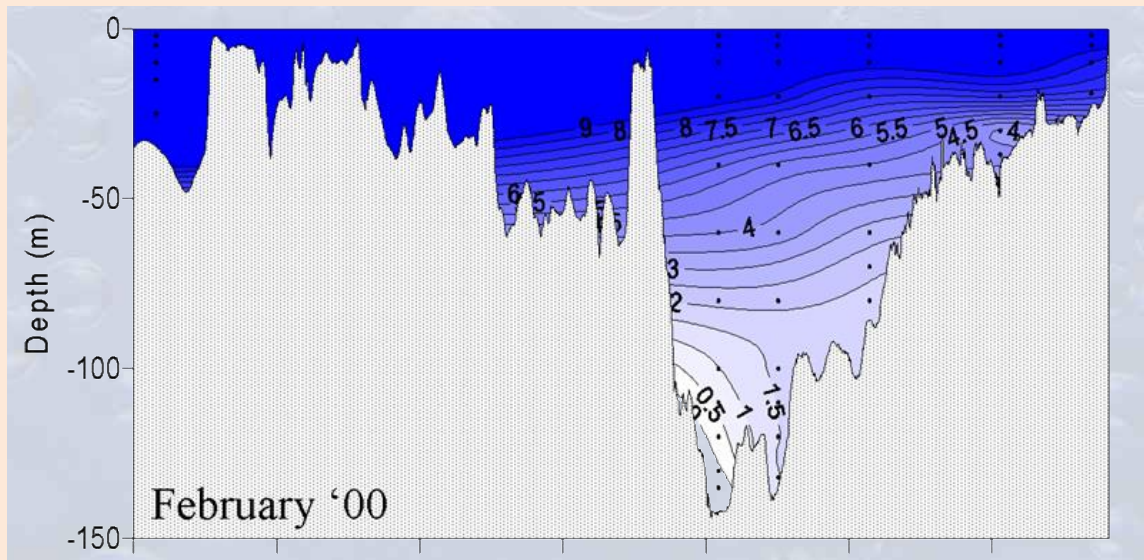
In principle, existing regulatory procedures, including accurate assessment of sites before operating licences are issued, should avoid the farm-scale effects described here for UKBAP habitats. However, this has not always been the case, as the maerl example shows.

Farm nutrients might locally enhance growth of opportunistic green algae, but this is not seen as an ecosystem problem if it is localised. Reports to OSPAR suggest that this was the case when hot-spot lochs were surveyed in 2002-2006. Absence of evidence of far-derived eutrophication suggests that loch-scale effects on water transparency, or on sedimentation of enhanced primary production, need not be of concern.

The occurrence or prediction of basin water hypoxia that might be intensified in a few lochs by salmon farm waste, points to the need for more detailed assessment of water replacement processes and oxygen consumption rates in these lochs.

¹¹ <http://jncc.defra.gov.uk/page-6023>

Figure 3.7: Vertical longitudinal section through Loch Etive in February 2000



Contours are dissolved oxygen (in mg L⁻¹). Hypoxia occurs when oxygen is than 2 mg L⁻¹ (Tett *et al.*, 2007). The sea is to the left; the Bonawe sill is the projection in the centre of the diagram, and it separates the deep upper basin, on the right, from the remainder of the loch.

Diagram from Stahl (2010). See also Overnell *et al.* (2002).

3.4 Prognosis and Mitigation

3.4.1 Prognosis

Most of the calculations relating to salmon farming impact refer to the period ca. 2000-2005, when salmon production was around 140,000 tonnes per year. Increasing annual production to ca. 200,000 tonnes by 2020, and, perhaps, 300,000 tonnes by 2030, will logically increase nutrient and organic waste inputs, unless the increase is compensated by changes in fish management, diet and physiology, leading to less waste per tonne of production or through the implementation of appropriate mitigation measures.

3.4.2 Mitigations

Avoiding UKBAP features

As discussed in Section 3.3, the avoidance of placing farms at sites where their footprint would disturb UKBAP benthic habitats should prevent damage to these sites. Models can determine an appropriate separation.

Use of models for site and zone selection and management

Three models have featured in this chapter (and others are available). DEPOMOD (Cromey *et al.*, 2002) has been in use for some years for determining the maximum stock size that, if licenced, will result in benthic conditions remaining within standards prescribed by SEPA. Its new version should improve simulations and extend the range of conditions that can be evaluated.

The ECE and benthic footprint models currently used for the Locational Guidelines, to identify lochs that are already at nutrient or organic waste assimilative capacity, seem to have been unchanged since 2002. The ECE model could be applied to summer as well as annual-average conditions, and estimates of exchange rate could be derived from more detailed models such as ACExR-LESV (Gillibrand *et al.*, 2013).

Physical modelling of the circulation of coastal waters, based on models such as FVCOM, has already proven useful in simulating the transport of larval sea lice (Adams *et al.*, 2016) and could be extended to estimate wide-area nutrient enrichment.

Recirculating Aquaculture Systems (RAS),

An alternative to releasing farm waste products into the wider environment is to culture the fish within a system where water exchange with the outside environment is restricted and controlled. Typically, these RAS are land based, but analagous closed containment systems are being developed for deployment at sea, such as the Hauge Aqua AS Egget.¹²

Fish in RAS generate waste water that is enriched with both dissolved and particulate waste. RAS therefore need to remove most of these to prevent recycled water becoming harmful to the farmed fish. Unlike some freshwater fish, which can be cultivated at high

¹² <http://www.haugeaqua.com/Technology/>

densities in very dirty water, salmon are sensitive to reductions in oxygen and the presence of ammonia.

The particulate waste from RAS systems is mainly comprised of uneaten feed, cell mass material from biofilters and faeces (Piedrahita, 2003). Removal technologies include swirl separators, mechanical filters, media filters, flocculation or foam fractionators (Cripps & Bergheim, 2000). However regardless of the technology used, there is a need to deal with the resultant aggregated solid waste. Amounts can be considerable, given that the waste may amount to 30% of the feed input (Cripps & Bergheim, 2000; van Rijn, 2013), and so 1000 tonnes of salmon may produce 400 tonnes of solid waste over the course of a production cycle. The first step in this, depending on the separation technology that has been used, is to dewater the waste, normally done using large geotextile bags (Sharrer *et al.*, 2009), aided by the addition of flocculation polymers. Given that for salmon production this waste is saline infused it may need to be de-salted before it can be used as a fertiliser or added to a standard anaerobic digester (van Rijn, 2013).

Although some excreted nitrogen, and more excreted phosphorus, is removed by filtering particulate waste, there is also the need to remove dissolved compounds of nitrogen and phosphorus. In the case of nitrogen, excreted mainly as ammonia, there are a number of different technologies available, either to reduce the toxicity of the nitrogen compounds through conversion (nitrification) of ammonia/ammonium to nitrate through the action of bacteria, or the incorporation of the nitrogen into bacterial biomass through the addition of a carbon source (van Rijn *et al.*, 2006). The latter adds to the solid waste for disposal, the former will lead to a build-up of nitrate unless a denitrification step is added.

Bregnballe (2015) notes that even a 'super-intensive' freshwater recirculating system should expect to replace about 10% of its water each day, and comments that "*[t]he higher the rate of recirculation the less new water will be used and the less discharge water will need to be treated. In some cases, no water at all will return to the surrounding environment. However, this kind of "zero discharge" fish farming is costly to build and the running costs for the waste treatment are significant.[even] for zero-discharge fish farming one should also be aware that a certain amount of water exchange is always needed to prevent the accumulation of metals and phosphorous compounds in the system.*"

In short, a RAS needs its own sewage treatment plant, but, like even the most effective plant used for urban waste water, will have a fluid discharge containing some nutrients and other compounds, and the requirement to get rid of solid waste. The usual regulation of such outputs will presumably apply, but it seems likely that any RAS discharging into the sea will need to make some use of nutrient assimilative capacity.¹³

Integrated Multi-Trophic Aquaculture (IMTA)

For open water systems such as caged based production of salmon the options for reducing the emissions from the production site are more limited than in the case of RAS. Within an IMTA system, emissions to the environment are recaptured through the trophic actions of organisms that are cultured alongside the salmon, known as extractive

¹³ The authors of this review have disagreed concerning the significance of such discharges.

organisms (Chopin *et al.*, 2012). For example, some of the dissolved nutrients could be absorbed by seaweed, the solid material sinking below the cage could be ingested by detritivores such as sea urchins and sea cucumbers, and fine suspended particulate matter could be ingested by filter feeding invertebrates. The ethos behind the IMTA concept is to use these waste streams to increase the growth rates of the extractive organism, and thus increase the profitability of the farms whilst reducing the environmental effect.

In the case of cage culture of salmon, the IMTA system would rely on natural water movements to distribute the waste to the extractive organisms, which would need to be spatially arranged to maximise their capture of the substances. However, modelling has shown there is a spatial mismatch between the extractive and fish components of the IMTA. Put simply, the amount of space to grow enough extractive organisms to cause a significant reduction in the dissolved component of the waste emissions are an order magnitude larger than the space required for the fin-fish production (Holdt & Edwards, 2014; Hughes & Black, 2016). However, this is not the case for the solid waste streams that impact the benthos directly below the cage. Modelling studies have suggested that, within this footprint, it is possible to grow sufficient detritivorous sea cucumbers to make a significant contribution to the reduction in organic matter deposited.

Sanderson *et al.* (2012) investigated the growth of seaweeds in the vicinity of fish farm cages in northwest Scotland, to see if the weeds could extract a significant amount of nutrients excreted by fish. *"Growth rates in summer for [the red dulse, Palmaria] palmata and [the brown kelp, Saccharina] latissima were enhanced by up to 48% and 61%, respectively, and biomass yields over a growth season were enhanced by 63% and 27%, respectively. ... Extrapolation show that under optimal conditions, a hectare of P. palmata could yield up to 180 tonnes wet weight per annum and a hectare of S. latissima 220 tonnes wet weight per annum. Conservative estimates of yields show that P. palmata could be expected to remove up to 12% and S. latissima 5% of the waste nitrogen released during the growth of 500 tonnes of salmon in the sea over 2 years."*

Filter-feeding shellfish, such as mussels, could remove some of the phytoplankton that might be generated by increased nutrients. Tett *et al.* (2012) added a simple mussel model to the ACExR-LESV model already described, and concluded that the growth of farmed mussels could in this way remove a part (between 1 and 16%) of salmon-excreted nutrients (Table 3.9). The nutrients they removed might have come from outside the loch, rather than originating from farmed fish. Nevertheless, the mussels (in the simulation) increase the lochs' assimilative capacities for farm nutrients.

These are research findings, and the real-world feasibility of IMTA will depend on regulatory, social and economic conditions that are beyond the scope of this review.¹⁴

Spatial planning and management

These suggested mitigation techniques are not widely adopted in Scotland. Therefore, it is likely that the main method for mitigating the environmental effects of salmon waste

¹⁴ As in the case of RAS, the review authors have differed in their assessment of the potential efficacy of IMTA as mitigation of salmon farming environmental effects.

and nutrients during the next decade lies in spatial planning and management. As recommended by Food and Agriculture Organisation (FAO) (Aguilar-Manjarrez *et al.*, 2017) this includes:

- Good site selection, which means identifying farm sites in water bodies of adequate assimilative capacity as well as avoiding impacts on Marine Protected Areas (MPAs);
- Planning suitable zones for expansion of the aquaculture industry;
- Adequate monitoring and adaptive management of sites and zones.

The application of marine spatial planning may be of great benefit as salmon farming moves offshore, into more dispersive environments, and links up with other 'blue' industries. Aquaculture in sea-lochs is currently governed by existing Scottish planning and consenting regulations (Anonymous, 2010) and subject to social as well as environmental constraints.

Site selection and zonal planning would benefit from the use of a range of models, including those discussed in this Section. Adaptive Management of farm sites and aquacultural zones is a recommended mitigation for many of the effects described in this report, and will be further discussed in Section 8.

Integrated monitoring of Scottish coastal waters

A final set of concerns relate to the biological components of assimilative capacity, and to changes that are taking place in the plankton in waters around Scotland. These changes have implications for shellfish cultivation, the occurrence of HABs, and for the marine pelagic food web (on which depend many fish, marine mammals and sea-birds). These changes in plankton community do not provide grounds for restricting the growth of salmon farming, but do need further investigation in order to understand the causes of change, and to determine if salmon farming plays any part. The recommendations by Rydberg *et al.* (2003) and Smayda (2006), concerning relevant studies, have only been partially implemented.

Table 3.8: Energy costs of three salmonid production systems used in Canada.

	Net-pen	Flow-through	Recirculating
Smolt or juvenile production	46.1	32.5	884
Grow-out infrastructure	2560	401	2470
On-site fuel use	798		14,400
Production of electricity used		70,100	291,000
feed production	23,500	21,500	34,700
Production of oxygen used		5820	
Production of chemicals used			9,970
By-product - fertiliser			-469
Total (MJ/tonne)	26,904	97,854	352,955
as kW-hr/kg	7.5	27.2	98.0
Global warming potential (tonnes CO₂ eq/tonne)	2,073	2,770	28,200

The flow through and recycling systems are land-based. The energy costs are in MJ per tonne live weight of fish produced. As electricity, 1 MegaJoule (J) is just over 1/4 KW/hr.

Source: Ayer & Tydemers (2010) - the corrected version of Table 3 from Ayer & Tydemers (2009)

Table 3.9: Potential for mussel farming to remove salmon-farm generated nutrient, as simulated by the ACExR-LESV model

	Mussel harvest, wet tonnes	N released or extracted, tonnes/yr	P released of extracted, tonnes/yr
1500 tonne farm releases		104	24
Creran	1039	18	2.5
Fyne	90	1.6	0.2
Sandsound	87	1.5	0.2
Spelve	827	15	2.0
Torridon	424	7.5	1.0

The ACExR-LESV model with additional equations for mussels, was used to simulate the effects of a 1500 tonne salmon farm in year 2 of the growth cycle), in the following water-bodies, in which a simulated farm containing 400 million small mussels was put out in January.

From Tett *et al.* (2012)

4 EFFECT OF THE DISCHARGE OF MEDICINES AND CHEMICALS FROM SALMON FARMING

Chemicals have been in use in intensive finfish aquaculture systems since their inception. Disease has long been one of the primary causes of losses to the industry, hence chemotherapeutants have been used to prevent and treat infections with pathogens and parasite. They are also used as feed additives and as anti-fouling treatments for aquaculture infrastructure. The following Section synthesises knowledge on these chemicals as they are currently used in the Scottish aquaculture industry, and on their potential environmental effects. Many of these chemicals are synthetic compounds, not naturally present in marine ecosystems, and there are concerns about their effects on organisms, populations and biological communities once they enter the environment.

The review refers primarily to salmon farming, since this is the most intensive and widespread form of aquaculture in Scotland. Production of other fin-fish species remains limited, and chemicals are not normally used in shellfish aquaculture.

Key questions are:

- Why are these chemicals needed?
- What are they, how are they used, and how much is used?
- How do they get into the environment and with what consequence?
- How is their use and effect controlled?

4.1 The Need for Chemicals in Salmon Farming

Several good reviews of chemical usage in marine cage farming exist, e.g. Costello *et al.* (2001) and BurrIDGE *et al.* (2010).

4.1.1 Dietary need

Farmed fish need copper and zinc, and so both are added to their diet (Dean *et al.*, 2007).

4.1.2 Sea lice

As described in Section 2.1, salmon farms in Scotland are affected by the ectoparasitic copepods *Lepeophtheirus salmonis* and to a lesser extent *Caligus elongatus*. These copepods are known commonly as sea lice. Their life cycle starts with a free-living stage, which metamorphose on contact with a fish and start feeding on host skin and tissues. The open wounds caused by untreated sea lice weaken the fish by loss of body fluids which may lead to death; the wounds also allow the proliferation of secondary bacterial and viral infections that can lead to mortality. Treatments are discussed in Section 2.1. Those relevant here include anti-sea lice treatments delivered in salmon feed or applied externally in baths.

4.1.3 Viral diseases

Farmed and wild salmonids suffer from a number of serious viral diseases, as discussed in Section 2.2. Vaccines are available to prevent some of these infections, but there are no known treatments for many fish viruses. Thus, preventive biosecurity, and destruction of infected stock along with site disinfection, are often the only ways to prevent the spread of these notifiable diseases.¹⁵ The relevant chemicals are those used for disinfection.

4.1.4 Bacterial/fungal/protozoan disease

There are numerous bacterial diseases in farmed salmonids, as reviewed in Section 2.2. Amongst these, furunculosis (caused by *Aeromonas salmonicida*) has largely been addressed by effective vaccines and occasional use of antibiotics. Antibiotics are still licensed for use on other bacterial infections.

What are usually called 'fungal' diseases on eggs and adult farmed salmonids are common (see Section 2.2).¹⁶ The fish are usually treated externally with either: Pyceze, active ingredient bronopol, or formaldehyde.

The amoebic gill disease in salmonids, caused by the protozoan *Neoparamoeba perurans*, is treatable by freshwater bath or hydrogen peroxide.

4.1.5 Fouling

Fish farming infrastructure in seawater can provide a habitat for seaweeds and attached animals such as mussels and barnacles. This causes drag on the equipment and in the case of nets, restricts water flow and thus oxygen to the caged fish. To combat this problem, antifoulants may be used to inhibit the growth of the microbial film that initially forms on new underwater surfaces and to prevent the development of algal sporelings. Some farms prefer mechanical cleaning of nets.

4.2 Chemical Application Methods

4.2.1 Feed additives

Three in-feed additives are currently authorised for use to combat sea lice: teflubenzuron, diflubenzuron and emamectin benzoate. The last of these is the predominant treatment in Scotland. There are also antibiotics authorised for in-feed treatment: oxolinic acid, amoxycillin trihydrate, trimethoprim/sulphadiazine, oxytetracycline hydrochloride, and sarafloxacin hydrochloride. In addition, copper and zinc compounds are added to fish feed as a dietary supplement, in excess of dietary needs.

¹⁵ <http://www.gov.scot/Topics/marine/Fish-Shellfish/aquaculture/diseases/notifiableDisease>

¹⁶ The causes of these diseases are not, according to strict taxonomy, fungi; they are better called microbial moulds, being organisms more closely related to micro-algae than fungi.

4.2.2 Injections

Vaccines such as Alphaject, Furogen and Aquavac Furovac are administered to anaesthetised fish *via* injection into the body cavity. Additionally, medicines to facilitate egg stripping in hatchery fish, e.g. Receptal, may be injected. Chorionic gonadotropin e.g. Gonazon, used to induce spawning, is also licensed for use. There is no demonstrable pathway for any of these to enter the environment, especially in the closed water systems of hatcheries, and they will not be further considered here.

4.2.3 Baths/dips

Baths and dips are used for several topical treatments, such as sea lice treatments with hydrogen peroxide, cypermethrin, deltamethrin and azamethiphos, and for antifungal treatments such as bronopol.

4.2.4 Paints and steepes

Antifouling compounds are applied in paint to structures, or used in the form of a liquid in which nets are steeped. Following the discovery of the harmful effects on marine invertebrates of the anti-fouling compound tributyl tin (TBT) (Balls, 1987; Bailey & Davies, 1991; Readman, 2006); it is now banned for use by fish farms and all small craft that anchor in coastal waters. Replacement products are based on copper metal oxides in combination with organic biocides and sometimes zinc (Guardiola *et al.*, 2012). For example, out of the 25 antifoulant products licensed for use in Scotland in 2003, 19 contained copper either as copper, copper oxide or copper sulphate (Bostock *et al.*, 2003).

4.3 Main Properties of Chemicals Used

'Chemical' here is a restricted group of mainly anthropogenic compounds categorisable to as follows:¹⁷

- Organic compounds with halogens (fluorine, chlorine and bromine), phosphorus, or tin;
- Carcinogens, mutagens and endocrine mimics;
- Persistent hydrocarbons and persistent bioaccumulatable organic toxic substances;
- Metals and their compounds;
- Biocides and plant protection products.

A compound may belong to more than one category.

4.3.1 Anti-sea lice chemicals

At present, six sea lice medical treatments are licensed and consented in Scotland: hydrogen peroxide, cypermethrin, deltamethrin, azamethiphos (all bath treatments), and

¹⁷ Taken from Annex VIII, Directive 2000/60/EC (the Water Framework Directive's 'Indicative List of the Main Pollutants')

teflubenzuron and emamectin benzoate (EMB) (in-feeds). A summary of their characteristics and mode of action is presented in Table 4.2 and more detail is provided in the following pages. Additional therapeutants used in other countries are also included in this overview, as well as the main therapeutant used to treat the fungal disease, *Saprolegnia*.

Table 4.1: Chemical use in Scottish aquaculture 2012-2016 for lice treatment.

Year	Delta-methrin kg	Cypermethrin kg	Aza-methiphos kg	Teflubenzuron kg	Emamectin Benzoate kg
Treatment mode	bath	bath	bath	in-feed	in-feed
2012	21	*	194	225	73
2013	12	*	154	262	59
2014	17	*	253	*	66
2015	12	*	282	*	71
2016	8	*	570	*	58
Total actual 2002-2016	123	118	2,417	920	818

*No cypermethrin used since August 2011; no teflubenzuron since January 2013.

Table 4.2: Summary of important characteristics of treatment chemicals used in fish farming in Scotland

Active ingredient	Product name	Purpose, use	Mode of action	Dispersion, decay	Risk
Hydrogen peroxide	Paramove, Salartect	Bath treatment for adult sea lice on Atlantic salmon and rainbow trout.	Mechanical paralysis, membrane peroxidation and enzyme inactivation. Not species specific.	Degrades to water and oxygen by 67% at 15°C after 7 days	Increasing use; low risk
Cypermethrin	Excis	Bath treatment for pre-adult and adult sea lice on Atlantic salmon and rainbow trout.	Synthetic pyrethroid. Acts on the nervous system by increasing sodium permeability of the nerve membrane. There is a greater effect on crustaceans than on fish or mammals.	Readily adsorbed onto particulates settling to seabed. Degrades rapidly; half-life 35-80 days	Thoroughly tested on a range of organisms
Deltamethrin	Alpha Max	Bath treatment for pre-adult and adult sea lice on Atlantic salmon and rainbow trout.	Synthetic pyrethroid. Acts on the nervous system by increasing sodium permeability of the nerve membrane. Greater effect on crustaceans than on fish or mammals.	Very low solubility; less readily adsorbed than cypermethrin; but rapid absorption by sediment and degradation. Marine sediment half-life 140 days.	More limited testing; but rapid degradation indicates low risk.
Azamethiphos	Salmosan	Bath treatment for pre-adult and adult sea lice on Atlantic salmon.	Organophosphate. Acts as a cholinesterase inhibitor across a wide range of animal groups with cholinesterase, particularly crustaceans.	Highly soluble; 9 day half-life	Lobster larvae used for EQS; rapid degradation means low risk.
Dichlorvos	Aquaguard	Bath treatment for adult sea lice on Atlantic salmon	Organophosphate. Acts as a broad species spectrum cholinesterase inhibitor.	Highly soluble; 4-8 day half-life	Not currently used due to widespread resistance

Teflubenzuron	Calicide	In-feed treatment to disrupt the development of larval and pre-adult sea lice.	Moult inhibitor which prevents the formation of chitin, and therefore affects primarily crustaceans/arthropods.	Ca 90% of teflubenzuron excreted and mainly ends up in sediment. May be detected in sediment 100 m from the farm. Half-life in sediment of 104-123 d	Not currently used in Scotland; not effective against adult stages. Difficult to get consents for all cages in a group.
Diflubenzuron	Lepsidon; Releeze	In-feed treatment to disrupt the development of larval and pre-adult sea lice.	Moult inhibitor which prevents the formation of chitin, and therefore affects primarily crustaceans/arthropods.	Dispersal mainly related to faecal deposition. Low water solubility; high affinity for organic molecules = slow degradation. Half-life reported as 4-17 days but reported persistence in sediments > 204 days.	EQS; but not consented for use in Scotland. No MA. Concerns over metabolites raised in Norwegian press.
Emamectin benzoate	SLICE®	In-feed treatment to control all parasitic stages of sea lice on Atlantic salmon.	Increases membrane permeability to chloride ions and disrupts physiological processes. Highest activity in crustaceans.	Low sea water solubility; high potential adsorption to particulate material/sediments; long half-life (164-175 days) in anaerobic sediments.	Scavengers, especially crustaceans, most at risk. SEPA has reassessed the EQS and imposed new limits.
Bronopol (2-bromo-2-nitropropane-1,3-diol)	Pyceze	Anti-microbial, used to treat fungal infections (<i>Saprolegnia</i>)	Causes inhibition of thiol-containing dehydrogenase enzymes that are membrane bound, resulting in cell leakage and eventual collapse. ¹⁸⁾	Highly soluble, does not tend to accumulate, rapidly metabolised	Considered non or slightly toxic to birds, moderately to highly toxic to marine invertebrates and slightly toxic to marine fish ¹⁹⁾ (EPA-738-F-95-029, 1995)

¹⁸ UK VMD Mutual Recognition Procedure. PUBLICLY AVAILABLE ASSESSMENT REPORT FOR A VETERINARY MEDICINAL PRODUCT. Pyceze 500 mg/ml concentrate for solution for fish treatment (UK VMD UK/V/0311/001/MR)

¹⁹ EPA-738-F-95-029, 1995

4.3.2 Anti-fouling chemicals

Modern paints and net-steeping liquids use metal compounds that dissolve slowly in seawater, releasing ions of copper and zinc. It is these ions that are harmful to micro-organisms that might settle and grow on the netting or cage. However, copper and zinc are needed in small amounts by living creatures, since they cannot be manufactured in the body and are essential for some biochemical reactions, and are toxic only at higher concentrations. The challenge for the designers of antifouling materials is, thus, to ensure that the materials release sufficient copper or similar active ingredient to kill bacteria and algal spores close to the surfaces they are intended to protect, but without dissolving too quickly, which would increase the risk of wider harm and would require more frequent treatments.

Consequently, some manufacturers add 'booster biocides' to augment the antifouling action, and these can take part in complex chemical reactions. For example, the synthetic chemical, copper pyrithione, is such a biocide. However, research suggests that when zinc is present, the pyrithione part can swap from copper to zinc, resulting in zinc pyrithione. This compound, used in anti-dandruff shampoos and as a fungicidal additive for plastics, has been found to be highly toxic to copepods as well as planktonic micro-algae (Hjorth *et al.*, 2006; Maraldo & Dahllöf, 2004), although degradation does occur in the short-term in well sunlit environments (Maraldo & Dahllöf, 2004).

4.4 Amounts of Chemicals Used

Since the publication of the last review and synthesis in 2002, (Black *et al.*, 2002) the amount of chemicals used in Scottish aquaculture has varied. Table 4.1 shows amounts of sea lice-treating compounds used in the last five years, plus their total amounts since 2002.

Deltamethrin has only been used in Scotland since 2008 but over the last five years usage has decreased. Cypermethrin has been used in Scotland since 1997 but usage ceased in 2011. Azamethiphos has contributed the highest values in total since 2002 (available since 1994) and the usage has increased in the last 5 years. In contrast, Teflubenzuron has not been used since 2013. Finally, EMB has been available in Scotland since 2000 and usage over the last 5 years is constant.

There are no publically available data on use of hydrogen peroxide, other disinfectants, antibiotics or antifouling paints in salmon farming in Scotland, and no synthesis of annual usage could be found, either per farm or for the country as a whole. An anonymous presentation quoted recent farm usage in Scotland of 0.02 to 0.38 grams of antibiotic per tonne (g/t) of harvested fish.²⁰ For comparison, use in 2013 in Norway averaged 1.3 g/t, in British Columbia, 43.7 g/t, and Chile, 701 g/t (Henriksson *et al.*, 2017).

²⁰ "Antimicrobials and Scottish salmonid aquaculture" attributed to Marine Scotland Science, presneted to FSR-AMR on 25 November 2015, no author. This resembles the figures given without obvious source by Watts *et al.* (2017).

4.5 Environmental Pressures

Some concerns about the effects of these chemicals relate to the welfare of the farmed salmon or staff or human consumers of the product. They are not considered here. This Section deals with routes from farm to environment and the consequent pressures generated by the presence of potentially toxic chemicals there.

4.5.1 Environmental Quality Standards (EQS)

The greatest environment concentration at which a chemical is deemed to be tolerable is set by an EQS. That is to say, a Pressure from a synthetic chemical resulting from salmon farming is deemed to be significant if concentrations exceed a relevant EQS on an appropriate spatial scale.

A value for an EQS is, typically based on laboratory experiments to find maximum concentrations that have no effects on test subjects. Results from laboratory experiments allow the derivation of Lowest Observed Effect Concentration (LOEC) and no observed effect concentration (NOEC). Based on these values obtained in the laboratory for a range of species, the predicted no effect concentration (PNEC) can be derived, which is established to ensure protection of non-target species and the wider environment. The PNEC is derived by applying a factor of 10, 100 or 1000 to the obtained values in the laboratory, depending on the data available, the degree of precaution required and the likelihood that the test organisms are more robust than most in nature. Protocols for the derivation of EQS values are well-established²¹, but the results can be controversial, especially when extrapolating to effects on interdependent communities of organisms.²²

4.5.2 Routes into the environment

Antifouling compounds continuously leach into the seawater around farms. They may reach the seabed through adsorption onto sinking matter or in falling flakes of paint (Dean, 2007; SARF, 2014).

Chemicals administered to fish in feed reach the sediment in uneaten food and in faeces. Bath treatments disperse into the water column. Treatments used in hatcheries may enter freshwater or seawater along with discharges of used water.

The resulting concentrations of the constituent chemicals in water or sediment depend on a number of factors, including rates of decay of the compounds, temperature, oxygen availability, water dispersion rates, and sedimentation and resuspension rates. Additionally, chemicals may be biologically transformed and enter in food webs, with indirect effects in higher trophic levels.

²¹ Derived by UK Technical Advisory Group (UKTAG) for the Water Framework Directive (WFD). SEPA, 2015. Supporting Guidance (WAT-SG-53) Environmental Quality Standards and Standards for Discharges to Surface Waters.

²² PNEC derivation (ECHA):

https://echa.europa.eu/documents/10162/13632/information_requirements_r10_en.pdf

PNEC/EQS values (OSPAR):

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/361476/OSPAR_RBA_Predicted_No_Effect_Concentrations_PNECs_Background_Document.pdf

4.5.3 Dispersion

Understanding the dispersion of bath treatments in the receiving water body is based on modelling studies by SEPA, in which dilution is estimated by dispersion coefficients and hydrographic characterisation of the site. From this model, predictions are compared with the EQS for the specific chemical, and attention is paid to whether multiple treatments in a short time would also breach the EQS (SEPA, 2008b). Bath treatment chemical plumes can extend up to 8 km (Page & BurrIDGE, 2014).

For in-feed medicines, SEPA rely on modelling the discharge with a particle tracking model DEPOMOD (Cromey *et al.*, 2002) which characterises the site using hydrographic and bathymetric data, predicting deposition within the Allowable Zone of Effect (AZE) and setting limits such that the EQS is not violated (SEPA, 2005; 2015). The EQS is limited to the upper, mixed layer of the sea bed (surficial 5 cm).

4.5.4 Retention in sediments

Anti-lice medicines deposited on the sea bed following treatments are subject to biological and physical processes. Burrowing creatures may bury compounds deeper into the sediment, or ingest it and bind them with mucosaccharides in faecal pellets; these medicines may affect feeding rates of these 're-worker' animals (Méndez, 2006). These compounds alternatively may be re-suspended by near-bed currents and transported further from the depositional site, or may be deposited in heavily enriched sediment where anaerobic processes prevail (BurrIDGE *et al.*, 2010; Haya *et al.*, 2005; Samuelsen *et al.*, 2015). In such conditions, retention may be indefinite. Consolidation and cohesion in accumulating environments may also act to retain these compounds.

4.5.5 Degradation

The degradation of veterinary medicines in the marine environment depends, *inter alia*, on a number of physical factors such as receiving water pH, solubility, chemical sorption, the volatility of the compound itself (Boxall *et al.*, 2003) and redox potential of sediments. Degradation is complicated by the slow release of some in-feed treatments; initial deposition post-treatment may be followed by months of post-treatment defaecation (Telfer *et al.*, 2006; Samuelsen *et al.*, 2015). Additionally, metabolites from the degradation of veterinary medicines, whilst not as active as the parent compound, may often persist with relatively unknown results (Boxall *et al.*, 2003). Laboratory experiments, however, can often overestimate the length of time needed for degradation in the natural environment (Díaz-Cruz *et al.*, 2003).

Nevertheless, some aquacultural chemicals have low biodegradability potential due to their intrinsic properties, and also affinity to organic matter, and thus may persist in the environment for extended periods. Metals do not degrade but they change form and can be more or less bioavailable/toxic, again depending on form, receiving environment and species (Tchounwou *et al.*, 2012).

4.5.6 Bioaccumulation and food chain transfers

Very little direct information on bioaccumulation and food chain effects is available from the literature. Inferences are largely drawn from degradation potential and persistence,

either in sediment or non-target species' tissues. Aznar-Alemany *et al.* (2017) assessed the effects of pyrethroids on farmed salmon and their conclusions were that although all sample fish had detectable levels of cypermethrin and deltamethrin, those levels did not lead to concerns regarding Acceptable Daily Intake (ADI) for humans. Telfer *et al.* (2006) and Langford *et al.* (2014) also detected levels of specific therapeutants in the flesh of a range of organisms but overall those levels were found to be below the Maximum Residual Level (MRL) levels for salmonids. MRL is the highest amount of an agricultural or veterinary chemical residue that is legally allowed in a food product. There is to date no evidence that the chemicals currently used in fish farming in Scotland persist and accumulate in the food chain, and no such evidence has been presented in appropriate assessment studies to date.

4.5.7 In-combination effects

Very few studies have addressed possible effects of several chemicals acting in concert at low concentrations, and given the complexity of testing that would be required this is unlikely to change. Various approaches to this problem have been suggested (Crane, *et al.*, 2006) including transforming and plotting presumed cumulative or additive effects of several chemical stressors. Careful monitoring and analysis will be required to address this issue and validate or otherwise any such approaches.

4.5.8 Copper in sediments

The effects of copper (and other metals) on the seabed specifically from fish farming activities has been reported in Scotland and other locations across the world (Dean *et al.*, 2007; Russell *et al.*, 2011; Kalantzi *et al.*, 2014; 2015); there is a large body of work on copper in marine sediments from other sources. There is good evidence that copper is generally unavailable to infaunal organisms in anoxic, or hypoxic, conditions that occur typically under fish cages (Brooks & Mahnken, 2003); similarly Brooks *et al.* (2003; 2004) concluded that both zinc and copper were unlikely to be toxic when sulphides were abundant in marine sediment. In a laboratory ecotoxicity study, Solan *et al.* (2008) found the amphipod *Corophium volutator* was able to tolerate concentrations of 0.2 parts per million copper and the polychaete *Hediste diversicolor*, 78 ppm.²³ Kalantzi *et al.* (2015) observed a greater uptake of metals in wild fish around fish cages than in the farmed fish.

4.5.9 Organohalide compounds

There have been concerns regarding the presence of organohalides, or halogenated organic compounds in farmed fish (Lohmann *et al.*, 2007; Hites *et al.*, 2004a; 2004b). These constitute a large class of natural and synthetic chemicals that contain one or more halogens (fluorine, chlorine, bromine, or iodine) combined with carbon and other elements. These compounds include pesticides (such as DDT, mirex and lindane), industrial compounds (such as polychlorinated biphenyls PCBs) or unintentional products (such as dioxins). Although many of these compounds have now been banned

²³ Parts per million given in main text for clarity; the cited work (Solan *et al.*, 2008) gives 193,326 µg Cu kg⁻¹ wet sediment (10-day Median Lethal Concentration-LC50) for the amphipod and 74,988 µg Cu kg⁻¹ wet sediment (10-day LC50) for the worm,

(Persistent Organic Pollutants (POPs), Stockholm Convention), they can be very persistent and transported long distances. They also tend to accumulate in fats, thus the potential to accumulate within the fatty tissue of fish, and thus to be present in fish meal and fish oil used in diets of farmed fish (Maule *et al.*, 2007). Levels of PCBs and polybrominated diphenyl ethers (PBDEs) in sediments around fish farms were investigated by Russell *et al.*, (2011), who found them comparable to other marine locations, thus indicating that proximity to fish farms did not lead to increase of organohalide compounds in sediments.

4.6 Effects on Ecosystem Function on Protected Species and Habitats

The main environmental concerns regarding chemical contamination are:

- Direct acute or chronic toxicity to non-target species;
- Effects particularly on species of conservation interest;
- Community effects, leading to decreases in diversity or function (for example, microbial or and geochemical processes that regulate the cycling, bioavailability, and fate of micro- and macronutrients;
- Food-web effects.

Local environment characteristics influence bioavailability of chemicals to organisms and thus toxicity. Bioavailability and toxicity are species specific and depend on their ecology, including mode of feeding, and the mechanism of toxicity which will make certain taxa more sensitive to certain chemicals. For example, all crustaceans are sensitive to sea anti-lice medicines that interfere with moulting and chitin production (Hosamani *et al.*, 2017). Similarly, the pelagic micro-algae of the phytoplankton are likely to be sensitive to the algicides used in antifouling compounds. Setting and enforcing appropriate EQS is intended to protect against these effects.

4.6.1 Effects of anti-lice compounds on ecosystems

Studies on the wider or longer-term impacts of fish farm chemicals are limited. An early year-long, study on teflubenzuron in Loch Eil found that although there was some evidence of impact at 50 m from the cages, there were no detectable adverse impacts on community structure and diversity including important key reworker species or on their bioturbation activity (McHenery & Ritchie, 1998; SEPA, 1999b). Mussels were found to depurate ingested teflubenzuron relatively quickly in this study, and a separate field ecotoxicity test on lobster larvae showed no effect beyond 25 m from the treated cages. Samuelsen *et al.* (2015) noted sediment trap concentrations of teflubenzuron to be higher than in-feed concentrations post-treatment, which they suggest indicated environmental accumulation in the short term, particularly if organic matter concentration was high since this chemical tends to associate with such compounds. These authors estimated the half-life (the time required for the amount of chemical to reduce to half of its initial value) of this compound to be of 170 days in their study. Other authors estimated the same compound to have a half-life of 115 days (SEPA, 1999b). REACH

states that a substance is considered persistent if the degradation half-life in marine sediment is higher than 180 days (European Chemicals Agency, 2017). Samuelson *et al.* (2015) indicated that although during medication most non target organisms sampled (a range of invertebrates and fish species) had teflubenzuron residues in their flesh, after 8 months only polychaete and some crustaceans contained drug residues.

Black *et al.* (2005) in a five year study found no far-field effects of a range of sea lice treatments in Scottish sea lochs on zooplankton, phytoplankton, sub-littoral settlement, intertidal communities, or sediment macro- or meiofauna, and although they acknowledged there could be some near-field effects, were unable to separate them from the co-linear effect of organic enrichment.

A shorter-term (one year) field study was performed in Loch Duich on the effects of EMB (SEPA, 1999a), and no discernible impact was detected on benthic macrofauna. In this study, mussel concentrations of EMB were also investigated, and creel invertebrates including crustaceans, echinoderms and molluscs examined for medicine retention in tissues. These scavengers showed medicine uptake, but at very low levels - less than 5.0 parts per billion (ppb), the lower limit of detection being 1.0 ppb - and only up to one month post-treatment (SEPA, 1999a).

Telfer *et al.* (2006) assessed the environmental effects of EMB under commercial conditions. The study showed that the chemical was found in sediments 10 m from the cages 12 months after treatment (1.8 ppb) but not detected further afield. It was clear that EMB was degrading in this environment. The values obtained are compliant with the current EQS value but not with those most recent proposed by WRC (Benson *et al.*, 2017). The study also showed EMB uptake, one week after farm EMB use, by mussels located 100 m from the cages, whereas only mussels located within 10 m of the cages contained detectable EMB 1 month post-treatment. This finding would indicate metabolism of the chemical. Macro infaunal samples analysed indicated no community impacts.

Langford *et al.* (2014) assessed levels of a range of aquaculture therapeutants (diflubenzuron, teflubenzuron, EMB, cypermethrin, and deltamethrin) in marine sediments around farms in Norway. They found that concentrations of EMB exceeded the UK EQS on five occasions in their study. In the case of teflubenzuron, the UK EQS was exceeded in 67% of the sediment samples. In the case of diflubenzuron it was exceeded in 40% of water samples. EQS values were not exceeded for the other therapeutants studied. A variety of organisms was also sampled. EMB was below two parts per billion (ppb) in mussels. Values for other therapeutants and species were found to be higher, for example crab had a median concentration of diflubenzuron of 340 ppb in their flesh. For comparison, the regulatory MRL for EMB in salmon tissue intended for human consumption is 100 ppb²⁴ and the MRL for diflubenzuron is 1000 ppb²⁵.

²⁴ Annex I of Council Regulation (EEC) No. 2377/90

²⁵ EMA (European Medicines Agency) (1998) The European agency for evaluation of medicinal products. Committee for veterinary medicinal products. Diflubenzuron. Summary report

4.6.2 Effects on ecosystems of antifouling compounds

Earlier antifoulants were based on TBT. However, following a long series of studies which clearly indicated toxicity to non-target organisms, including endocrine disruption (Balls, 1987; Bailey & Davies, 1991; Readman, 2006), and persistence in the environment (Vigilino *et al.*, 2004), these compounds were banned for a variety of uses, including aquaculture (Sousa *et al.*, 2014). Interest switched to copper-based products. Copper in its ionic form is extremely toxic to algae, invertebrates and fish, but less to mammals (Environmental Protection Agency (EPA), 2016). In the natural environment effects are less acute due to chelation and binding to organic matter and other compounds, such as carbonates (Fathi *et al.*, 2012), and acclimation and detoxification (e.g. via metallothionein induction). Nevertheless sub-lethal effects can occur (e.g. genotoxicity; Anjos *et al.*, 2014). Brooks and Waldock (2009) indicate that the overall impact of copper in the marine environment is low, although there are areas where hotspots could occur.

More recently other anti-foulant substances have emerged, which have included zinc pyrithione amongst others (Guardiola *et al.*, 2012). Most of these chemicals are algicides (Dafforn *et al.*, 2011). Zinc pyrithione concentrations in the UK have been found below the limit of detection (Thomas, 1998; 1999). It is considered that zinc pyrithione photolysis and degradation are relatively rapid (a few hrs; Konstantinou & Albanis, 2004), however if light conditions are reduced the compound can persist for longer (Dalhöf *et al.*, 2005). Reported acute toxicity values of zinc pyrithione are in the part per billion range, with the more sensitive organisms being macroalgae, oyster, and juvenile rainbow trout (Dahlhöf *et al.*, 2005). The same authors reported that it can affect microbial functions and interfere with nutrient cycling.

The toxicities of antifouling compounds in suspension-cultured fish cells and sea urchin eggs and embryos were found in decreasing order as follows: zinc pyrithione>Sea-nine 211>Diuron>Irgarol 1051 (Okamura *et al.*, 2002; Kobayashi & Okamura, 2002).

Bao *et al.* (2008) studied joint effects of zinc pyrithione and copper on three marine species. This is particularly relevant if they are applied jointly as antifoulants. Synergistic effects were observed in the presence of both compounds at realistic concentrations, with the toxicity of zinc pyrithione greatly increased.

4.7 Antimicrobial Resistance

An area of concern is the development of antimicrobial resistance in marine bacteria in proximity to fish farms (Shah *et al.*, 2014; Watts *et al.*, 2017). Buschman *et al.* (2012) reported a significant increase in both numbers and population fractions of bacteria resistance to specific antibiotics in sediments from an aquaculture site in Chile compared to those from the control site. They suggest that it is possible that the current use of antimicrobial compounds in the Chilean aquaculture may lead to selection of antimicrobial-

EMA/MRL/486/98-Final. Available at www.ema.europa.eu/docs/en_GB/document_library/Maximum_Residue_Limits_-_Report/2009/11/WC_5000_13852.pdf

resistant bacteria in marine sediments. As mentioned earlier, the use of antibiotics in the Chilean salmonid-farming sector has been much larger than in Norway or Scotland.

4.8 Controls on Chemical Use

4.8.1 Legal framework

The use of medicines in UK aquaculture is regulated by the Medicines Act 1968 and the Marketing Authorisations for Veterinary Medicinal Products Regulations 1994;²⁶ these regulations are enforced by the Veterinary Medicines Directorate (VMD) of Department for Environment, Food & Rural Affairs (Defra). The marketing of all veterinary medicines is regulated by the European Union's directives, collectively known in the UK as "The rules governing medicinal products in the European Union, Volume 5 - Pharmaceutical legislation - Medicinal products for veterinary use".²⁷ Before any veterinary medicine may be used in the UK, it must receive a Marketing Authorisation (MA) from the Veterinary Medicines Directorate. This must contain a MRL from the European Medicines Evaluation Agency and address environmental concerns.

The use of VMD authorised chemicals in fish farming in Scotland is additionally controlled through the issue of an authorisation under the Water Environment (Controlled Activities) (Scotland) Regulations 2005 (As amended) – often referred to as "CAR". These are also designed to ensure environmental protection and comply with the Water Framework Directive (2000/60/EU) and the Dangerous Substances Directive (76/464/EEC) (DSD).

In addition, the Aquaculture and Fisheries (Scotland) Act (2007), makes sea lice management and monitoring a statutory process.²⁸

4.8.2 Regulation of chemical use by SEPA

The SEPA is responsible for the implementation of CAR in respect of fish farming, and in so doing seeks to achieve a balance between site productivity and environmental disturbance. SEPA (2015) gives full details.

An authorisation to discharge chemicals (sometimes referred to as a "consent to discharge", or "CAR license") must be obtained from SEPA as part of the wider process of applying for a seabed lease from the Crown Estate and seeking planning permission from the Local Authority for the establishment, modification, or expansion of a fish farm. Specific consent conditions are drawn up on a site-by-site basis and include cage position and number, species farmed and biomass limits based on the carrying capacity of the receiving environment. The authorisation allows a fish farmer to discharge organic and inorganic wastes and approved chemicals (i.e. those with a VMD Marketing Authorisation) subject to compliance with EQS.

²⁶ SI 1994/3142

²⁷ http://ec.europa.eu/health/documents/eudralex/vol-5/index_en.htm

²⁸ <http://www.legislation.gov.uk/asp/2007/12/part/1/crossheading/parasites>

Authorisations are not time limited, although SEPA will review such licenses from time to time. New or modified consents may be required if there is significant change in the size or configuration of a farm, or where new chemicals are being introduced. Although the consent does not specifically limit frequency of chemical use, it does require that SEPA be notified whenever authorised chemicals are used, and that full records of use be kept.

EQS are set by SEPA, in close consultation with VMD, for each medicine following a risk assessment. Chemical manufacturers provide a dossier on effects, including ecotoxicology studies. SEPA has these independently peer reviewed, and then applies a safety factor to generate the EQS. SEPA reviews standards for each consented medicine on a regular basis, and assesses consents in the light of new scientific evidence or monitoring results.

The requirement to impose standards and safety factors is mandated by the EU Dangerous Substance Directive (67/548/EEC) which specifies List I and List II substances on the basis of environmental harm; additionally in the UK the Environmental Protection Act 1990 requires EQS for the most dangerous chemicals, including the Red List substances. Thus, all chemicals discharged into the marine environment have statutory standards; lists of these EQS are compiled by the UK National Centre for Environmental Toxicology (WRc plc) and are available from SEPA (2015).

In order to be issued with an authorisation permitting the discharge of medicines, a safe limit on the scale or rate of release of medicines must be established for each fish farm site. This is derived on a site-by-site basis dependent upon the configuration of the site, the tidal regime, the bathymetry, proximity of special features etc. The precise approach is also varied dependent upon which medicine and which method of administration is used (i.e. bath or in-feed treatment).

For example, for the in-feed medicine SLICE®, discharges are restricted based upon the imposition of two licence limits, the Total Allowable Quantity (TAQ) and the Maximum Treatment Quantity (MTQ), these limits being derived by site-specific modelling processes. The TAQ is the maximum amount of EMB which is predicted can be released whilst still ensuring compliance with the far field EQS, and this in turn depends upon modelling dispersion, advection, decay etc. In practice, for the day to day operation of a site, the maximum amount of a particular product normally permitted for treatment at a particular site is called the MTQ, and is calculated based on the quantity required to treat the maximum licensed biomass. Where SLICE® has been previously used and residues are still predicted to be present in the sediment, a lesser amount will be permitted to be discharged such that the subsequent sediment concentration does not exceed the EQS. The MTQ may however be exceeded, following consultation with SEPA, if the veterinary surgeon responsible considers that the welfare of the farmed stock is at risk. In such circumstances, while the MTQ may be exceeded, the EQS must still be complied with, and the TAQ limit determined for the medicine at the farm cannot therefore be exceeded.²⁹ This approach allowing veterinary discretion only applies to the use of EMB

²⁹ The Water Environment and Water Services (Scotland) Act 2003, Regulation 4(1) Condition A1.9). (c.f. SEPA, 2008a)

and the standard which ensures far field environmental protection will not be endangered where such an approach is endorsed.

In the case of EMB, the EQS approach now encompasses two separate standards, a near-field (within the so-called AZE) and a far-field standard (outwith the AZE) (SEPA, 2017; Benson *et al.*, 2017). This approach accepts a limited degree of risk and environmental impact near the farm and no risk distant from the farm. The near-field standard is set such that organisms that re-work sediment within the AZE are protected, as their activities are considered beneficial. SEPA will, on an annual basis, randomly sample fish farms sites to determine the level of medicine residues in the environment, and whether unlicensed treatments have been used. The results of these surveys are published on SEPA's website. Farmers are required to notify SEPA prior to each treatment being carried out and in any growth cycle where SLICE® has been used farmers are also required to commission or undertake monitoring of residues.

The approach taken for the other in-feed product "Calicide" (active component teflubenzuron) is similar in that a sediment standard has been derived and SEPA sets limiting conditions in authorisations and limits on-going use to ensure that this is not breached. Environmental standards have also been derived for bath treatments to ensure environmental protection.

4.8.3 Code of practice

The Code of Good Practice for Scottish Finfish Aquaculture is the main self-regulatory instrument and contains monitoring practices for sea lice control, and environmental monitoring policies in Scotland – consistent with SEPA and European requirements. The large majority of farms in Scotland are signatories to this code, which includes annual, independently accredited audits.

4.8.4 Practical constraints

Not all medicines currently authorised for use in Scotland are employed in practice. There may be factors which influence the degree of usage and ability to treat certain sites effectively that constrain operators. Handling safety of some chemicals, multiple treatments potentially violating EQS or site dispersion characteristics may preclude the use of all available treatments at some sites. For example, there may be large sites where all stock cannot be treated at the same time without breaching the EQS (especially for teflubenzuron and EMB). As farms become larger this may become a significant issue.

4.9 Salmon Farms and Conservation Features

There is significant coincidence between natural heritage values and site suitability for fish farming. This is because the requirements for a good farm site (high water quality; good water exchange; shelter; moderate depth) tend also to favour high levels of biodiversity. The correlation between suitability for aquaculture and the likelihood of high conservation value was demonstrated clearly in studies undertaken for the Scottish Aquaculture Research Forum (SARF) (Hunter *et al.*, 2006).

The actual correspondence between aquaculture developments and areas of conservation importance was summarized in map form for the Scottish Government Expert Working Group on Siting of Aquaculture facilities in Scotland, and further analysed for SARF 046 (Hambrey *et al.*, 2008). The latter showed that a quarter of (salmon) production takes place within or in close proximity to areas identified as important for Biodiversity Action Plan habitats or species; and around 10% of production takes place within or in close proximity to Natura 2000 sites (Special Areas of Conservation / Special Protection Areas). The sensitivity of these habitats to fish farm activity was also assessed by the SARF 036 project (Wilding & Hughes, 2010). SEPA recently addressed Priority Marine Features (PMFs) and Marine Protected Areas (MPAs) with respect to fish farming in its interim EMB policy statement (SEPA, 2017).

4.9.1 Vulnerabilities

Sensitivity assessments of priority habitats, including most of the Scottish Priority Marine Features (PMFs) and species, to various pressures (including aquaculture chemicals) are extremely limited in the published literature. As SEPA's EQS are precautionary in nature, it should be emphasised that the actual threat to these features should be minimal so long as standard procedures and protocols are adhered to, given the limited range of organisms that have been used in testing. SEPA's Interim Policy (2017) addresses PMFs and MPAs with respect to EMB discharges specifically.

In general, the greatest levels of concern would be associated with complex assemblages/communities of organisms from many different Phyla, and to those species groups with slow growth, and/or erratic or periodic recruitment - in particular:

- Burrowed mud habitats containing sea pen and burrowing megafaunal communities (SS.SMu.CFiMu.SpMmeg)³⁰; the tall sea pen *Funiculina quadrangularis*; the fireworks anemone *Pachycerianthus multiplicatus*;
- Flame shell (*Limaria hians*) beds in tide-swept sublittoral muddy mixed sediment (SS.SMx.IMx.Lim)³¹;
- Horse mussel (*Modiolus modiolus*) beds with hydroids and red seaweeds on tide-swept circalittoral mixed substrata. (SS.SBR.SMus.ModT)³²;
- Maerl or coarse shell gravel with *Neopentadactyla mixta* in circalittoral shell gravel or coarse sand. (SS.SCS.CCS.Nmix)³³;
- Native oyster (*Ostrea edulis*) beds.

Due to the deposition of organic material in the form of waste food and faeces, the primary local effect from marine fish farming is in the form of organic enrichment of the sea bed. In-feed treatments reach the sea bed together with the organic wastes, and the depositional footprint around the cages will be similar. Thus, any in-feed chemical effects will tend to co-vary with enrichment effects, and causation will be difficult to attribute. Bath treatment chemicals being liquid tend to disperse more widely. Deposition of these

³⁰ <http://jncc.defra.gov.uk/marine/biotopes/biotope.aspx?biotope=JNCCMNCR00001218>

³¹ <http://www.jncc.gov.uk/marine/biotopes/biotope.aspx?biotope=JNCCMNCR00001221>

³² <http://www.jncc.gov.uk/marine/biotopes/biotope.aspx?biotope=JNCCMNCR00000657>

³³ <http://jncc.defra.gov.uk/marine/biotopes/biotope.aspx?biotope=JNCCMNCR00000170>

chemicals usually occurs after adsorption to organic molecules in the water column which then settle out.

Siting of fish farms in close proximity to Special Areas of Conservation, Biodiversity Action Plan habitats or PMF is therefore more likely to cause concern from an enrichment/smothering perspective than from chemical use.

4.10 Discussion of Regulatory Effectiveness

If the SEPA procedures as set out above are rigorously implemented, neither conservation features nor ecosystem function outside the allowable zone of effect of a fish farm should be exposed to harmful concentrations of chemicals. This assumes that:

- a) The exposure modelling is accurate;
- b) The EQS represent safe levels for both periodic and chronic exposure for all important organisms characteristic of the feature;
- c) Effects of chemicals on key ecosystem functions (e.g. primary production, food web transfers, sediment aeration by burrowers) are well understood.

Estimation of exposure, based on modelling of dispersion and deposition is based on many assumptions and simplifications, but the models have now been used and refined over many years and have been shown to be broadly accurate; the regulatory model DEPOMOD was calculated to be accurate to within 13-20% (Cromey *et al.*, 2002). However, more recent work has indicated accuracy estimates between 63-85%, based on sulphide concentrations (DFO, 2012). However, this more recent study does address issues of periodic re-suspension, and there are significant uncertainties relating to degradation, whose rate will vary substantially according to chemical conditions in the sediment and to a lesser extent the water column. Crane *et al.* (2006) suggest that the models currently in use do not work well for hydrophobic chemicals such as cypermethrin, which would indicate that the dispersion of these compounds is not adequately understood.

With regard to safe concentrations, the picture is not straightforward. The EQS may be regarded as highly precautionary but are based on rather limited data. To obtain a marketing authorisation (MA), all medicines will have been subject to ecotoxicity studies on indicator species considered to be representative of the biota of the receiving environment. These might include for example *Corophium volutator* (amphipod), *Acartia tonsa* (marine copepod), turbot, and blue mussel *Mytilus edulis*. Such tests normally follow guidelines and determine LC50, EC50, LOEC, and No Observed Effect Concentration (NOEC) values,³⁴ the test design having been evaluated independently by

³⁴ NOEC = no observed effect concentration

PNEC = predicted no effect concentration

LOEC = lowest observed effect concentration

LC50 = median lethal concentration, i.e. concentration resulting in 50% mortality of sample/organisms

EC50 = median effective concentration, i.e. concentration of a compound where 50% of the population exhibit a response

several laboratories. Additional tests may be required by the VMD or SEPA to address specific concerns. These concentrations are then multiplied by a safety factor agreed at European level (several orders of magnitude) in order to determine EQS. For example, freshwater data on cypermethrin toxicity to algae and invertebrates including arthropods give a NOEC of 10 parts per trillion (ppt); the PNEC_{freshwater} is set at 0.1 ppt (Crane *et al.*, 2007).

However, Crane *et al.* (2006) note that there is significant uncertainty about the protectiveness of current EQS for cnidarians, and there are remarkably few data available specifically on the effects of medicines on priority species, sensitive habitats or ecosystems. Nor are there good data on the long-term chronic effects of medicine concentrations below the EQS.

Although Crane *et al.* (2006) considered the EQS for EMB to be protective for SACs, and routine farm monitoring and most studies in the wider environment undertaken to date provide no evidence for significant effects on species and ecosystems outside the AZE, a recent report (SARF, 2016) concluded that the medicine was responsible for depletion of crustaceans at distance from treated fish farms, although it was acknowledged that a direct cause-effect relationship could not be derived. Nevertheless, the main impact of EMB is likely to be on benthic crustaceans, rather than the “vulnerable” PMF assemblages detailed above; and its low water solubility means that it should have relatively little impact on the zooplankton.

4.11 Diagnosis

Whilst regulatory procedures are rigorous, and are designed to prevent disturbance outside the AZE, there remain substantial uncertainties relating to both exposure and effects of aquaculture chemicals in the marine environment. Concern has mainly focussed on anti-lice compounds, but similar uncertainties apply to antibiotics and antifouling compounds. Issues are:

- Occasional non-adherence to consents and protocols by fish farmers (though this is probably relatively rare);
- Possible inaccuracies in dispersion modelling – in particular the behaviour of hydrophobic chemicals; far-field deposition and periodic re-suspension events;
- Uncertain knowledge of rates of decay, which may vary substantially according to chemical and physical conditions;
- Lack of knowledge of effects on animal groups and species other than those normally tested – especially cnidarians;
- Lack of knowledge of effects of long term chronic exposure of priority marine habitats and species to low concentrations of chemicals;
- Lack of knowledge of bio-accumulation and in-combination effects.

The threat from the anti-sea lice chemicals in Table 1.1 is potentially that from EMB: it is widely used; it decays only slowly in sediment; it is especially toxic to crustaceans, but affects physiological processes more widely.

4.12 Prognosis and Mitigation

Expanded salmon production is likely, all other things unchanged, to lead to more usage of medicines and antifouling compounds. Increase in farm size implies larger doses and hence greater local environmental impact. Compounding these concerns is the development of resistance by lice to both in-feed and bath treatments. There is evidence of resistance in sea lice to dichlorvos, azamethiphos, and cypermethrin (Aaen *et al.*, 2015), and increasing evidence of resistance to EMB (Espedal *et al.*, 2013; Aaen *et al.*, 2015) (See Section 2). Consequently, there is demand from the salmon farming industry for licensing of a broader spectrum of chemical treatments to ensure more complete and effective control of sea lice. This is accompanied by the reasonable argument that a more effective suite of chemicals would result in lesser use and possibly lower likelihood (or at least delayed) development of resistance.

Whatever the merits or otherwise of these arguments, it is clear that the key to mitigation in the medium and long term is reduced use of chemicals - following on from reduced incidence of sea lice and other diseases. Options to achieve this were discussed in Section 2.1 and include the vigorous pursuit of existing management initiatives to reduce exposure to sea lice, and to disrupt transmission between fish, between cohorts and between sites, utilising e.g. synchronised lice treatments (Arriagada *et al.*, 2017). Additional options include siting in areas less susceptible to sea lice, further development and implementation of area management agreements, strategic production scheduling and fallowing. Additionally, Ernst *et al.* (2014) suggested the use of well boats instead of cage tarpaulins/skirts for bath treatments could reduce the amount of medicine used by one third.

Commercial use of 'cleaner fish' wrasse and lumpfish as a biological control is growing, while research and development work on these species is also continuing (Powell *et al.*, 2017). Efficient use of these biological controls has great potential for mitigating chemical use in aquaculture. While an effective vaccine against furunculosis largely removed the need for antibiotic use in marine cage farming, similar vaccines against sea lice have proven elusive to date. Recent developments show promise, however (Carpio *et al.*, 2011), and there is one vaccine currently on the market in Chile.

Monitoring is a key part of regulatory procedures. It could be improved in two ways: first by increasing the sensitivity of measurement of chemicals, and second by harmonising chemical sampling with sampling of the seabed community. A long-term research study of benthic and pelagic community change in relation to chemical use in a typical sea-loch would be useful for the better understanding of subtle and long-term effects on marine ecosystems.

5 ESCAPEES FROM FISH FARMS AND POTENTIAL EFFECTS ON WILD POPULATIONS

This Section deals with another type of interaction between wild and farmed salmon. It seeks to answer the following questions:

- Do farmed salmon escape and if so survive to mix and interbreed with wild populations?
- Is there, consequentially, a flow of genes from the escapees into wild populations, and could this weaken the viability of those populations?
- Are there other interactions between escapees and wild fish that might harm populations of the latter?
- Does the presence of fish-farms change the coastal marine environment away from that to which wild salmon are adapted?

The specific answers to these questions in Scotland are for the most part uncertain as research in Scotland has to date been sporadic and restricted to a small number of older and limited historical studies. These questions have, however, for the most part been extensively studied in Norway where the answers to these questions, with the exception of the last, is “yes”; the answer to the last is “most probably”. However, what is not clear is whether the extent of the problem in Scotland is the same, lower or higher.

5.1 Introduction

Biological theory teaches that the traits of organisms are an expression of information encoded in DNA, in units called genes; that changes in DNA within a gene will likely result in trait modification; and that both natural and artificial selection of organisms acts on the set of genes that define a population or species. Whether population or species, natural selection favours genes and traits that adapt to environment and so determines reproductive success; artificial selection favours genes determining traits of benefit in human management. In the case of salmon, the population (adapted to conditions in a particular river system) seems to be the effective unit of selection, although there must have been sufficient interbreeding between wild populations to maintain *Salmo salar* as a single species.

Glover *et al.* (2017) gives four reasons why farmed salmon are genetically different to wild salmon:

- Directional selection for commercially important traits within breeding programmes (which changes both target traits and any others which may be subject to linked genes);
- Domestication selection (inadvertent genetic changes associated with general adaptation to the human-controlled environment, and its associated reduction in natural selection pressure, as well as trait shifts due to trade-offs);

- Random genetic changes during domestication (initially founder effects and thereafter genetic drift across generations);
- Ancestry differences as farmed salmon may be of non-local or mixed-origin.

Collectively, these factors will result in genetic differences that can affect the ability of individuals to survive and reproduce successfully in the wild (i.e. their fitness) and, thereby, the overall ability of the population to sustain itself in the future (i.e. its viability).

Genetic changes can potentially arise from two types of interactions. Direct interactions can arise if farm fish escape and interbreed with wild salmon. Indirect interactions can arise from changes to the environment caused by the presence of salmon farms. Indirect interactions can result in changes in the selection pressures on wild populations, and thus alter the genetic types of wild salmon that would otherwise be expected to survive.

5.2 Escapes and Survival of Farmed Fish

It is documented that farmed salmon in both freshwater and marine stages of production do escape (Carr & Whoriskey, 2006; Uglem *et al.*, 2013; Verspoor *et al.*, 2016; Glover *et al.*, 2017), and it is accepted as unavoidable by the aquaculture industry in open water net pen rearing operations (Bentsen & Thodesen, 2005). In Scotland between October 2002 and October 2017 approximately 2,193,886 Atlantic salmon were reported³⁵ to have escaped, with causes as listed in Table 5.1. Numbers per escape event ranged from 1 to 336,470, with sizes of escapees ranging from 0.8 kg to 12 kg. It is usual to distinguish between catastrophic events, for example where major damage to cages result in escapes of large numbers of fish, and 'drip' escapes, for example, where unrecognised smaller holes in nets through which fish escape, or where some stocked smolts are small enough to go through the mesh on cages. The latter are difficult to identify and quantify and not encompassed by reported escape events but has been estimated in Norway to be substantial (Glover *et al.*, 2017).

³⁵ http://aquaculture.scotland.gov.uk/data/fish_escapes.aspx

Table 5.1. Causes of salmon escape events in Scotland

(Totals, from October 2002 through October 2017)

Recorded Cause of Escape Event	Number of Escape Events
Chafe/ snag	2
Equipment damage	7
Equipment wear and tear	3
Hole in Net	28
Human Error	30
Inappropriate use of equipment	1
Mooring Failure	1
Net Failure (not including hole)	1
Other	1
Predator	20
Screen failure	1
Transfer pipe failure	3
Unknown	6
Weather	26

Data from http://aquaculture.scotland.gov.uk/data/fish_escapes.aspx

Is two million a big number? Escapes average about 146 thousand per year, less than half of one percent of the 30 million or more salmon harvested each year during this period. However, this number of escapes equates very roughly to about half the total numbers of adult salmon in Scottish rivers (estimating from the UK total in Section 1). So their potential effect will depend on the extent to which the escapees survive in the wild

The official register does not fully reflect the totality of the farmed escapes in Scotland, as the evidence demonstrates that unreported escape events are occurring. For example, Verspoor *et al.* (2016) netted free-living salmon smolts in Loch na Thull and identified them as being of farmed origin because of their morphological traits, scale growth

patterns and sizes. A freshwater pen site existed in the loch, but had not recorded escapes during or before the research netting period.

A more recent study by Gilbey *et al.* (2017) investigated the likely origin of juvenile Atlantic salmon captured in the River Shin system in Scotland. A total of 220 fish of unknown origin were genetically screened in an attempt to allocate them to three reference baseline strains. Overall, they reported between 25 and 37 percent of the fish were classified as originating from one or other of the farmed strains. Interestingly, a number of the fish that could not be assigned to any of the three groups' exhibited traits that indicated that they were of a non-wild fish origin.

A number of studies have demonstrated that the majority of salmon that escape from farms will not survive to interact with wild fisheries populations, but this does vary depending on the life stage of the escaped salmon (Skilbrei, 2010; Hansen, 2006; Whoriskey *et al.*, 2006). Salmon that do survive have been identified in the wild in some cases (Saegrov & Urdal, 2006).

5.3 Gene Transfer

Whilst in fresh waters, female salmon lay eggs that are then fertilised by male sperm: it is at this stage that there is potential for genes from escaped salmon to enter a wild population. The process of gene flow is called **introgression**.

Introgression studies in Scotland are limited. Recently Verspoor *et al.* (2016) found no detectable evidence for introgression in a microsatellite analysis of salmon in a small coastal stream in western Scotland. This study does, however, have limitations due to its limited sample size and use of historical data in the analysis, which weakens the resulting findings. A study of 109 Norwegian rivers by Karlsson *et al.* (2016) found a strong statistically significant link between genetic introgression and farmed salmon. The highest levels of introgression were associated with the most intensive areas of salmon farming. This conclusion was supported by a previous study by Glover *et al.* (2013), which found a correlation between the incidence of escapees in rivers and introgression levels, across 20 Norwegian populations.

5.4 Effects on Fitness and Viability of Wild Salmon

Gene flow from domesticated animals interbreeding with wild populations has long been anticipated to induce genetic changes because of their genetic differentiation. A wider review, focused outside of Scotland and largely on Norway and Ireland, highlights documented genetic changes in wild populations as a result of farmed escaped salmon successfully spawning (Skaala *et al.*, 2006; Glover *et al.*, 2012; Glover *et al.*, 2013; Heino *et al.*, 2015; Karlsson *et al.*, 2016).

The environmental consequences of escapes and introgression can have short-term fitness and long-term evolutionary impacts on the recipient populations (Glover *et al.*, 2017). When introgression occurs, the native wild population will experience changes associated with phenotype and life-history traits. Such changes include:

- Impacts on freshwater growth and body shape;
- Timing of smolt migration;
- Age of smoltification;
- Incidence of male parr maturation;
- Sea age at maturity;
- Growth in the marine environment.

(Fleming *et al.*, 2000; McGinnity *et al.*, 1997; 2003; Skaala *et al.*, 2012).

Consequently, these changes will have a negative impact on wild salmonid populations, as the changes introduced by the farmed fish are a maladaptation to their native environment. Due to genetically determined body, physiological, predator avoidance, and life-history, traits being strongly related to fitness in the wild, any changes introduced in the direction of the farmed strain will likely cause a reduction in fitness of the wild population (Garcia de Leaniz *et al.*, 2007; Fraser *et al.*, 2011).

A more recent study has shown that such changes are widespread in wild populations of Atlantic salmon (Bolstad *et al.*, 2017). In 62 of these populations, including seven populations ancestral to strains of the domesticated salmon, wild individuals with high levels of farm genes in them (i.e. high levels of gene introgression) were found to have altered age and size at maturation. This provides unequivocal evidence that interbreeding and genetic mixing of farm salmon with wild populations can have impacts on the life-history of wild populations, which can negatively influence the dynamics and viability of populations. The long term effects on wild salmonid populations from introgression also include reduced genetic variability, which will reduce a species' ability to cope with a changing environment (McGinnity *et al.*, 2009; Satake & Araki, 2012).

The available evidence from outwith Scotland provides a strong basis for concluding that the negative consequences of introgression, when it occurs, will alter wild populations. In the short term, the genetic character of wild populations will change, and their abundance will reduce. In the long term, introgression will result in wild populations that are less resilient and less adaptable to environmental change, such as associated with global climate shifts. Ironically, the loss of genetic variability (due to reduced population sizes and the loss of wild populations) may also lead to the loss of genetic variation that could be a significant resource for the salmon farming industry (e.g. as sources of genes for disease or pathogen resistance). This type of impact is observed with respect to the loss of wild populations of other domesticated plants and animals.

5.5 Escaped Farmed Salmon and the Environment of Wild Salmon

Resource scarcity is common in river systems, particularly for fish with respect to territory and food availability (McGinnity *et al.*, 1997; 2003; Fleming *et al.*, 2000; Bacon *et al.*, 2015). When the offspring of farmed salmon compete with wild salmon for resources such as food and space, the pressures on these resources are increased (Ferguson *et al.*, 2007; Skaala *et al.*, 2012). Competitive displacement of wild salmon from farmed

salmon offspring and hybrids has been shown to occur, with wild fish having a poorer survival rate when coexisting with farmed fish than if found alone (Sundt-Hansen *et al.*, 2015).

Escaped farmed salmon can alter the natural environment by indirectly affecting aspects of the wild population behaviour, disease interactions and predation. Behaviourally, wild salmonids display strong territorial and social dominance traits. Aggression will become elevated when farmed salmon escape and compete with wild salmonids. The consequences of this behavioural interaction are increased stress levels, decreased growth, and potentially mortality of wild salmonids (Weir & Fleming, 2006).

The consequences of increased fish densities that arise when farmed fish escape can lead to the attraction of predators. This changed prey-predator interaction can lead to increased mortality among wild fish (Youngson & Verspoor, 1998). Diseases and parasites have been introduced to wild stocks with consequential negative impacts, as previously discussed in Section 2 of this review.

5.6 Changes in the Environment can Cause Genetic Changes

That environmental changes, in addition to interbreeding, can lead to genetic changes is widely recognized, and is an acknowledged concern relating to the impacts of salmon farming on wild populations (Youngson & Verspoor, 1998). Genetic impacts can occur indirectly for two reasons. Altered environmental conditions can reduce population numbers, which will in turn increase inbreeding and the loss of genetic diversity. Additionally, environmental changes will influence which individuals survive, and thus will alter the genetic composition of wild populations (compared to what would be expected in the absence of fish farming operations).

The loss of genetic diversity associated with reductions in population size are fully consistent with theoretical expectations, (Verspoor *et al.*, 2015) and are well documented by a vast literature of species and population specific studies, including Atlantic salmon. The potential long-term impacts of indirect interactions by cultivated salmon on wild populations involve decreasing wild population numbers and increasing genetic drift, with increasingly negative impacts expected under global climate change and scenarios of increasing environmental temperature (McGinnity *et al.*, 2003).

The genetic differences among individuals will often, in interaction with their environments, determine survival chances and reproductive success. The changes within farmed salmon populations for traits for which there is no deliberate selection, is an obvious example of such indirect selection. It can also occur in the wild, although demonstrating that selection occurs due to a particular change in the environment presents a complex scientific challenge. Unlike direct interactions, there is no requirement for direct contact between farm and wild fish, as indirect effects may arise from changes to the type and level of a disease or pathogen, or to changes in water quality, or induced changes in fish behaviour. Indirect interactions can only be ruled out where farming activity and its impacts on the environment can be evidenced to be effectively isolated from the wild populations of interest.

Not surprisingly, the scientific literature related to indirect genetic impacts of salmon farming is small (Verspoor *et al.*, 2015). Changes in the genetic variability of genes involved in immunity have been observed in wild brown trout in Ireland following the establishment of salmon farms (Coughlan *et al.*, 2006; De Eyto *et al.*, 2011). This was thought to arise from stronger selection in favour of particular alleles, and against others, due to increases and changes in disease and pathogen exposure. In salmon, variation in the MHC II (major histocompatibility complex) gene appears to be important in natural temperature-related pathogen resistance (Dionne *et al.*, 2007). As such, losses and changes to this gene within a wild population could change in the long-term adaptive capacity of the population to deal with future natural changes in pathogen exposure, as might occur with respect to climate change, or the natural evolution of a new strain of natural pathogen (Pulkkinen *et al.*, 2010). For example, it is known that sea lice can evolve resistance to chemo-therapeutants and this can lead to elevated sea lice levels despite treatment (Denholm *et al.*, 2002).

5.7 Diagnosis

It is likely that in Scotland both drip leakage of fish, and large scale one off escapes, will continue at an uncertain level, unless there are major changes in technology such as fully contained land-based farming systems. Available evidence suggests that a detectable proportion of salmon escaping from farms in Scotland can survive to spawn in the wild, and that they will interbreed with wild fish, so that some degree of genetic mixing is occurring. Genetic differences between farmed and wild salmon are the result of selection for different environments, and so genetic mixing may make wild salmon less fit for the conditions they experience in rivers and the sea.

In some circumstances that would not be a problem, because natural selection would weed out unfit individuals. However, if the viability of a wild salmon population is already threatened by other pressures, increased mortalities due to genetic mixing would be of concern. Additionally, the value of wild salmon as a cultural ecosystem service may be diminished if they are perceived as losing something of their essential qualities.

However, the extent of the problem in Scotland is not clear. The proportions of fish in wild stocks that are of farm, or of mixed farm and wild ancestry, are not known, nor is the effect of such mixing on population dynamics. What is known from studies in Norway and Ireland is that there is a *prima facie* case to be made that some adverse effects are occurring in at least a proportion of rivers in areas with salmon farming operations.

5.8 Prognosis and Mitigation

All other things remaining the same, any increase in salmon production is likely to lead to an increase in escapes, and increase in farm size may result in more fish escaping in a single incident. Given probable underestimation of numbers, and the lack of knowledge of effects of escapees on wild populations in Scotland, this may be a concern. The suggested mitigations deal first with knowledge gaps and then with additional technical

measures. They will work best if integrated into a programme of Adaptive Management for salmon farming at national or at least regional level.

5.8.1 Assessment of numbers of surviving escapees

Accurate accounting of numbers of surviving escapees in Scotland's river stocks of salmon regular annual surveys, using methods that can unambiguously discriminate farm and wild fish, e.g. testing of random samples of juvenile salmon for being of farm or hybrid origin with diagnostic genetic markers, would provide information needed for the adaptive management of farm escapes.

5.8.2 Assessment of levels of introgression

Accurate assessment of current levels of introgression in Scotland's river stocks monitored using an objective methodology based on electrofishing of juveniles and genetic typing using informative molecular markers would provide information needed for the adaptive management of farm escapes.

5.8.3 Reducing Farm Escapees and Their Entry into Rivers

The industry accepts that in open rearing systems (as are the norm in Scotland) escapes are inevitable. Reducing and minimizing escapes could be achieved by a policy that incentivises the up-take of farming practices such as closed containment or the use of larger fish in open cages, or/and that reduces the likelihood that escapes can interbreed with wild fish or establish feral farm populations. The latter should include the use of sterile or triploid fish, or fish bred so as not to migrate to rivers to spawn. However, experiments to develop triploid strains have so far not proven commercially successful (Benfey, 2015).

5.8.4 Assessment of Indirect Interactions

Current uncertainties would be reduced by research to assess key wild salmon stocks in farming areas for evidence of indirect genetic changes attributable to environmental changes arising from salmon farms.

6 SUSTAINABILITY OF FEED SUPPLIES INCLUDING SUBSTITUTION WITH PLANT-DERIVED INGREDIENTS

The natural diet of salmonids in the ocean are oil-rich plankton and small fish, and feeds developed for salmon farming mimic this mix of protein and essential oil. This Section addresses the following questions:

- What do farmed salmon need in their diet for growth, welfare and marketability?
- What are the current sources of raw materials for feed manufacture?
- Are those sources sustainable, in terms of (a) supplying the needs of a growing industry and (b) avoiding environmental damage?

The original sources were marine, but there has been a trend to including (in most cases) increasing proportions of plant-derived material. Because salmon's content of 'omega-3' fatty acids is a key part of its appeal to human consumers, and because these fats are not produced by land plants, there is a final question:

- How can the feed industry obtain sufficient 'omega 3'?

6.1 Salmon Feeds

Feeds for Atlantic salmon are based largely on protein and fat/oil, as carbohydrate has no major role as a supplier of energy in carnivorous fish like salmonids. This is likely simply an evolutionary adaptation to a natural diet that contains very little carbohydrate.

6.1.1 Protein and oil

Thus, efficient feeds for Atlantic salmon must have high protein contents and this limits the usefulness of many traditional animal feed ingredients. Current formulations of salmon feeds in Scotland contain around 35-36 % protein and 32-33 % oil although absolute levels can vary depending upon raw ingredient costs with feeds formulated to a specific **Feed Conversion Ratio** (FCR) that can be equally achieved with different protein/oil combinations. The oil content of salmon feeds has increased over the years with the development of "high-energy" feeds that exploit the fact that twice as much energy per unit mass is provided by **lipid (e.g. fat/oil)** compared to protein (or carbohydrate). This enables digestible energy: digestible protein (DE:DP) ratio and growth potential to be maximised through the concept of "protein sparing", which is the process by which the body derives energy from sources other than protein (e.g. dietary fat/oil) conserving dietary protein for production of muscle tissue. The lipid level has now stabilised with maximum levels of around 35%, which has been shown to provide greatest growth while minimising excess lipid deposition in the flesh that can have adverse effects during down-stream processing.

Modern salmon feeds in Scotland have sustainability built into their formulations and therefore they are currently based on a blend of high levels of terrestrial plant meals (VM) and vegetable oils (VO) with only low levels of marine ingredients, essentially fishmeal (FM) and fish oil (FO), although krill products are also used in small amounts in some

feeds. While detailed feed formulation data are often lacking in Scotland, the great similarity of the Scottish and Norwegian industries means that Norwegian data (Ytrestøyl *et al.*, 2014) provide a good approximation to the situation in Scotland:

- In Norway in 1990, salmon feed formulations contained around 90% FM and FO with only 10% derived from plant ingredients;
- By 2013, this had largely reversed with feed formulations containing around 70% plant-derived ingredients (VM and VO) and less than 30% FM and FO.

Although accurate data are not yet available, replacement of marine ingredients has increased in the last three years and, in 2017, it is likely that feed formulations in Norway contained up to 80% plant-derived ingredients and only around 20% FM and FO. While the Scottish industry has employed a slightly more conservative approach to FM and FO replacement it still shadows the Norwegian industry with the average levels of FM and FO in Scottish salmon feeds generally reflecting the levels used in Norway 1-2 years previously (Shepherd *et al.*, 2015; 2017).

The main non-marine protein source in Norway is currently soy protein concentrate along with smaller amounts of other plant protein concentrates such as wheat or corn/maize gluten and pea protein concentrate (Ytrestøyl *et al.*, 2014). Other plant meals such as sunflower expeller, wheat and faba (field or broad) beans are included as ingredients that supply a mix of protein and starch. Starch is included in salmon feeds primarily as a nutritional binder and for its physical properties in extruded pellets, enabling pellets to expand via starch gelatinisation during extrusion, rather than as an energy nutrient.

The situation in Scotland is very similar. Rapeseed oil is the VO used almost exclusively in combination with FO both in Norway and Scotland, although small amounts of palm oil and, perhaps, linseed oil, may be included. Pigment source in Scotland has also changed in recent years from synthetic astaxanthin to natural products such as extract of the red yeast, *Phaffia rhodozyma* (Shepherd *et al.*, 2015; 2017). Pigment is required in feed to ensure that flesh of farmed salmon is the same pink colour as wild salmon that also obtain this pigment in their natural food.

6.1.2 Efficiencies

Various ratios have been calculated and used over the years to assess the “efficiency” of finfish aquaculture, and salmon farming in particular, specifically in relation to the use of FM and FO derived from wild (forage) fisheries (Ytrestøyl *et al.*, 2015).

- Environmental Non-Governmental Organisations (NGO’s) have tended to use the so-called *fish in/fish out ratio* (FIFO), which takes the amount of FM and FO used to produce a kilogram of farmed fish and uses that to calculate back to the weight equivalents of wild fish. For example, 20 million tonnes of forage fish reduces to about 5 million tonnes of FM and 1 million tonnes of FO.
- The *forage fish dependency ratio* (FFDR) is the amount (Kg) of wild caught fish used to produce the amount of FM and FO required to produce 1 Kg of salmon.

From 1990 to 2013, the FFDR for FM decreased from 4.4 to 0.7 in Norwegian salmon farming (Ytrestøyl *et al.*, 2015). This clearly demonstrates that the replacement strategy

has been successful in ameliorating the state of affairs that had led to damaging headlines when salmon farming was a net consumer of marine fish. However, FM and FO are simply ingredients that deliver nutrients (protein, lipid etc.) and, therefore, ratios such as Fish in/Fish out (FIFO) and FFDR, that rather crudely compare weight to weight do not account for the different nutrient contents of the salmon products and the wild forage fish used for FM and FO production.

An arguably much more accurate assessment of the “efficiency” of salmon farming in relation to the use of marine ingredients requires analysis of the use of nutrients and not ingredients (Crampton *et al.*, 2010). Thus, marine nutrient dependency ratios express the amount of marine protein and oil required to produce 1 kg of salmon protein and oil (Crampton *et al.*, 2010). The marine protein dependency ratio (MPDR) and the marine oil dependency ratio (MODR) are calculated as:

$$\text{MPDR} = \frac{(\% \text{ of MP in feed}) \times (\% \text{ of protein in MP}) \times (\text{kg of feed consumed})}{(\text{final bodyweight} \times \% \text{ of body protein}) - (\text{initial bodyweight} \times \% \text{ of body protein})}$$

$$\text{MODR} = \frac{[\% \text{ of MO in feed} + (\% \text{ of MP in feed} \times \% \text{ of fat in MP})] \times (\text{kg of feed consumed})}{(\text{final bodyweight} \times \% \text{ of body fat}) - (\text{initial bodyweight} \times \% \text{ of body fat})}$$

Where MP is the marine protein source (e.g. FM) in feed and MO is the marine oil source (e.g. FO).

Research studies showed that salmon fed diets with very low levels of FM and FO can be net producers of marine protein (Crampton *et al.*, 2010; Bendiksen *et al.*, 2011). The results of this research have been applied by the industry commercially. This has meant that, in 2013, the MPDR showed that more protein in the form of farmed salmon was produced in Norway than the protein consumed from forage fisheries. Therefore, commercially farmed salmon in Norway is a net producer of marine protein (Ytrestøyl *et al.*, 2015). While the levels of replacement of FM and FO in Scotland have lagged slightly behind those in Norway (see below), commercially farmed salmon in Scotland will also be net producers of marine protein.

It is also highly pertinent to highlight that none of the above ratios have a basis in nutritional physiology and none are measures of production efficiency. The only practical use that a FIFO can serve is perhaps as a monitor of how different aquaculture sectors are developing because, with expanding production and finite supplies of FO (and FM), average FIFO must fall.

It is well established that aquaculture is generally very efficient. Top performing species such as Atlantic salmon (Torrissen *et al.*, 2011) have a better feed conversion ratio (FCR) than any terrestrial animal production with commercial values of 1.1 to 1.2 compared to ~2 for poultry, ~3 for pigs, and > 6 for lamb and beef (Shepherd & Little, 2014). In addition, salmon show higher protein, nutrient and energy retentions, and harvest and edible yields, than terrestrial meat production (Shepherd & Little, 2014). Life cycle analysis (LCA) has also demonstrated that salmon farming has a lower carbon

footprint and makes better use of resources than pigs or chicken, and that using FM and FO from forage fish provides more marine protein, energy, and n-3 Long Chain Polyunsaturated Fatty Acids (LC-PUFA) (Eicosapentaenoic Acid EPA and Docosahexaenoic Acid DHA) for human consumption than utilising these marine resources directly as human food (Shepherd *et al.*, 2015; 2017).

6.1.3 Omega-3

The term 'omega-3' refers to a group of polyunsaturated fatty acids (PUFA), especially EPA and DHA, which are common in marine oils and originally made by some types of marine micro-algae (phytoplankton) before passing up the food chain to fish. The technical term n-3 LC-PUFA refers to 'Long-Chain Polyunsaturated Fatty Acids' with a double bond at the third carbon atom from the end of the carbon chain that forms the backbone of these molecules.

Vertebrates (including humans) need n-3 LC-PUFA for their metabolism but in general have difficulty synthesising them from other foodstuffs. Terrestrial plants contain the related short-chain omega-3 and 'omega-6' PUFA, some of which are also essential for human metabolism but which cannot substitute for omega-3 LC-PUFA.

Enabling commercially farmed salmon to become net producers of marine oil, specifically EPA and DHA, is a much greater challenge than enabling them to become net producers of marine protein. Although research studies have demonstrated that, with very low inputs of dietary EPA and DHA, it is possible for farmed salmon to have Marine Oil Dependency Ratio (MODR) below one and, thus, to be net producers of marine oil (Sanden *et al.*, 2011; Turchini *et al.*, 2011), this is slightly misleading. The amounts of EPA and DHA that can be synthesised by salmon themselves are relatively low and, although sufficient to satisfy the physiological needs of the fish to prevent essential fatty acid (EFA) deficiency, they cannot match the levels found in fish supplied with EPA and DHA in their feed, whether in the wild or in farmed fish fed diets containing FM and FO (Tocher, 2015a). Therefore, the majority of EPA and DHA in farmed salmon in both Norway and Scotland are still derived from the diet and, currently, this means from FM and FO. Thus, the levels of inclusion of marine ingredients, especially FO, in salmon feed is currently being largely driven by the requirement to maintain the levels of these key omega-3 LC-PUFA (Jensen *et al.*, 2012; Ytrestøyl *et al.*, 2014; 2015).

6.1.4 Marketing considerations

While the salmon industry has embraced increasing replacement and enhanced sustainability as described above, the Scottish salmon market is highly consumer driven via the major retailers and each retailer also has its particular niche market and, within a retailer, niche products (Shepherd *et al.*, 2017). Therefore, feeds for Scottish salmon consist of a large and diverse range of bespoke products tailored to meet a variety of markets. The differences in formulation between the feeds are based on specifications dictated by salmon producers that, in return are responding to retailer specifications. Commonly, although not exclusively, the specifications include the amount of marine ingredients (FM and FO) and may or may not include reference to specific (minimum) levels of n-3 LC-PUFA, specifically EPA and DHA, in feed or flesh. The range and

relative proportions of alternative ingredients to FM and FO that are used in each formulation will be dictated by these specifications within the overall nutritional requirements of salmon.

Finally, although modern, sustainable feeds for salmon in Scotland contain far lower levels of both FM and FO, and levels of EPA and DHA have reduced, farmed salmon remain an excellent source of “omega-3” for human consumers (Jensen *et al.*, 2012; Henriques *et al.*, 2014; Sprague *et al.*, 2016; 2017a). Indeed, the contents of EPA and DHA in farmed salmon are higher than in wild salmon, and thus farmed Scottish salmon delivered, on average, double the dose of EPA and DHA than wild salmon. Therefore, the recommended dose (500 mg/d or 3.5 g/week) of EPA and DHA for lowering risk of cardiovascular disease could be achieved by eating two 150 g portions of farmed salmon, whereas 4-5 portions of wild salmon would be required (Henriques *et al.*, 2014).

6.2 Fishmeal (FM) and Fish Oil (FO)

In Scotland in 2017, the marine ingredients, FM and FO, likely constituted around 20-25% of the raw materials used in salmon feeds.

6.2.1 Sources

The main sources of FM and FO used in Scottish salmon feeds are derived from generally well-managed fisheries from either the west coast of South America or from Northern Europe. At least 50% of the FM and FO used in Norwegian salmon feed in 2012 was from Peru and Chile (Ytrestøyl *et al.*, 2014) and the Scottish sourcing profile is likely very similar. Production of FM and FO is subject to environmental influences and, while the potential impact of climate change is still unclear (Callaway *et al.*, 2012), some research has predicted that global warming will reduce omega-3 LC-PUFA production in phytoplankton thus potentially affecting long-term sustainability (Hixson & Arts, 2016). In contrast, acute environmental phenomena, including El Niño, have well-known consequences, particularly for Peruvian fisheries, reducing catches and consequent FM and FO production (Pike & Tocher, 2016). An increasing proportion of FM, and to a lesser extent FO, is derived from seafood and aquaculture by-products, including by-catch and trimmings etc. Thus, around 25 and 27% of FM and FO, respectively, used in Norwegian salmon farming in 2013 were derived from seafood industry by-products (Ytrestøyl *et al.*, 2014), with Scottish proportions likely to be broadly similar.

6.2.2 Sustainability of marine ingredients

Sustainability of the fisheries for FM and FO depends on appropriate management, which requires public regulation and enforcement. Although some sources of FM and FO are poorly managed with debatable, if any, enforcement, the South American and European reduction fisheries are regarded as generally sustainable. The 28 principal forage (reduction) fisheries around the Atlantic and South America were rated in 2012 by the Sustainable Fisheries Partnership according to sustainability assessment. Based on the quality of management and the status of the stock, it was concluded that most of the assessed fisheries operated within the limits that were consistent with current good practice in single species management regimes (Sustainable Fisheries Partnership,

2012). By far the largest reduction fishery is that for Peruvian anchovy (*Engraulis ringens*) and it is significant that Peru was ranked the highest out of 53 maritime countries for the sustainability of its fisheries (Mondoux *et al.*, 2008). Since then Peru has further reduced fishing capacity and improved management by the introduction of maximum catch limits per vessel.

6.2.3 Certification

The Code of Good Practice for Scottish Finfish Aquaculture (COGPSA) seeks 'to enhance the industry's reputation for respecting the environment through adoption of best practice and greener technologies and reducing the impact on wild fisheries by increasing use of alternative feed sources' (<http://www.thecodeofgoodpractice.co.uk/>). In addition to recommendations on feed formulation and use (e.g. source from suppliers participating in the Universal Feed Assurance Scheme (UFAS)), the code therefore requires that fish-catch supplies used in the manufacture of FM are sourced from fisheries that are properly and responsibly managed, either by reference to the FAO Code of Conduct for Responsible Fisheries (<http://www.fao.org/fishery/code/publications/guidelines/en>), or the IFFO RS scheme (<http://www.iffonet.net/iffors>), or by another globally recognised standard for responsible operation.

For marine ingredients used in aquaculture feeds there are six commonly used standards, all claiming to be based on the key principles underlying the FAO Code of Conduct for Responsible Fisheries:

- The MSC (Marine Stewardship Council) standard certifies fisheries;
- IFFO RS certifies fishmeal factories;
- ASC (Aquaculture Stewardship Council), BAP (Best Aquaculture Practice) and GlobalGap all certify fish farms;
- BAP also has a feed mill standard;
- Friend of the Sea certifies fisheries, fishmeal plants, feed mills and fish farms.

The use of certified ingredients has been adopted by Scottish feed suppliers and farmers in order to demonstrate responsible sourcing of salmon feed. IFFO RS certification is probably universal in Scotland for marine feed ingredients, and provides evidence of traceability back to responsibly managed fish stocks, avoidance of IUU (illegal, unreported and unregulated) fish, and control of by-product raw material, with an associated chain of custody (Shepherd *et al.*, 2015; 2017).

6.3 Alternative Protein Ingredients (plant proteins)

In terms of supply, cost and sustainability, the most favourable alternatives to FM as protein ingredients for salmon feeds are products of terrestrial agriculture, namely, plant-based meals (Hardy, 2010).

6.3.1 Sources

The plant protein products currently being used in salmon feeds can be placed into three broad categories:

- The oilseed meals (soybean, rapeseed/Canola, sunflower expeller etc.);
- Pulses/legumes (pea and bean etc.);
- Grains (wheat and corn/maize etc.).

Plant protein ingredients differ from FM in their nutrient contents and composition, which affects and potentially limits the range and levels of plant proteins in salmon feeds. The main issues that must be taken into consideration when formulating feeds are related to energy density/protein content, amino acid composition, anti-nutritional factors and palatability. In addition, much of the phosphorus in plant proteins is present as phytic acid. This is poorly digested by most fish, and, consequently, there has been much research into the use of phytase to improve phosphorus utilisation from plant feedstuffs.

6.3.2 Environmental effects and sustainability of plant ingredients

Until recently, environmental NGOs tended to focus on the environmental effects of the use of marine ingredients (FM and FO) in aquaculture, whilst largely ignoring those of plant ingredients. The potential environmental problems (e.g. rain forest degradation) associated with uncontrolled soya production, especially in South America, are now becoming recognised. A Norwegian study showed that changing the salmon diet composition from 88 % marine ingredients to 85% plant ingredients resulted in almost the same carbon footprint (Ytrestøyl *et al.*, 2011). This suggests that increased utilisation of plant ingredients may not necessarily increase sustainability.

As mentioned above, the use of certified ingredients has been adopted by Scottish feed suppliers and farmers to demonstrate responsible sourcing. There are at least three main schemes employed for plant ingredient sourcing for fish feed, primarily for soya. The Round Table on Responsible Soy (RTRS) Association approved its Standard for Responsible Soy Production in 2010 (<http://www.responsiblesoy.org/en/>). The ProTerra Foundation Standard Version became effective in 2015 and includes soya (<http://www.proterrafoundation.org/index.php/certification>). Cert ID is focused on Non-Genetically Modified Organism (GMO) certification and has become the benchmark for Non-GMO identity preservation (<http://www.cert-id.eu/>).

6.4 Alternative Oil Sources

Global oil and fat production is projected to exceed 220 million metric tonnes (mt) in 2017-18, with total production of VO at over 195 million mt, and animal fats including tallow, lard and butter totalling another 25 million mt. Therefore, alternatives to FO are plentiful but they all suffer from the same major drawback in contrast to FO in that they are not sources of the n-3 LC-PUFA, EPA and DHA. Higher plants generally only produce short-chain PUFA (fatty acids with chain length of 18 carbons, C₁₈) and so the LC-PUFA (with carbon chain lengths of 20 and 22 carbons, C₂₀ and C₂₂) are not

components of any VO, and animal fats are dominated by saturated and monounsaturated fatty acids with only low levels of PUFA in general.

6.4.1 Supply of n-3 LC-PUFA

FO is currently the only realistic source of EPA and DHA. The n-3 LC-PUFA are important nutrients with key metabolic and functional roles in salmon and there are physiological requirement levels, albeit these are relatively low and can be possibly satisfied by supplying dietary linolenic acid (LNA) (Tocher, 2010). The major problem in replacing FO in salmon feeds is maintaining n-3 LC-PUFA in farmed fish at the high levels that have salmon universally recognised as a beneficial and healthy part of the human diet. As FO and, to a lesser extent, FM are the primary sources, this implies that the current global supply of n-3 LC-PUFA is similarly finite and limited.

Based on the most commonly recommended dose for cardiac health (500 mg/day; see GOED, 2014), the total annual demand for n-3 LC-PUFA is over 1¹/₄ million metric tonnes whereas total supply is optimistically estimated at just over 0.8 million tonnes indicating a shortfall of over 0.4 million tonnes (Tocher, 2015a). The majority of supply (almost 90%) is from capture fisheries, whether as food fish or via FO and FM, with relatively small additional amounts from seafood by-products and recycling, unfed aquaculture and algal sources. While it is acknowledged that the calculations contain some assumptions and estimates, and the precise extent of the difference can be the argued, the fact that the gap exists is not in question irrespective of how it is calculated (Naylor *et al.*, 2009). There is a fundamental, global lack of n-3 LC-PUFA to supply all human needs, whether by direct consumption or via aquaculture. Consequently, there is an urgent need to find alternative sources of the omega-3 LC-PUFA, EPA and DHA (Sprague *et al.*, 2017b).

6.4.2 Other marine sources of n-3 LC-PUFA

Other sources of marine oils including those derived from lower trophic levels and mesopelagic fish are being researched. Although there may be evidence that harvesting krill, and potentially copepods, could be sustainable, there are still significant environmental and ecological concerns (Olsen *et al.*, 2011). While mesopelagic fish have not been the subject of commercial exploitation, and they do not compete with existing or potential human feed production, there are significant biological, ecological, technical, and nutritional issues. Fisheries by-catch and seafood by-products are potential sources of FO and, although there is currently some production, the contribution of these sources to overall FO supply is not well quantified (Shepherd & Jackson, 2013).

6.4.3 Micro-organisms

Unlike land plants and green algae, most **micro-algae** synthesise n-3-LC-PUFA. Thus, their cultivation could offer the ideal long-term, sustainable solution to the problem of n-3-LC-PUFA supply. However, up-scaling of production of **phototrophic** microalgae to the volumes required for algal oil and/or algal biomass to supply the amount of n-3 LC-PUFA required to replace FO in commercial aquafeed production has significant biological and technological challenges (Chauton *et al.*, 2015).

In contrast, large-scale biofermentor technology is widely used to grow **heterotrophic** micro-organisms using commercially available dissolved organic compounds as a source of food and energy. Amongst these are species of *Cryptocodinium* and *Schizochytrium*, sometimes (inappropriately) called micro-algae. The first is a dinoflagellate that lacks chloroplasts, and the second is a thraustochytrid. Both have been used to produce DHA in commercial quantities.

Substituting FO with thraustochytrid oil or biomass from *Schizochytrium* and *Cryptocodinium cohnii* had no deleterious effects in feeds for fish including salmon. Several nutrition companies have marketed what they term dry 'algal' biomasses aimed specifically for use in aquaculture.³⁶ These include 'DHA Natur™' (Archer Daniels Midland [ADM] Animal Nutrition™), 'ForPlus™' (Alltech®), which is also incorporated 'NeoGreen', an FM- and FO-free range of trout diets (Coppens International), and 'AlgaPrime™ DHA' (TerraVia Holdings Inc. and Bunge Ltd.). Use of these biomasses in salmon feeds is limited due partly to the relatively high carbohydrate content and partly to issues regarding bioavailability of the oil when present in whole cells. In contrast, DSM (Heerlen, Netherlands) and Evonik Industries AG (Essen, Germany) have a joint venture, *Veramaris*, to produce an EPA and DHA-rich microbial oil with full-scale production anticipated in 2019. The extracted algal oil is expected to provide 15% of current annual demand by the salmon farming industry for EPA and DHA (DSM, 2017). The fact that *Veramaris* will be an oil and not biomass could represent a game-changing development in this field. While all the products from heterotrophic 'micro-algae' may have niche markets in marine hatcheries, particularly for high-value marine species, production volumes would have to be increased and costs reduced before any could be viable for use in salmon farming. The DSM-Evonik *Veramaris* product is the most promising and, arguably, the one most likely to be commercially successful on a large scale.

6.4.4 Transgenic oilseed crops

Non-bacterial micro-organisms represent a highly valuable source of genes encoding for the biosynthetic enzymes required for n-3 LC-PUFA production. If these genes could be transferred to other organisms that have oil deposition as a major trait, the result would be entirely novel sources of n-3 LC-PUFA (Sayanova & Napier, 2011).

Oilseed crops dominate world oil production and there is a highly organised and well-established infrastructure for the cultivation, harvest, processing, distribution, marketing and utilisation of vegetable oils (VO). Therefore, oilseed crops although not naturally synthesising n-3 LC-PUFA, are highly practical platforms from which to develop a novel, renewable supply of these fatty acids (Haslam *et al.*, 2015).

Transfers of the relevant genes have been made. Transgenic *Camelina sativa* lines have been developed to produce oils containing FO-like levels of EPA and DHA. These oils have been extensively tested in feeds for salmon and sea bream and been shown to effectively replace FO, maintaining high levels of n-3 LC-PUFA, with no detrimental impacts on fish growth or health, and no transgenes detected in feeds or fish tissues

³⁶ What the companies call 'algae', implying photosynthetic organisms, are actually heterotrophs, using organic carbon compounds. This means that they can be grown in fermentation reactors.

(Betancor *et al.*, 2015a; b; 2016a; b; 2017). Scalability of this technology has no major scientific, technological or environmental barriers.

However, irrespective of the advances in science, it will be necessary to change public opinion towards acceptance of GM products before these oils can be used commercially in Europe. Furthermore, the current ban on the growing of any GM crops in Scotland prevents the use of this technology here (Tocher, 2015b).

6.5 Environmental Impacts and Sustainability of New Sources of n-3 LC-PUFA

Micro-heterotroph production of EPA and DHA using fermentation technology relies on organic carbon feedstocks such as dextrose/corn syrup (Veramaris) obtained from corn/maize production in the USA, or sucrose (Algaprime DHA) from sugarcane production in Brazil. Therefore, sustainability of this production of EPA and DHA is partly linked to the availability of these feedstocks from terrestrial agriculture and the associated sustainability issues they may have now and in the future. TerraVia, one of the companies involved in production and marketing of the 'AlgaPrime™ DHA' product filed for bankruptcy in the USA in August 2017.

The 'false-flax' *Camelina sativa*, a member of the cabbage family, has desirable agronomic traits including relatively low requirements for water and pesticides and ability to thrive in semi-arid conditions. Several US States are growing *Camelina* for biofuels, indicating the wide acceptance of this crop platform for the production of oils, whatever the final use. Ultimately, all food animal production will depend on terrestrial plants/agriculture and this requires land. However, it is pertinent to emphasise that the production of n-3 LC-PUFA in terrestrial oilseed crops such as transgenic *Camelina* need not necessarily require additional arable land as the ideal solution would be to switch some VO production from strains producing the usual n-6 PUFA to the GM strains synthesising n-3 LC-PUFA.

6.6 Diagnosis

Feed for farmed salmon requires protein and oil. Both were initially obtained from marine sources, but are now partly substituted from vegetable sources.

In Scotland in 2017 between 20 and 25% of protein and oil still came from marine sources, mainly from catches of small plankton-eating fish caught in well-managed fisheries in other parts of the world. With global fish stocks either at or beyond their maximum sustainable yield, there is increasing global competition for this finite resource.

The vegetable protein comes from soy, grains and legumes, the oil mainly from rapeseed. Although salmon are efficient converters of feed into fish, there is concern that by using products of agriculture, aquaculture is not fulfilling its potential as an additional source of food for humanity.

Finally, health benefits provided to consumers of salmon through the fish content of n3-LC-PUFA, depends on an assured source of these fatty acids. They are not a natural

component of vegetable oils, and the main source is currently fish oils, of finite and likely insufficient supply.

6.7 Prognosis and Mitigation

Notwithstanding further improvements in the growth and nutrient conversion efficiencies of farmed salmon, increased salmon production in Scotland will require increased supply of feed, and thus of the protein and oil from which it is made. The limitations already apparent, especially in respect of 'omega-3', will become more severe. This may manifest in higher feed costs, as the feed industry competes with other demands for the raw materials, and it may increase pressure for unsustainable harvesting of fish or the further conversion of rain-forest to soy or palm plantations. The market for protein and oil is global, and Scottish salmon farming is in competition with, for example, Norwegian farming, which may increase towards 5 million tonnes.

If salmon farming is to avoid increasing dependence on terrestrial agriculture, and thus competition for land and other resources used to grow crops, greater use could be made of marine resources. The global harvest of forage fish is already at its limit, but it may be possible to increase recycling of by-catch and waste from fish processing. Sea-loch cultivation of brown seaweeds, and of mussels that consume planktonic algae and retain their omega-3, are options for protein and omega 3 that could be explored. (The case for IMTA has already been made in other Sections of this review).

In the medium-term, it is the global shortage of n3-LC-PUFA that is likely to provide the most severe feed-related constraint on salmon farming expansion. It may be possible to use micro-organisms cultivated in industrial-scale fermenters to produce these compounds; the alternative option, of using genetically modified oil-seed plants is currently ruled out by "public" opinion and Scottish government policy.

7 EMERGING ENVIRONMENTAL IMPACTS

This Section deals with emerging areas of concern, especially:

- Effects of salmon farming on protected populations of marine mammals and sea-birds;
- The demands on wild populations of wrasse and lumpsucker resulting from the use of these fish to remove lice from farmed salmon.

7.1 Effects on Marine Mammals and Birds

Scottish inshore waters are home to a diverse array of marine mammals and birds. These animals are typically long-lived and wide-ranging, but they reproduce slowly, which makes them vulnerable to the effects of anthropogenic pressures. Some are migratory, whilst others occur in Scottish waters year-round. Many are top predators that feed on fish, including juvenile and adult salmonids. This part of the report lists the species of birds and mammals involved in interactions with salmon farming and seeks to answer the following questions:

- How does the salmon aquaculture sector interact with marine mammals and birds in Scottish waters?
- What are the direct and indirect effects of these interactions?
- What, if any, mitigation measures can be employed to successfully reduce or mitigate negative interactions?

7.1.1 Mammals and birds under review

The following groups of mammals and birds occur at least periodically in inshore Scottish waters and are considered relevant for the purposes of the present review. The mammal groups include:

- **Cetaceans:** whales, dolphins and porpoises, including common inshore species such as harbour porpoise (*Phocoena phocoena*), bottlenose dolphin (*Tursiops truncatus*) and minke whale (*Balaenoptera acutorostrata*);
- **Seals (Pinnipeds):** including harbour or common seal (*Phoca vitulina*) and grey seal (*Halichoerus grypus*);
- **Mustelids:** Coastal populations of the European otter (*Lutra lutra*) and American mink (*Neovison vison*), the latter being a non-native species.

Bird groups include:

- **Divers:** Gaviidae;
- **Seaducks:** Mergini, including species such as eiders (*Somateria mollissima*), mergansers and scoters;
- **Hérons:** Ardeidae, notably coastal populations of the blue heron (*Ardea cinerea*);

- *Gulls and terns*: Laridae;
- *Cormorants*: Phalacrocoracidae, represented in Scotland by great cormorant (*Phalacrocorax carbo*) and European shag (*P. aristotelis*);
- *Auks*: Alcidae, including such species as razorbill (*Alca torda*), black guillemot (*Cepphus grylle*) and Atlantic puffin (*Fratercula arctica*).

Only species that are likely to interact with the marine component of the salmon aquaculture industry are included in the present report. It is, however, worth noting that terrestrial or freshwater-based salmon hatchery and grow-out operations could conceivably involve additional interactions with otters, mink and other mammal and bird species.

7.1.2 Legal protection

The Scottish Government is committed to the EU Marine Strategy Framework Directive (2008/56/EC), which requires healthy populations of birds and marine mammals as part of '**Good Environmental Status**'. Marine mammals and birds in Scotland are additionally protected by other legislation, which are detailed below.

Marine mammals

Marine mammals are protected under the following legislations:

- Conservation (Natural Habitats, &c.) Regulations 1994 in combination with the Nature Conservation (Scotland) Act 2004 and the Offshore Marine Conservation (Natural Habitats, &c.) Regulations 2007, which implement species protection requirements of the European Union (EU) Habitats Directive (92/43/EEC) in Scotland, on land, inshore and offshore waters;
- Wildlife and Countryside Act 1981;
- The Marine (Scotland) Act 2010 and the Marine and Coastal Access Act 2009 (which devolved authority for marine planning and conservation powers in the offshore region (12-200 nm) to Scottish Ministers).

All species of cetacean occurring in UK waters are listed in Annex IV (species of community interest in need of strict protection) of the EU Habitats Directive as European Protected Species (EPS), whereby the deliberate killing, disturbance or the destruction of these species, or their habitat, is banned (this is reflected in their inclusion on Schedule 2 of the Habitats Regulations). Furthermore, two species, the harbour porpoise and bottlenose dolphins, are listed in Annex II under the EU Habitats Regulations, which means that these native species should be conserved through the designation of Special Areas of Conservation (SACs).

Cetaceans are listed in Schedule 5 of the Wildlife and Countryside Act 1981 which prohibits their deliberate killing or disturbance. The Nature Conservation (Scotland) Act 2004 makes amendments to the Wildlife and Countryside Act 1981 in Scottish waters, including the addition of 'reckless' acts to species protection which make it an offence to intentionally or recklessly disturb a cetacean.

UK seals do not have the strict protection of EPS through the Habitats Directive, but are listed in Habitats Directive Annex V (Schedule 3 of the Habitats Regulations) as species of community interest; disturbance, injury or killing of seals may therefore be subject to management measures. Two species, the grey and harbour seal, are also listed in Annex II of the Habitats Directive, which requires SACs to be designated for these species. Amongst other responsibilities the Marine (Scotland) Act, 2010 and the Marine Coastal Access Act (2009), make it an offence to disturb seals at any designated haul out location and to kill or injure seals anywhere (but see below for exemptions).

Birds

Birds in the Scottish marine environment are protected under the following legislation:

- Conservation (Natural Habitats, &c.) Regulations 1994 in combination with the Nature Conservation (Scotland) Act 2004 and the Offshore Marine Conservation (Natural Habitats, &c.) Regulations 2007 which implement species protection requirements of the EU Habitats Directive (92/43/EEC) in Scotland and Wild Birds Directive (2009/147/EC);
- Wildlife and Countryside Act 1981 (as amended).

The Habitats Regulations implement the requirement of the EU Wild Birds Directive in the UK. To comply with Article 4 of the Birds Directive, emphasis is given to the protection of habitat for rare species listed under Annex I of the Directive as well as for migratory species by means of the establishment of a coherent network of Special Protection Areas (SPAs).

The Wildlife and Countryside Act (WCA) protects wildlife within the terrestrial environment and inshore waters within Great Britain. Amendments to the legislation, such as the Nature Conservation (Scotland) Act 2004, have altered application of the WCA in Scotland. Part 1 of the WCA relates to the protection of wild birds affording various levels of protection to different species. SNH can designate Sites of Special Scientific Interest (SSSIs) to form a network of best examples of natural features.

7.1.3 Depredation

Salmon farms can attract marine mammals and birds seeking to forage on fish contained within the pens, an activity commonly referred to as depredation (Coram *et al.*, 2014). Depredation has long been observed among Scottish salmon farms (e.g. Hawkins, 1985; Ross, 1988; Carss, 1994; Quick *et al.*, 2004; Northridge *et al.*, 2010). The most important species known to engage in depredation include harbour seal, grey seal, European otter, American mink, European shag, great cormorant, blue heron, and various gulls (Quick *et al.*, 2004). Of these, the two seal species have traditionally been considered to cause the most damage (Quick *et al.*, 2004; Northridge *et al.*, 2013; Coram *et al.*, 2014).

Depredation behaviour by seals can impact farm operations in several ways, including

- Injury and mortality of salmon due to the predators attacking them;
- Increased stress levels among fish as a result of predator presence, potentially reducing their growth rate (and eventual market value);

- Damage to fish pen infrastructure due to depredation attempts (potentially resulting in large numbers of farmed salmon escaping into the environment).

These impacts can have substantial financial consequences for the fish farm operator, as well as effects on wild salmon stocks when depredation results in escapes (Northridge *et al.*, 2013 and references therein). However, depredation is likely only undertaken by a small subset of seal populations (Graham *et al.*, 2011). Seals are regularly seen around fish cages even when the farms are experiencing no seal-related problems. This suggests that many seals around cages are doing no harm but merely foraging on wild fish, which are themselves consuming the waste from the farms or using the shelter provided by the cages.

7.1.4 Lethal control measures

As a result of real or perceived depredation risk, fish farm operators have traditionally been able to resort to lethal control measures (typically shooting) of animals observed at or near fish farm locations (e.g. Hawkins, 1985; Carss, 1993; 1994).

In recent years, shooting or otherwise killing of birds has been mitigated through the use of top nets, preventing birds gaining access to the fish from above. However, despite the recognition of birds as species of concern in the aquaculture context, little information is available on the effectiveness of this approach, or indeed the current status of bird/aquaculture interactions in Scotland and elsewhere (e.g. Price *et al.*, 2016).

More information is available on the lethal removal of seals, which remains an active management tool for the Scottish aquaculture sector. Prior to 2010, seals in Scotland were managed under the Conservation of Seals Act 1970³⁷, which included an exemption that permitted the killing of seals under certain circumstances, such as to prevent a seal from damaging fishing nets, although it also offered some protection to seals through establishment of closed seasons during breeding periods. When the Marine (Scotland) Act 2010 was introduced, this exemption for fishermen and the aquaculture sector was removed and replaced with a new seal licensing system, which has been administered under Part 6 Conservation of Seals of the Act by Marine Scotland since 2011³⁸. The present system, which applies to coastal fisheries as well as the aquaculture sector, prohibits the killing of seals except under license. The license can be granted for various reasons, including “to protect the health and welfare of farmed fish”, and/or “to prevent serious damage to fisheries or fish farms” (S.110(1), Marine (Scotland) Act 2010). It sets limits on the number of seals of either species (grey and harbour seals) that can be shot per annum through application of the Potential Biological Removal (PBR) methodology (Marine Scotland, 2017). These limits are to ensure that Scottish seal populations are maintained at levels consistent with their status under the EU Habitats Directive (92/43/EEC). If a license is granted, accompanying licensing conditions also specify how, where and under what circumstances seals are to be shot, including the requirement for recovery of resulting carcasses for post-mortem examination where practicable.

³⁷ <https://www.legislation.gov.uk/ukpga/1970/30/contents>

³⁸ <https://www.legislation.gov.uk/asp/2010/5/part/6>

A review covering the first four complete years of the new licensing scheme (2011-2014) was published by Marine Scotland (2015). The review reported a significant reduction in reported shootings of seals at fish farms and coastal fisheries during this period. This was considered to have been driven by a number of factors, including improvements in non-lethal seal deterrent measures such as correct net tensioning techniques, prompt removal of dead fish, antipredator netting, and use of Acoustic Deterrent Devices (ADDs). Subsequent data reported by Marine Scotland suggest that numbers of seal licenses issued, and associated numbers of seals reported shot, have continued to decline (Marine Scotland, 2017). By 2016 (the most recent year for which complete data are available), numbers of harbour and grey seals reported shot under the present regime represented <0.1% of their respective populations across Scotland, although there was some regional variation in seals reported shot (SCOS, 2016; Marine Scotland, 2017). An average of 51% of licensed shootings took place at fish farms during the 2011-2016 period, with the remainder carried out by coastal fishery boards and other wild fisheries-related stakeholders (e.g. to safeguard wild Atlantic salmon stocks; Marine Scotland, 2017) although the fraction of shootings associated with fish farms varied annually.

Although the present licensing system has resulted in a decline in the number of seal shooting licenses issued, there are several areas where additional attention is still required (discussed in detail by Nunny *et al.*, 2016). The data made available by Marine Scotland (2017) are based upon self-reporting by license holders, and are not presently verified independently, potentially risking under-reporting or shooting of seals without license. Shooting of seals also raises a number of significant animal welfare issues that need to be considered. Despite being a license condition, most shot seals are not presently made available for necropsy, thereby preventing an independent assessment of whether seals are shot according to the Scottish Seal Management Code of Practice and in such a manner to “*ensure against a prolonged and painful death*” (Marine Scotland, 2011). In Scotland, seals are always shot while in the water, raising the possibility of animals being wounded rather than killed and dying elsewhere some time afterward, which clearly has implications for their welfare. It is presently unclear how many seals are ‘struck and lost’ in this manner.

A sizeable proportion (>30%) of the number of carcasses made available for necropsy to date have involved pregnant or lactating seals (Nunny *et al.*, 2016 and references therein), which has obvious welfare implications. The shooting of such animals may also have larger impacts on seal populations than accounted for by assessment of numbers alone. Reintroduction of closed seasons aligned with seal breeding periods, to eliminate the shooting of female seals nursing dependent pups, would address this issue.

Finally, the current practice of licensed seal shooting as a depredation control method in Scottish aquaculture might have wider implications for the UK economy. Farmed salmon was the second largest food and drink export from the UK in the first half of 2017 (H.M. Customs and Excise). The United States, an important export market (with particular significance in the light of Brexit), has recently finalised regulations under the US Marine Mammal Protection Act (MMPA), requiring any country exporting fish to the US to abide

by marine mammal protections equivalent to those in the US (81 FR 54389, NOAA 2016). Seal shootings will thus likely not be tolerated by the US market in the future.

Alternative methods to address problems with seal depredation include locating fish farms away from seal haul-out sites (particularly as seals may visit cages to forage on wild fish under the cages), properly weighted and tensioned nets, newer netting materials such as high density polyethylene (HDPE), and other technical innovations (such as low voltage electric fields; e.g. Coram *et al.*, 2016; SCOS, 2016). These non-acoustic (see below for environmental impacts of acoustic deterrence) mitigation measures to decrease depredation could be further investigated and actively promoted to further reduce, and eventually phase out, the practice of shooting seals as a mitigation tool in Scottish aquaculture.

7.1.5 Acoustic deterrence and noise pollution

Acoustic Deterrent Devices (ADDs, also referred to as ‘seal scarers’ or Acoustic Harassment Devices [AHDs]) are widely deployed on Scottish fish farms as a nonlethal method to reduce seal depredation risk by producing loud, aversive underwater sounds (see review Götz & Janik, 2013). ADDs were first introduced to Scotland in the mid-1980s; since then their use has steadily increased (Hawkins, 1985; Ross, 1988; Quick *et al.*, 2004; Northridge *et al.*, 2010; Coram *et al.*, 2014). Despite their widespread use in Scotland, the ability of ADDs to actually deter seals from fish farms has not yet been convincingly demonstrated (e.g. Jacobs & Terhune, 2002; Quick *et al.*, 2004; Graham *et al.*, 2009; Götz & Janik, 2013; SCOS, 2016).

Although ADDs are intended to keep predatory seals from making direct contact with cages and farmed salmon, the aversive sounds produced by ADDs does not stop at farm boundaries, but propagates out into the wider environment as an acoustic pollutant. Individual farms often use multiple ADDs and most are left to operate continuously. There is a risk of impacting marine mammals and other acoustically sensitive species in the wider environment that are not interacting with aquaculture interests.

Three main types of ADDs are currently used in Scottish salmon aquaculture (Northridge *et al.*, 2010; Coram *et al.*, 2014). These different brands of ADD differ considerably in terms of their sound output (i.e. loudness, frequency range, duty cycle; Lepper *et al.*, 2014). Although various options exist to reduce ADD output (e.g. Kastelein *et al.* 2010; Götz & Janik, 2013; 2014), these have yet to widely penetrate the market. Considerable variability also exists in terms of ADD deployment strategies among fish farms, including types and numbers of devices being used, as well as the monitoring of device status. There is presently no formal process (e.g. as part of site licensing conditions) to monitor ADD usage or associated sound outputs in Scottish waters. SNH is a statutory consultee at the planning stage and can object to the planned use of ADDs under the Conservation (Natural Habitats, &c.) Regulations 1994. Despite this, the absence of a consistent ADD monitoring scheme and/or licensing process currently poses a significant challenge to the assessment of the scale of ADD-related noise pollution and consequently its impact on marine species.

Anthropogenic underwater noise as a form of environmental pollution is being addressed through various international policy initiatives, including OSPAR (OSPAR 2014-08) and

the EU Marine Strategy Framework Directive (2008/56/EC). However, while specifically mentioned in these policy frameworks, ADDs are currently not being recorded consistently in any national marine noise register (Dekeling *et al.*, 2014; Merchant *et al.*, 2017).

Underwater sound generated by ADDs used in Scottish aquaculture is a significant contributor to noise pollution in Scottish waters (e.g. Götz & Janik, 2013) and may impact marine mammals and other acoustically sensitive species, whether they are interacting with aquaculture facilities or not. Potential impacts include disturbance (leading to behavioural change and habitat exclusion), as well as physical injury (temporary or permanent hearing damage; Southall *et al.*, 2007, Brandt *et al.*, 2013; Götz & Janik, 2013; Lepper *et al.*, 2014). There is also potential for long-term chronic impacts such as increased stress levels with associated health implications due to continuous noise exposure (Rolland *et al.*, 2012).

ADDs have been shown to elicit strong evasive responses from non-target species such as harbour porpoises (Johnston, 2002; Olesiuk *et al.*, 2002; Northridge *et al.*, 2010; 2013; Brandt *et al.*, 2013; Mikkelsen *et al.*, 2017). This has important implications for the application of ADDs in environments such as Scottish coastal waters, as sound levels required to deter the target species (i.e. seals) can lead to excessive impacts on non-target species (e.g. more acoustically sensitive cetaceans; Brandt *et al.*, 2013; Mikkelsen *et al.*, 2017). This is of particular relevance along the west coast of Scotland, where a SAC was recently established to protect the harbour porpoise, a species previously shown to be particularly sensitive to acoustic disturbance (Lucke *et al.*, 2009, Tougaard *et al.*, 2015; Marine Scotland, 2016).

7.1.6 Indirect mortality

Entanglement in ropes, lines, nets and other artificial materials is a significant cause of mortality for many marine species worldwide, mostly associated with commercial fisheries (e.g. Read *et al.*, 2006; Bull, 2007; Reeves *et al.*, 2013). Nonetheless, animals foraging in the immediate vicinity of fish farms can also become entangled among the cages, anti-predator netting and/or mooring lines (e.g. Carss, 1993; Kemper *et al.*, 2003 and multiple references therein; Quick *et al.*, 2004). In the Scottish context, this mortality can include a range of species including birds and marine mammals.

Despite several early studies indicating that entanglement among fish farm infrastructure could be significant (e.g. Carss, 1993; 1994), there is little current information on actual numbers of animals involved. Accordingly, the impact of this mortality on wild populations of marine mammals and birds remains difficult to assess. However, Ryan *et al.* (2016) reported at least one case of a humpback whale (*Megaptera novaeangaliae*) entanglement involving a salmon aquaculture sea pen off Scotland.

It has been suggested that increased tensioning of anti-predator nets may reduce entanglement risk for birds and pinnipeds (Quick *et al.*, 2004; Price *et al.*, 2016). However, in Scotland, detailed and standardised reporting of bird and marine mammal entanglement in aquaculture infrastructure is currently lacking. This makes it difficult to properly assess the risk and develop potential solutions to the problem of entanglement interactions.

Finally, artificial lights associated with marine industries are known to attract birds at night, often with fatal consequences (e.g. Montevecchi, 2005 and multiple references therein). The role of aquaculture in this regard remains poorly understood, and further research is required to determine its relative importance.

7.1.7 Competition for resources

As described in Section 6, marine resources continue to make a major contribution to ingredients of salmon feed despite significant efforts to reduce the importance of fish meal and fish oil (e.g. Kristofersson & Anderson 2006; Naylor et al. 2009). Over a third (36%) of global landings from fisheries are used for the production of the world's fishmeal and fish oil, which are traded globally (Natale *et al.*, 2013; Bonaldo *et al.*, 2017). The Scottish aquaculture sector made use of an estimated 220,000 tonnes of feed, of which about 40% was derived from marine sources. This implies a need for about 55,000 tonnes of fishmeal (25% of the total feed) and 33,000 tonnes fish oil (15% of the total; Bonaldo *et al.*, 2017). At least 50% of this amount needs to be imported annually, mainly from elsewhere in the North Atlantic but also from Chile and Peru (Bonaldo *et al.*, 2017).

Concerns have been raised that this reliance on wild fish can result in unsustainable exploitation of small schooling fish upon which marine mammals, birds and other marine predators depend (e.g. Naylor *et al.*, 2000; Olsen & Hasan, 2012). Given the global nature of trade in fishmeal and fish oils, the Scottish salmon aquaculture sector may be in indirect competition for fish with marine mammals and birds both in Scottish waters and elsewhere. The extent and consequences of this competition remain, as yet, poorly understood for many marine mammal and bird species.

7.1.8 Local changes to prey abundance

Significant numbers of wild fish (like saithe, *Pollachius virens*) can be attracted to the vicinity of fish farms (e.g., Callier *et al.*, 2017). These concentrations of wild fish may in turn attract top predators, including marine mammals and birds.

Little is currently known about the extent to which Scottish salmon farms might aggregate wild populations of prey fish and attract marine mammals and birds, although there are some suggestions that foraging around fish farms may be locally important. For example, research by Carss (1993) on stomach contents of great cormorants shot close to fish farms in western Scotland suggested that most fish consumed had come from wild fish populations. In addition, birds appear to be attracted by the physical structure of fish farms (which may serve as roosting platforms) and by waste feed (Buschmann *et al.*, 2009a; 2009b).

Although quantitative information is lacking, it seems likely that marine mammals common in Scottish waters, including seals (Northridge et al. 2013), harbour porpoises (Haarr *et al.*, 2009) and bottlenose dolphins (Díaz López *et al.*, 2005; Piroddi *et al.*, 2011), could also be attracted to fish farms by increased densities of, and enhanced opportunities for feeding on, wild prey. This indirect effect of at-sea aquaculture on marine mammal and seabird behaviour may increase risks of depredation, exposure to noise pollution, entanglement or other interactions with fish farms as summarized here, but further information is needed.

7.1.9 Chemical pollution and marine litter

Fish farms may negatively impact their immediate surroundings through discharges of excess feed and waste products as well as through consumption of dissolved oxygen, which may result in deterioration of local benthic communities (see Section 3). Marine mammals and birds, being mobile and dependent on atmospheric oxygen, are unlikely to be directly affected by these interactions. However, they may be affected indirectly by local changes in the food chain (e.g. Callier *et al.*, 2017).

The effects of antibiotics and medication used to treat infectious diseases and parasites among farmed salmon on marine mammals and birds through bioamplification has not yet been investigated, and further research is needed to determine potential effects in Scottish species.

Other chemicals that are used in aquaculture (e.g. antifouling products) contain metals (e.g. copper, zinc), as well as polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs). While levels of PCBs and PBDEs in sediments around Scottish fish farms appear to be comparable to other marine locations (Russell *et al.*, 2011), they may affect Scottish marine mammal and bird populations due to bioaccumulation through the food chain. For example, a greater uptake of metals has been observed in wild fish around fish cages than in the farmed fish (Kalantzi *et al.*, 2015). A recent study on the effects of chemical pollution found low recruitment consistent with PCB-induced reproductive toxicity in small populations of killer whales and bottlenose dolphins in the North East Atlantic (Jepson *et al.*, 2016).

Marine litter has received increasing attention in recent years and is integrated in different (inter)national policies such as the EU Marine Strategy Framework Directive (EU MSFD) and the Marine Litter Strategy for Scotland (Marine Scotland, 2014). While there is no data available on the extent of the contribution of Scottish aquaculture to floating marine debris (FMD) to the environment, a study in Chile concluded that most FMD had their origin in sea-based activities such as mussel farming (styrofoam) and salmon aquaculture (food sacks) (Hinojosa & Thiel, 2009).

The impact of marine debris on cetaceans has been shown to be significant for some populations, inducing mortality rates between 0-22% of stranded animals according to a recent literature review (Baulch & Perry, 2014). Seabirds are similarly affected by marine plastic with 20% of seabird species investigated in Scotland showing ingestion of plastic marine litter (O' Hanlon *et al.*, 2017).

7.1.10 Diagnosis

The main impacts of the aquaculture industry on marine mammals are currently direct mortality (i.e. shooting of seals) and acoustic pollution through use of ADDs. The seal shooting is a licensed activity in Scotland with associated reporting mechanisms. Concerns have, however, been raised about lack of independent validation of reporting, as well as various welfare-related problems (seals shot but not immediately killed; shooting of pregnant or nursing female seals; Nunny *et al.*, 2016). Much less is known about the current impacts of aquaculture on birds.

Despite their widespread use in Scottish aquaculture, the long-term effectiveness of ADDs as a seal deterrent remains unproven. Their use is largely unmonitored at present, leading to growing concern about unintended and widespread underwater noise pollution from ADDs in Scottish waters which may be harmful to other species (cetaceans in particular).

Although a potential risk, there are currently insufficient data available to quantify the magnitude of entanglement risk to marine mammals or birds among fish farms in Scottish coastal waters.

Salmon farming has a number of indirect effects on marine mammals and birds. At a local level, these species may for example benefit from increases in wild fish around farms. However, this simultaneously raises the risk of negative interactions such as the attracted predators then being attracted to and interfering with nets. It also increases their exposure to potentially injurious high intensity noise produced by ADDs. On larger scales, sustained demand for fishmeal and oils for salmon feed may result in increased competition between these wild predators and commercial fisheries in Scottish waters and further afield.

7.1.11 Prognosis and mitigation

Given proposed expansion of the Scottish salmon aquaculture sector, interactions between salmon farms and marine mammals and birds are likely to continue to occur. Of these, interactions involving seals are likely to remain the most significant. Although current downward trends in seal shootings (both in numbers of licenses awarded and seals reported shot) are encouraging, these may stabilise or reverse in case of significant future expansion of the industry including into more remote, exposed and/or offshore areas. Although numbers of seals currently reported shot represent a small proportion of Scottish populations, there are various important methodological and animal welfare-related problems associated with the current seal licensing scheme, based on a lack of independently verified data on adherence to the Scottish Seal Management Code of Practice, and lack of closed seasons aligned with seals' breeding periods. The recent implementation of more stringent U.S. import regulations, which could negatively impact Scottish salmon exports on the basis of ongoing seal shooting, provide additional incentive to further reduce dependence on lethal control and instead encourage alternative depredation prevention options.

There is an urgent need to further develop and promote alternative non-lethal depredation prevention methods that do not also have such a widespread impact on the surrounding environment as ADDs. Over the years, the Scottish salmon sector has invested heavily in ADDs as a non-lethal alternative to shooting seals. Significant fundamental questions remain, however, about the mechanisms and long-term efficacy of ADDs in deterring seals. In other words, whether they actually work has yet to be convincingly proven. At the same time, current ADDs emit substantial amounts of acoustic pollution into Scotland's coastal waters, with the potential to cause both acute and chronic negative effects on marine mammals and other wildlife. ADD use is presently largely unregulated and unmonitored; the extent of these impacts therefore remains

poorly understood although it is widespread. Expansion of ADD usage in line with expanding salmon production capacity, as proposed, will only exacerbate this situation.

Given these concerns and continuing uncertainty about ADDs' long-term ability to successfully prevent seal depredation, there is a need to improve monitoring of ADD use and resulting sound emissions. The comparative effectiveness of alternative non-lethal mitigation methods (e.g. improved net tensioning, stronger net materials) could be investigated and, if found to significantly reduce depredation, use of these methods may be promoted over the use of ADDs. If ADD use cannot be avoided, the use of versions with significantly reduced noise output (e.g. Götz & Janik, 2014) is to be encouraged. If 'traditional' ADDs are to be used at all, there is a need to definitively establish whether they actually work in terms of long-term, effective deterrence of seals and which signal characteristics and/or modes of operation contribute to ADDs' effectiveness. The acute and chronic effects of ADD-generated noise pollution might be on both seals and other sensitive species not directly involved in the issue also require investigation. Results of such studies would stimulate discussions on the extent to which ADDs might continue to be considered an appropriate method to mitigate seal depredation of farmed salmon in Scottish waters.

On the other hand, the presence of salmon farms may have local benefits to individual birds and marine mammals, through provision of novel foraging opportunities on wild fish that may themselves be attracted to the shelter and food provided by the farm. Foraging or migrating birds may also take advantage of resting or perching opportunities afforded by fish farm infrastructure. It is evident that increased attraction of marine mammals and birds to farms also increases the potential risk of negative interactions, including (but not limited to) depredation, ADD noise exposure or entanglement in nets, mooring infrastructure or the like. The occurrence, extent and consequences of attracting marine mammals and/or birds to fish farms need to be better understood to facilitate appropriate management decisions and reduce negative interactions where possible.

Finally, the larger-scale issue of competition between the fish-feed sector and wild marine mammals and birds for marine resources, especially those of forage fish used in salmon feed, is currently being addressed by the use of alternative sources of meal and oil, as discussed in greater detail in Section 6.

Overall, there is a need to work towards a more harmonious relationship between marine mammals and birds and the aquaculture industry. Examples to draw on include those from good agriculture practices that contribute to maintaining populations of protected birds. Given the interest among the Scottish public in the well-being of marine mammals and birds, moving towards such harmony would be beneficial for the industry's public image.

7.2 The use of Wrasse as Cleaner Fish in the Salmon Farming Industry

Earlier sections have discussed the need to treat sea lice infestations of farmed salmon and the problems related to chemical treatments. An alternative is biological: the use of 'cleaner fish' to pick off the lice. This section addresses the questions:

- What kind of fish can be used for this purpose?
- How can they be provided in sufficient numbers for salmon farming?
- What are the implications of their harvesting from wild populations?

7.2.1 The biology of fish used as lice cleaners

Two kinds of fish are currently used as cleaners: wrasse (family Labridae) and lumpsuckers (family Cyclopteridae). The former are small, brightly coloured warm-water fish, the latter found mainly in cold waters, usually drab in colour, and distinguished by a sucker formed from modified pelagic fins.

Wrasse

There are about 600 species of wrasse around the world, but only eight are found in UK seas and some of these are rare or occasional visitors (Table 7.1). In the temperate waters of north-western Europe, they are found around rocky shores and often within beds of macroalgae (large seaweeds such as the kelps, wracks and rockweeds). Because they are associated with rocky habitats, their UK distribution is predominantly on western coasts.

Many of the tropical wrasses act as cleaner fish removing parasites from other species of larger fish. Such behaviour is often signalled by bright coloration of the cleaner fish, along with behavioural signals made by both the cleaner and cleanee. Although cleaning behaviour may not be so widespread in temperate wrasses, it has been recorded in corkwing, goldsinny and rock cook (Potts, 1973; Hiltén, 1983).

Lumpsuckers

Lumpsuckers are a stout-bodied fish possessing bony plates in the skin. There is a well-developed sucker on the underside of the body, which gives them their common name. They are primarily a bottom dwelling fish among rocks from low-water to around 200 m depth. They reach maximum sizes of 40-50 cm (Wheeler, 1978).

7.2.2 Use of 'cleaner fish'

Compared to chemical treatments, biological control of sea lice using a natural predator is an attractive option for several reasons:

- Cleaner fish help to keep sea lice numbers low without risk for human health;
- They can be co-cultured with salmon, which do not suffer additional stress even under non-optimal health condition;

- They can feed on sea lice continuously, even at low levels of infestation;
- They are not toxic for the environment;
- Sea lice cannot develop resistance to cleaner fish, although there may be increased selection pressure for lice to better evade their predation (Gonzalez & de Boer, 2017).

Although the use of cleaner fish will rarely eliminate sea lice completely, their presence in salmon cages can suppress lice numbers, and thus help reduce the use of chemicals.

Wrasse

The first scientific publications (Bjorndal, 1988; 1990) on use of wrasse as cleaner fish in fish farms suggested that goldsinny and rock cook could be effective at reducing infestations of salmon lice on salmon smolts, whilst female cuckoo wrasse had only a moderate effect. Current practice is to use different wrasse species and sizes for different stages of the salmon production cycle. Small goldsinny and rock cook are preferred during early post-smolt stages, while larger corksiding and ballan wrasse are introduced when the salmon reach 3-5 kg in weight (Gonzalez & de Boer, 2017).

The early experiments suggested a ratio of 1 wrasse to 50 salmon smolts for effective cleaning (Skiftesvik *et al.*, 2013). More recent papers report optimum wrasse:salmon ratio between 1:25 (Viking Fish Farms Ltd., 2013) and 1:150 (Gonzalez & de Boer, 2017). It may be that only some of the wrasse introduced into cages specialise in removing sea lice (Deady *et al.* 1995). A concentration on this mode of feeding therefore seems to be a matter of choice, or perhaps a learned response by individual fish.

During periods when sea lice are not abundant supplemental feeding of the wrasse is needed (Skiftesvik *et al.*, 2013). Because, when wrasse is first introduced to the cages, they may experience aggression from the salmon, the provision of hides for the wrasse to rest in is now common practice (Helland *et al.*, 2014).

Once added to the cages there are losses of wrasse due to escapes, predation and disease, so that additional cleaner fish need to be introduced to avoid the ratio of cleaners to salmon falling too far (Gonzalez & de Boer, 2017). Corksiding wrasse in particular appear to be vulnerable to bacterial infections (Skiftesvik *et al.*, 2014).

There is not much published data on loss rates of wrasse in salmon cages but a study run by Viking Fish Farms Ltd. (2013) reported between 7.3-8.6% in one year. Some of these mortalities resulted from swim bladder over-inflation when nets were raised quickly during sea lice chemical treatments, so would be avoidable with more careful husbandry.

According to Gonzalez & de Boer (2017) re-use of cleaner fish is not recommended between production cycles due to concerns about cross-contamination with respect to disease transfer. Thus, in Norway, most wrasse are released when the salmon are harvested, and subsequently replaced, thus keeping demand for wrasse high.

Concerns over transmission of disease in Ireland led to wrasse initially being harvested close to the farms (Darwall *et al.*, 1992), but this pattern was not adopted in Scotland and Norway where extensive transport of wrasse between areas has occurred (Skiftesvik *et*

al., 2014; Gonzalez & de Boer, 2017; Jansson *et al.*, 2017). Wrasse do not seem to act as vectors for diseases that affect salmon (Treasurer, 2012), but they can be infected by pathogens and parasites, such as *Paramoeba perurans*, the main causative agent of Ameobic Gill Disease (AGD), while in the salmon cages (Powell *et al.*, 2017).

Lumpsucker

Mortality of wrasse tends to become high below 4 °C, so they are not so suitable for use in northern Norway. Lumpfish are better adapted to cold temperatures (Gonzalez & de Boer, 2017).

Numerous recent papers have dealt with use of lumpsuckers as cleaners in salmon farms (Imsland *et al.*, 2014a; 2014b; Nytrø *et al.*, 2014; Imsland *et al.*, 2015; Imsland *et al.* 2016a; 2016b). Imsland *et al.* (2014a) first reported on the use of lumpfish for controlling sea lice in salmon cages, emphasising their toleration of lower water temperatures. Since then the use of lumpfish has accelerated dramatically (Powell *et al.*, 2017), so that in 2015 in Norway 64% of the 25 million cleaner fish used were lumpfish (meaning that over 11 million wrasse were also used).

7.2.3 Sources of 'cleaner fish'

Based on 48 million smolts put to sea in Scotland in 2014, and a target wrasse:salmon ratio of 1:50, the potential Scottish demand for wrasse could be at least a million per year, more if losses are replaced. There might be substitution by lumpsucker, but in either case there are only two sources: capture fisheries, or cultivation.

Wrasse fishery

Traditionally, wrasse has had little commercial value in the UK and elsewhere in northern Europe. Only the larger ballan and cuckoo wrasses were the subject of recreational angling (Darwall *et al.*, 1992). However, following the early reports that wrasse could be used to control sea lice an increasing number of farms in Norway, Scotland and Ireland took up their use (Deady *et al.*, 1995). There was a decline in interest between roughly 1998 and 2005 when effective chemical treatments became available, but recent concerns over residues and sea lice resistance have led to renewed demand for cleaner fish (Skiftesvik *et al.*, 2014). Thus, targeted fisheries for wrasse have become sufficiently lucrative to attract inshore fishers in the summer months. Box 7.1 provides an example for South West England.

In 2010 an estimated 10 million fish were used in Norway, being sourced from as far away as Sweden (Skiftesvik *et al.*, 2014). This rose to over 20 million in 2016 based on landings data (Gonzalez & de Boer, 2017). Ballan wrasse were recorded as the most heavily utilised species in Hardangerfjord, followed by goldsinny and corkwing, although Skiftesvik *et al.* (2014) questioned whether the species identification in the early records was correct. Since 2013 Norwegian data are considered more reliable, and recent returns suggest the species being utilised are corkwing, followed by goldsinny, with small numbers of ballan and rock cook (Gonzalez & de Boer, 2017).

Skiftesvik *et al.* (2014) also pointed out that there will be some mortality of wrasse between their capture and placing in the salmon cages. The actual harvest rates will thus

be higher than indicated by the figures from the fish-farms so that accurate landings data are a more reliable indicator of the true exploitation rate (Gonzalez & de Boer, 2017).

In Scotland wrasse catches since 2014 have been estimated at between 0.5 and 6 million fish. The reason for the large uncertainty is that landings are only recorded by weight, so assumptions must be made in converting these weights to numbers of fish. The reported biomass landed has increased to over 50 tonnes in 2016. The majority of the landings were recorded between Aug-Dec, which corresponds with when sea lice infestation tends to increase on the farms (Salama *et al.*, 2017). Official statistics report that 1,752,000 lumpsuckers and 1,000,000 wrasse were bought by the Scottish salmon farming industry in 2016 (Munro & Wallace, 2017).

Wrasse cultivation

Given the issues around harvesting of wrasse from the wild, there has been considerable focus on their artificial cultivation with a view to replacement of wild-sourced cleaner fish (Helland *et al.*, 2014). Such efforts have been encouraged by experiments which suggested that cultivated wrasse are as effective at removing lice from salmon as wild caught wrasse (Leclercq *et al.*, 2014; Skiftesvik *et al.*, 2014).

Ballan wrasse were first reared in Scotland in the early 2010s, and 650 were used in the sea trials funded by the Scottish Aquaculture Research Forum (SARF) (Viking Fish Farms Ltd., 2013). In Norway commercial rearing is currently restricted to ballan wrasse, and the volume produced remains low. Farmed wrasse represented less than 15% of the total 21 million cleaner fish used in Norway in 2016 (Gonzalez & de Boer, 2017). One reason is the cost of hatchery facilities and husbandry, given that the young wrasse can take up to 1.5 years to reach a size where they are useful as cleaners (Helland *et al.*, 2014).

Lumpsuckers

The majority of lumpsuckers used are now commercially reared. Compared with wrasse, lumpsuckers reach a useful size much faster (four months compared with 1.5 years for ballan wrasse), and are more suited to deployment in the colder northern Norwegian farms (Powell *et al.*, 2017). However, wild fish are still harvested to provide parental stock, and this may be putting pressure on wild populations. This is in addition to 'traditional' fishing pressure in countries including Norway, Iceland and Denmark, where lumpsuckers are harvested for its roe. Lumpfish is also frozen for export to China (Lorance *et al.*, 2015).

Full control of the lumpfish reproductive cycle in captivity would allow production of disease-free, certified fish (Powell *et al.*, 2017). Full captive rearing would also allow selective breeding for desirable traits (Powell *et al.*, 2017). Balanced against this, there is a risk that a proportion of fish introduced into sea cages as cleaners will inevitably escape, and could potentially interbreed with local stock. Where the source of the introduced fish is non-local, or fish have been bred for certain traits, such inter-breeding could cause problems in wild populations.

The trend noted above regarding preference of rearing lumpfish over wrasse also seems to be being mirrored in Scotland. Munro & Wallace (2017) reported that in 2016 a total of

262,000 lumpsucker were reared, versus 118,000 wrasse. Wrasse broodstock were reported to be all of domestic origin, but 3,200,000 lumpsucker ova were imported, although their origin was not published.

Box 7.1: Wrasse fishery in SW England

A 2016 report by the Devon & Severn Inshore Fisheries Conservation Authority (IFCA) describes the development of the wrasse fishery in the south west of England. This fishery appears to have started around spring 2015 using specially designed parlour pots that allow small wrasse to escape. Around 120–200 pots are deployed each day, catching 200-500 fish. The fish are stored in cages off the harbour until at least 6,000 fish have been caught. At this point they are collected by lorry for transport to salmon farms in Scotland. The fishery is quite lucrative with prices between £1.30 to £2.50 per wrasse. The stated demand is for up to 100,000 fish per year, potentially driving an expanding fishery in the south west.

The species which are collected for use in salmon farms are goldsinny, corkwing, rock cook and juvenile ballan wrasse. Although there is a long time-series of inshore fish abundances off Plymouth, but this is derived from trawl sampling on soft ground and wrasse do not appear in the resulting species listed in McHugh et al. (2011).

The Devon & Severn IFCA has used its flexible permit byelaw system to introduce measures to restrict the live wrasse fishery in and around the Plymouth area. The fishery is limited to a few months of the year, primarily between July and November within a designated area, and there is an official closed season during April, May and June to allow the fish to spawn. Minimum and maximum landing sizes have also been set to assist breeding. The IFCA has also introduced weekly landing returns, specific marking of the pots and strings, and on-board surveys of catches by IFCA officers. Centre for Environment, Fisheries and Aquaculture Science (CEFAS) is also carrying out fish welfare inspections, and the management of the fishery is supported by Natural England, CEFAS and DEFRA. A full review of the current management measures were to be undertaken in November 2017.

Sources: Davies, (2016). A review of wrasse ecology and fisheries interactions. Devon and Severn Inshore Fisheries Conservation Authority A review of wrasse ecology and fisheries interactions In, 25 p

- <http://fishingnews.co.uk/news/carefully-managed-sw-wrasse-fishery/>

7.2.4 Effects of wrasse fisheries

Direct effects

The main methods for collection of wrasse in the UK are baited pots, but fyke nets and beach seines have also been used in Norway (Bjordal, 1987; Halvorsen *et al.*, 2017). Pots are often baited with crushed mussel or crab (Darwall *et al.*, 1992). Generally, fish over 10 cm length are required due to the mesh sizes of salmon cages, so baited pots incorporate escape openings that ensure small fish are not retained (Devon & Severn Inshore Fisheries Conservation Authority).

Habitat impacts from wrasse pots are thought to be generally low (Devon & Severn Inshore Fisheries Conservation Authority), so concerns are mainly about the sustainability of harvested wrasse stocks themselves, and indirect ecological consequences of the removal of wrasse.

Pots will attract non-target organisms (by-catch), which would generally be returned to the sea close to the capture location. Given that the pots are usually fished in relatively shallow water, the survival rates of by-catch are likely to be high, although there are no published studies on this aspect (Halvorsen *et al.*, 2017).

Concerns about over-exploitation of wrasse as cleaner fish date back to the early 1990s (Darwall 1992). A recent Norwegian study by Halvorsen *et al.* (2017) showed declines in abundance of goldsinny and corkwing wrasse compared within and without MPAs.

The scale of removal of wrasse from the wild needs to be balanced against natural fluctuations in their abundance. In Norway, the abundance of wrasse appears to have increased in recent years, probably as a consequence of increased sea temperatures (Gonzalez & de Boer, 2017). In Scotland, Sayer *et al.* (1993) estimated the summer abundance of goldsinny as up to 4 per m² in its preferred habitat of shallow boulder scree. Apart from this, there does not appear to be any scientific monitoring of wrasse abundances in UK inshore waters. Indeed time-series sampling of inshore fish populations remains a gap in UK marine monitoring (Moffat *et al.*, 2011).

Indirect Effects

In addition to direct effects of fisheries on populations of wrasse and lumpsucker, there are indirect effects both on these populations and on the food web that depends on them:

- Cuckoo and ballan wrasse are hermaphroditic, with females changing into males as the fish grow. Large-scale removal of smaller fish could therefore reduce the abundance of potential males;
- In Norway a study of corkwing wrasse has shown regional sexual size differences (Halvorsen *et al.*, 2016). This has important implications for harvesting because the fishery is size selective and managed using a minimum landing size, which may need to be regionally adjusted;
- Gonzalez *et al.* (2016) showed genetically distinct sub-populations of corkwing wrasse exist along the Norwegian coast, and suggested that such genetic structuring could be disrupted by moving fish from one locale to another;

- Wrasse naturally predate invertebrates, such as urchins, which are grazers on seaweeds (Figueiredo *et al.*, 2005). Removal of wrasse might lead to a proliferation of grazers with subsequent negative impacts on the macroalgae;
- Wrasse are also prey for seabirds such as shags and cormorants (Steven, 1933) and for marine mammals such as grey seals, albeit as a relatively minor component in one seal diet study (Gosch *et al.*, 2014). Potential impacts of localised large-scale removal of wrasses on their predators are not known.

7.2.5 UK Management of the Inshore Fisheries

Fishing in UK waters currently comes under the EU Common Fisheries Policy (CFP). How fisheries will be managed post-Brexit is currently unclear. Nevertheless, even under the CFP, access to the inshore waters (out to 6 nautical miles) is limited to UK vessels. This inshore zone probably covers the areas where the majority of the wrasse fishing occurs, although there does not appear to be any published analysis of the spatial distribution of wrasse fishing effort in UK waters. The distribution of several of the wrasse species of interest does however extend into deeper waters (see Table 7.1).

In Scotland, the inshore fisheries are managed by Marine Scotland, with advice from Scottish Natural Heritage, Marine Scotland Science and other statutory consultees. The inshore fishing industry is represented through a number of Regional Inshore Fisheries Groups (RIFGs, formerly the Inshore Fisheries Groups [IFGs]). More details of management in other parts of the UK are given in Box 7.2.

Although wrasse are not listed as Priority Marine Features (PMF) in Scotland, the habitats they are frequently associated with are so designated, namely 'Kelp and seaweed communities on sublittoral sediment' and 'Kelp beds' (Tyler-Walters *et al.*, 2016). A Habitat Regulation Assessment (HRA) would help prevent a fishery impacting such protected habitats. In Scotland, fishers require a licence to capture wrasse for sale, with the licences obtained through Marine Scotland. Otherwise, because wrasse are not subject to the CFP, there is no management of the fishery and no formal stock assessments on which catch quotas can be based (Salama *et al.*, 2017).

Box 7.2: Management of wrasse and inshore fisheries elsewhere in the UK

In Wales inshore fisheries are controlled through various Welsh legislation and byelaws:

<http://gov.wales/topics/environmentcountryside/marineandfisheries/SeaFisheries/commercialfishing/compliance-monitoring/byelawsgeneral/?lang=en>

In England inshore fisheries are managed by Inshore Fisheries Conservation Agencies (IFCAs) who have byelaw powers for regulating the fisheries.

Across the UK, Habitat Regulation Assessments (HRAs) are required to be undertaken by the appropriate authority where fisheries activities may impact protected areas such as Special Areas of Conservation (SACs).

In England, impacts of any wrasse fisheries on SACs and Marine Conservation Zones (MCZs) need to be taken into account by the IFCAs when considering how the wrasse fisheries should be managed (Devon & Severn Inshore Fisheries Conservation Authority).

Wrasse are not managed under the Common Fisheries Policy so there are no formal stock assessments on which catch quotas can be based (Salama *et al.*, 2017). This has led to concerns from a number of NGOs about both the sustainability of the wrasse fisheries and their wider ecological impacts, as evidenced by articles such as:

<https://www.theguardian.com/environment/2017/jun/10/salmon-farmers-put-wild-wrasse-at-risk--sea-lice-scotland-anglers>;

<http://www.fishlegal.net/news.asp?section=1481§ionTitle=Latest+News+from+Fish+Legal&itemid=3909>;

<http://www.marinet.org.uk/devon-wildlife-trust-launches-wrasse-petition-and-says-new-measures-are-not-enough.html>.

There is developing local interest in wrasse. An objective to develop local management of the emerging creel fishery for wrasse was included in the Small Isles and Mull IFG management plan. However, wrasse are not mentioned in the current West Coast Regional Inshore Fisheries Group - Fisheries Management Plan (WCRIFG, 2017).

Managing fisheries for wild wrasse in a sustainable manner is not greatly different to any other fishery. The management measures that can be used include technical controls, such as minimum landings sizes, effort controls and catch quotas, as is demonstrated by the byelaws instituted by the Devon & Severn IFCA (Box 7.1). Such regulations have been steadily introduced in Norway since 2011, with a minimum landing size (MLS) and fishing closure in spring to protect spawning fish. New regulations were introduced in 2015 setting separate MLS for corkwing and ballan wrasse at 12 and 14 cm respectively. The closed fishing season has also been extended in some localities. In 2016, Norway

set a catch limit of 18 million fish (although this seems to have been exceeded), and recreational fishers have also been brought into the rules (Gonzalez & de Boer, 2017).

However, the generally poor understanding of wrasse biology and ecology, the lack of stock assessments combined with the relatively rapid development of the fisheries (Salama *et al.*, 2017) are making it challenging to develop effective management measures in the UK.

Transport of live captured fish

Stress during capture and transport may make the fish more susceptible to infections such as atypical *Aeromonas salmonicida*, whilst physical abrasion can cause skin loss and damage to fins and result in secondary *Flexibacter* infections. According to Viking Fish Farms Ltd. (2013) mortalities from these pathogens occur two to four weeks after stocking wrasse in pens, and the diseases may not be spotted when the fish are received. The handling, capture and transport of wrasse has been incorporated into the RSPCA Freedom Foods welfare standards for farmed salmon (2015 revision).

7.2.6 Diagnosis

Wrasse and lumpsucker appear to provide an effective means to control lice infestations, or, at least, to reduce the frequency of chemical treatment of infected salmon. The issue for this Section is that of the effects of the fishery for cleaners on the wild populations of goldsinny, corkwing, rock cook and juvenile ballan wrasse.

Although wrasse can be reared in hatcheries, production is at present limited to ballan wrasse and is inadequate to meet demand. In recent years, use of lumpsuckers as cleaner fish has overtaken wrasse, as lumpsuckers are easier to rear. This species may fulfil a large proportion of future demand although it is unclear if it can totally replace the use of wrasse.

Inshore fisheries management within the UK is devolved and the approach varies substantially from country to country. There do not seem to be any specific management measures relating to the wrasse fisheries in Scotland, apart from the need to possess a licence in order to sell live-caught wrasse.

In the absence of such measures, and the lack of scientific evidence about wrasse biology and population dynamics, there is concern about the fishery effects of the wrasse populations. This does not apply to lumpsucker populations.

7.2.7 Prognosis and mitigation

Expansion of salmon production (in both Scotland and Norway) will lead to an increase in demand for wild cleaner fish if (a) there is continuing or increasing use of cleaners as alternatives to chemical control of sea lice, and (b) cultivation is unable to keep up with demand for fish. Even if cultivation supplies demand, the requirement for broodstock may lead to continued fisheries. It has been estimated that annual demand in Norway by 2020 will be 40 million cleaner fish, and 10 million for the UK (Powell *et al.*, 2017). However, most of this is likely to be lumpfish (*Cyclopterus lumpus*), rather than wrasse, and the UK figure seems high given established cleaner:salmon ratios and the probable size of the Scottish industry in 2020.

There is uncertainty about how long the demand for wild-caught wrasse will continue. Although the salmon farming industry has stated that its requirements for cleaner fish will be met from hatcheries by 2019, this will be difficult, given expansion targets for salmon production and the low levels of production of farmed wrasse in Norway. A detailed evaluation of future demand for cleaner fish, and the prospects of fully meeting this demand using hatchery reared cleaner fish are recommended.

Should it seem that demand cannot be met from cultivation; a number of issues would need to be addressed. These include:

- *Accurate recording and reporting of wrasse catches by species.* At present wrasse caught in Scotland are recorded on FISH 1 forms, but only as weight and often using generic categories (Salama *et al.*, 2017). Such data are inadequate to understand how the fisheries are evolving and which species are being targeted;
- *Accurate recording of wrasse discard rates.* As farms only want top quality wrasse, damaged fish are likely to be discarded by fishers. Recording discard rates would not only allow better understanding of total catches (as opposed to reported landings), but would also allow identification of practices leading to poor quality and allow targeting of training in live fish handling and maintenance;
- *Improving biological data.* Data on growth and maturity rates of the target wrasse species is essential for setting appropriate minimum landing sizes. Biological information is also required for design and evaluation of local protected areas for wrasse. Studies on wrasse population genetics are needed to inform on the likely consequences of large-scale translocations of wrasse which at present are largely unknown;
- *Developing wrasse stock assessments.* Ultimately it may be necessary to set regional catch limits which would need to be under-pinned by stock assessments;
- *Developing a unified approach for recording traceability of cleaner fish.* At present in Scotland the information on the origins of cleaner fish appears limited. This makes it difficult to assess risks associated with such transplantations and imports;
- *Improving best-practice for fishers with regard to good handling and providing optimum environmental conditions for wrasse during capture and transport.* This promotes wrasse welfare and ensures that the wrasse reaching the farms are of good quality and less prone to infection.

Table 7.1: UK wrasse species

Species	Common name	Max. age (yr)	Description/ notes
<i>Labrus mixtus</i>	Cuckoo wrasse	20	West coasts UK and Ireland, slender looking, elongate head and snout. Females and immature males yellow, reddish orange; males blue head, sides blue, orange, yellow streaks. Size up to 35 cm, associated with reefs and algal zone of rocky shores, shallow sub-tidal to 180 m; eggs laid in nests generally in macroalgae beds.
<i>Labrus bergylta</i>	Ballan wrasse	29	West coasts UK and Ireland, deep bodied, snout not elongated. Variable coloration but generally green-brown. Size up to 60 cm, associated with reefs and algal zone of rocky shores, sub-tidal to 20 m, eggs laid in nests generally in macroalgae beds.
<i>Acantholabrus palloni</i>	Scale-rayed wrasse	Unknown	South-west UK coast but rare, slender bodied, coloration green-brown, size up to 30 cm, rocky habitats at depths 50-270 m.
<i>Centrolabrus exoletus</i>	Rock cook	6	West coasts UK and Ireland, deep-bodied but small wrasse, coloration green-brown or red on back, lighter on sides, yellowish belly, size up to 15 cm, associated with algae-covered reefs and eelgrass beds shallow sub-tidal to 25 m, eggs laid in nests generally in macroalgae beds.
<i>Coris julis</i>	Rainbow wrasse	7	South-west UK and Irish coasts but very rare, more common along warmer Atlantic coasts, slender bodied, coloration variable, size up to 25 cm, associated with rocks and sea-grass inter-tidal- 60 m.
<i>Ctenolabrus rupestris</i>	Goldsinny	8	West coasts UK and Ireland, slender bodied with pointed head, coloration brown or reddish-orange, dark spots on upper fins and tail, size up to 18 cm, associated with algae-covered reefs and eelgrass beds shallow sub-tidal to 50 m.
<i>Crenilabrus bailloni</i>	Baillon's wrasse	Unknown	South UK coast but rare, deep-bodies wrasse, coloration dull green –brown with dark spots on upper fin and in middle of tail area, size up to 20 cm, probably reef associated at depths between 1-50 m, rather little is known of its ecology, males guard egg nests.
<i>Symphodus (Crenilabrus) melops</i>	Corkwing wrasse	9	West coasts UK and Ireland, occasionally east coast UK, deep-bodied, coloration variable, dusky spots behind the eye and in front of the tail, size up to 25 cm, shallow inter-tidal down to 30 m, males guard nests.

Compiled from Devon & Severn Inshore Fisheries Conservation Authority, Wheeler (1978), Darwall *et al.* (1992), www.fishbase.org

8 DISCUSSION AND CONCLUSIONS

This Section concludes the report by briefly:

- Appraising methods used for assessing significance;
- Comparing this review's findings for Scotland with those from a risk analysis of the environmental impact of salmon farming in Norway;
- Assessing the potential of Recirculating Aquaculture Systems (RAS) and Adaptive Management for reducing environmental effects.

Both RAS and Adaptive Management are potential mitigation measures that are relevant to more than one of the issues considered in Sections 2 through 7.

8.1 Criteria for Significance

The purpose of this report was to document a review of available literature on the environmental impacts of salmon farming in Scotland, and the actions available to mitigate them. It has aimed to:

- i. Update the 'Review and Synthesis of the Environmental Impacts of Aquaculture' report commissioned by the Scottish Executive Central Research Unit in 2002;
- ii. Review and synthesise current scientific and grey literature on this subject;
- iii. Review current literature on approaches to mitigating identified environmental impacts.

Section 1 introduced the DPSIR chain, which analyses interactions between people and nature. The chain follows (Luiten, 1999) "*the linkages between the driving forces within society (D), the pressure on the environment (P), the state of the environment itself (S), the impact on people and nature (I), and the desirable response (R).*"

In this review *environment* has been understood as comprised of ecosystems, which have biological and physico-chemical components, and which include habitats and populations of species. *Effect* has been used to mean any change in the state of these components that can be related to a pressure associated with the activities of salmon farming; there are also effects due to other pressures, such as those due to fishing or climate change. A major part of the review has involved assessment of evidence for causal links between salmon farming pressures and observed changes in state. *Impact* has been used to mean an effect that has been evaluated in relation to the criteria set out in Section 1.

Scientific disciplines have criteria for deciding if a link has been demonstrated with adequate confidence. In some cases, experts have reported lack of adequate evidence to make such a decision; nevertheless, additional research should be able to provide an answer. Where matters grow more complex, however, is in assigning significance to the change in an environmental state associated with a demonstrated link to a pressure. This is because the criteria for assessing significance (i.e. for deciding if there has been an

Impact of concern) are set by society rather than science. This means that the same scientific evidence can be interpreted in different ways by different sectors within society.

Although an account of the legal framework for regulation of the environmental effects of salmon farming was outwith the scope of this review, assessments of significance have nevertheless been informed by current regulation. For example, quite drastic changes to seabed communities in the neighbourhood of fish farms are deemed tolerable in relation to ecosystem health, so long as they do not affect more than a small percentage of the loch bed. However, a similar effect would be deemed intolerable if it impacted a legally protected habitat. Conclusions about significance might be disputed by those who think different criteria should have been applied.

An overall assessment of the impact of salmon farming in Scotland depends not only on the criteria used to assess significance, but also on the weighting given to the various issues considered in Sections 2 – 7. Therefore, an overall diagnosis of the impact of salmon farming has not been attempted within this review.

8.2 Norwegian Assessment

A recent risk assessment of the environmental impact of salmon farming in Norway (Taranger *et al.*, 2015) encountered similar methodological issues. The assessment is summarised in Table 8.1, where the 'process of concern' corresponds to what this review has called 'pressure-state links'. The results in the 'findings' column were established by scientific investigation, but they were evaluated against 'endpoints of concern' related to five goals for the development of aquaculture set by the Norwegian government in 2009. These goals are reproduced in Table 8.2.

Table 8.1. Risk assessment of the environmental impact of Norwegian Atlantic salmon farming

Hazard	Process of concern	Endpoint of concern	Finding
Genetic interaction	Farmed escaped salmon successfully interbreed with wild salmon populations	Changes observed in the genetic characteristics of wild salmon populations	21 of the 34 wild salmon populations investigated indicated moderate to high risk for genetic introgression from farmed escaped salmon
Salmon lice	Salmon lice from fish farming affects wild fish	Salmon lice from fish farming significantly increase the mortality of wild salmonids	Of 109 stations investigated along the Norwegian coast for salmon lice infection, 27 indicated moderate-to-high likelihood of mortality for salmon smolts while 67 stations indicated moderate-to-high mortality of wild sea trout.
Viral diseases	Disease transmission from fish farming affects wild fish	Viral transmission from fish farming significantly increase the mortality of wild salmonids	Viral disease outbreaks in Norwegian salmon farming suggest extensive release of viruses in many areas. However, screening of wild salmonids revealed low to very low prevalence of the causal viruses
Discharges of organic material	Emissions of organic materials to the surrounding environment		
	(i) local effects	Unacceptable change in sediment chemistry and faunal communities in the production zone	From ca.500 yearly investigations of local organic loading under fish farms, only 2% of them displayed unacceptable conditions in 2013
	(ii) regional effects	Significant change in bottom communities beyond the production zone: i.e. regional impact	The risk of organic load beyond the production area of the farm is considered low
Discharges of nutrients	Emissions of nutrients to the surrounding environment		
	(i) local effects	Nutrients from fish farms results in local eutrophication	No data
	(ii) regional effects	Nutrients from fish farms results in regional eutrophication	The risk of eutrophication beyond the production area of the farm is considered low

source: Taranger *et al.*, 2015

Table 8.2. Primary goals for the future development of the Norwegian aquaculture industry as established by the Norwegian government in 2009

	Goal	Target
1	Disease	Disease in fish farming will not have a regulating effect on stocks of wild fish, and as many farmed fish as possible will grow to slaughter age with minimal use of medicines.
2	Genetic Interaction	Aquaculture will not contribute to permanent changes in the genetic characteristics of wild fish populations.
3	Pollution and Discharges	All fish farming locations in use will maintain an acceptable environmental state and will not have higher emissions of nutrient salts and organic materials than the receiving waters can tolerate.
4	Zoning	The aquaculture industry will have a location structure and zoning which reduces impact on the environment and the risk of infection.
5	Feed and Feed Resources	The aquaculture industry's needs for raw materials for feed will be met without overexploitation of wild marine resources.

source: Taranger *et al.*, 2015

Although the present review has addressed a broader range of issues, its conclusions relating to effects and impacts on wild salmon and of organic and nutrient waste, are broadly similar to those of the Norwegian study. This is perhaps unsurprising in the case of wild salmon; the lack of Scottish studies has meant that this review has drawn intensively on Norwegian research in making assessments on the impacts for this issue.

8.3 Recirculating Aquaculture Systems (RAS)

Recirculating Aquaculture Systems (RAS) might seem a logical solution to many of the environmental problems associated with salmon farming. By isolating fish from the natural environment, RAS provide security from diseases, infestations and predators and eliminate the risk of harming wild salmon. By retaining wastes, they prevent organic and nutrient impacts on the environment. Thus they address many of the issues considered in Sections 2 - 5 and 7.

Their potential commercial use in Scotland was reviewed by Murray *et al.* (2014), who identified their use in hatcheries and increasingly for salmon smolt production. Although freshwater RAS are widely used to rear freshwater fish (see also Bregnballe, 2015), there is less experience of salt water systems. Murray *et al.* (2014) recommended on both economic and technological grounds "*a cautious but positive approach towards the adoption of RAS technology*" for growing adult salmon in sea water.

Relevant to this review of environmental effects are energy costs and efficiency of removal of organic waste and nutrients. On the basis of Canadian experience (Table 3.8), the energy costs for pumping and treating large amounts of water are high, about ten times those of net-pen rearing. Unless this energy is supplied from renewable sources, RAS will add to emissions of carbon dioxide. As discussed in Section 3.4, the removal of organic waste results in solid material that needs to be disposed of, and 100% nutrient stripping from recirculated water seems unlikely. RAS wastes will therefore continue to make some demands on environmental assimilative capacity; however, there is uncertainty as to the extent to which this may occur.

Significant RAS will either be large floating structures or will occupy extensive land alongside lochs. At least one example of the former is in commercial development.³⁹ The pressures and consequent environmental effects generated by such systems have yet to be researched, and might include disturbance by moorings and effects on seabirds, as well as the organic waste and nutrient issues already mentioned. Finally, there is the possibility of chemical inputs both from external antifoulants and chemotherapeutants in outflows.

There are a few, comparatively small examples of land-based RAS used for growing adult salmon farming (Murray *et al.*, 2014), whereas there is increasing use of this technology in hatcheries and smolt-rearing units. An example is currently under construction at Barcaldine by Loch Creran.⁴⁰

A logical development would be that of salt-water RAS for on-growing smolts in order to reduce time spent in cages,⁴¹ and thus reduce lice and disease problems. However, it could also result in increased fluxes of organic waste and nutrients if sites are used more intensively.

It seems likely that the majority of salmon production in the sea will, for the foreseeable future, continue to take place in net-pens.

8.4 Adaptive Management

Adaptive Management has been suggested as a mitigation mechanism in several sections of this report, and is recommended by the FA as part of the Ecosystem Approach to Aquaculture (Aguilar- Manjarrez *et al.*, 2017). It is defined by Ehler (2014) as *"the incorporation of a formal learning process into management actions ... [i.e.] the integration of planning, implementation, monitoring and evaluation to provide a framework to systematically test assumptions, promote learning, and provide timely information for management decisions"*.

Adaptive Management already takes place to some extent at farms and within interactions between farms and regulators. However, there is a deficiency of integration. Monitoring, for example, is used to check observance of EQS or other CAR stipulations.

³⁹ <http://www.haugeaqua.com/Technology/>

⁴⁰ <https://www.fishfarmingexpert.com/news/builders-start-work-on-scottish-sea-farms-hatchery/>

⁴¹ <https://www.fishfarmingexpert.com/news/world-largest-land-based-salmon-farm-is-granted-license/>

However, beyond this it appears that monitoring data are not designed to feed into a learning process at farm or industry level, or to help distinguish whether changes in Scotland's marine ecosystems result from salmon farming or are due to other causes. Care must however be taken to ensure that co-operation between industry and regulators is not seen collusion, leading to public distrust of the latter.⁴²

At the national level, Adaptive Management of the salmon farming industry will require an enhanced approach to research, in which farmers, regulators, citizens and scientists work together to co-produce knowledge that can guide operational and planning decisions. Methods for such integration have been trialled, for example in relation to Integrated Coastal Zone Management in the EU research project SPICOSA project (Tett *et al.*, 2011b). Such trials went beyond simple 'knowledge exchange'. By including citizens in the knowledge-building process, they build on what has been learnt about gaining social consent for the mining industry (Prno, 2013).

⁴² Some evidence for this distrust was gained during a Case Study in Scotland by the EU project Aquaspace: see Strand and Bergh, eds. (2017).

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10 GLOSSARY

Adaptive Management: A systematic process for continually improving management policies and practices by learning from the outcomes of previously employed policies and practices.

Alga (plural, Algae): The earliest forms of plant life to have evolved on our planet are Cyanobacteria, once called 'blue-green algae' but now distinguished from other aquatic photosynthesisers because their cells contain no nucleus. An Alga is any simple photosynthetic organism with cells containing nuclei and Chloroplasts (the organelles of photosynthesis). Many are single-celled (and referred to as Micro-Algae), others are multicellular: these are the Macro-Algae, commonly known as brown, red and green seaweeds. 'Higher plants' evolved from green algae that adapted to conditions on land, although some re-adapted to aquatic conditions as sea-grass. The term Macrophyte includes both higher plants and seaweeds.

Allowable Zone of Effect (AZE): Spatial area around a fish farm defined by SEPA Regulation; AZEs are defined as *"the area (or volume) of sea bed or receiving water in which SEPA will allow some exceedance of a relevant Environmental Quality Standard (EQS)."* SEPA, 2005.

Anaerobic, Anoxic, Hypoxic: Most animals have a predominantly aerobic metabolism, which means that they require oxygen. A Hypoxic environment contains too little oxygen to support normal metabolism; an Anoxic environment contains no free oxygen. Only organisms with an Anaerobic metabolism can live under these conditions. Whereas aerobic metabolism typically uses oxygen to 'burn' carbohydrate, producing energy, carbon dioxide and water, anaerobic metabolism uses, for example, sulphate instead of oxygen and produces toxic hydrogen sulphide instead of water.

Anadromous: Anadromous fish migrate from the sea into fresh water bodies to spawn.

Anoxia: Areas of sea water, fresh water, or groundwater that are depleted of dissolved oxygen and are a more severe condition of hypoxia.

Amnesic Shellfish Poisoning (ASP): Illness caused by consumption of the marine biotoxin called domoic acid, which is produced naturally by marine diatoms. When accumulated in high concentrations by shellfish during filter feeding, domoic acid can then be passed on to birds, marine mammals and humans via consumption of the contaminated shellfish. In mammals, including humans, domoic acid acts as a neurotoxin, causing permanent short-term memory loss, brain damage, and death in severe cases

Assimilative Capacity: *"...the ability of the ecosystem in a water body to absorb anthropogenic inputs of substances without damaging the health of the ecosystem or its ability to provide goods and services."* (Tett *et al.*, 2011a) The Health of a marine ecosystem is societally defined by concepts such as 'Good Ecological Status' according to the Water Framework Directive or 'Good Environmental Status' according to the

Marine Strategy Framework Directive: Ecosystem Services are *"'exports' from ecosystems to human economies that bring benefits to the people in these economies"*

(Turner & Schafsma, 2014); examples are fish caught by a fishery, coastal protection by a salt marsh or seagrass meadow, and assimilative capacity itself.

Balance of Organisms: A state of dynamic equilibrium within a community of organisms in which genetic, species and ecosystem diversity remain relatively stable, subject to gradual changes through natural succession

Basin: A drainage basin or 'catchment area' is any area of land where rainfall collects and drains off into a common outlet, such as into a river, bay, loch or other body of water.

Benthos, Benthic: The Benthos (adjective: Benthic) is the biotic community living on or in the seabed; it includes many burrowing or tube living animals (bivalves, worms, prawns, brittlestars, etc.) plus smaller worms and crustaceans that live in the spaces between sediment particles, and protozoa and bacteria. Phytobenthos includes seaweeds and seagrasses which produce organic matter by photosynthesis, but they can only live where sufficient light reaches the sea-floor, and most of the food of the benthos is that produced by phytoplankton and arrives in the form of sinking matter: dead or dying phytoplankton, or the faeces of animals that have fed on phytoplankton.

Bioturbation: The disturbance of sediment layers by biological activity i.e. animals burrowing, crawling through the sediment etc.

Chalimus: Stage of the sea lice life cycle where the parasite, once attached to a suitable host feed for a period of time prior to moulting to the chalimus I stage. Sea lice continue their development through 3 additional chalimus stages each separated by a moult. A characteristic feature of all 4 chalimus stages is that they are physically attached to the host.

Chlorophyll: Refers to any of several related green pigments found in cyanobacteria and the chloroplasts of algae and plants. Chlorophyll is essential in photosynthesis, allowing plants to absorb energy from light.

Copepods: Group of small crustaceans found in the sea and nearly every freshwater habitat.

Cyanobacteria: Formerly called 'blue-green algae': see Alga

DAIN, DIN, DON: DAIN stands for 'Dissolved Available Inorganic Nitrogen', including ammonium and nitrate; these are more commonly aggregated as 'Dissolved Inorganic Nitrogen', DIN; however, the greatest amounts of nitrogen in seawater are as dissolved nitrogen gas, which is inorganic but not directly available to most micro-algae; DON stands for 'Dissolved organic Nitrogen', including urea, amino acids, and similar organic compounds.

DAIP: Stands for 'Dissolved Available Inorganic Phosphorus'; which is mainly phosphate; the acronym is perhaps not needed, as there is no free unavailable form of inorganic phosphorus (unlike nitrogen)

Deoxygenation: Chemical reaction where oxygen atoms are removed from a molecule.

Diatoms: Silicon-requiring micro-algae, with cells that often take pill-box or lozenge shapes with glassy (i.e. silica-strengthened) walls, often with spines and in many species

forming short chains of cells; conventionally held to be the 'good' members of the phytoplankton, giving rise to the spring bloom and providing much of the primary production used by marine food webs; however they include the genus *Pseudo-nitzschia*, capable of causing Amnesic Shellfish Poisoning, and blooms of spiny diatoms have been linked to damage to the gills of farmed fish

Dinoflagellate: Dinoflagellates are a large group of flagellate dinoflagellate that constitute the phylum Dinoflagellata. Most are marine plankton but they are common in freshwater habitats, as well. Their populations are distributed depending on temperature, salinity or depth. Many dinoflagellates are known to be photosynthetic, but a large fraction of these are in fact mixotrophic, combining photosynthesis with ingestion of prey (phagotrophy).

Diarrhetic Shellfish Poisoning (DSP): Causative agent is okadaic acid, which is produced naturally by marine phytoplankton. The symptoms include intense diarrhoea and severe abdominal pains, with nausea and vomiting also sometimes occurring. DSP and its symptoms usually set in within about half an hour of ingesting infected shellfish, and last for about one day.

Ecosystem: Is a community of living organisms in conjunction with the non-living components of their environment (air, water and mineral soil), interacting as a system.

Ecosystem Functioning: A general term that includes stocks of materials (e.g., carbon, water, mineral nutrients) and rates of processes involving fluxes of energy and matter between trophic levels and the environment.

Ecosystem Resilience: Is the capacity of an ecosystem to respond to a perturbation or disturbance by resisting damage and recovering quickly.

Ecosystem Services: Are the many and varied benefits that humans freely gain from the natural environment and from properly-functioning ecosystems. Such ecosystems include, for example; agroecosystems, forest ecosystems, grassland ecosystems and aquatic ecosystems. Ecosystem services are defined into 4 categories, Provisioning services (e.g. food, resources); Regulating services (e.g. waste decomposition, water purification); Cultural services (e.g. ecotourism, historical) and supporting services which assist in the delivery of the other 3 categories.

Environmental Quality Standard (EQS): Is a value, generally defined by regulation, which specifies the maximum permissible concentration of a potentially hazardous chemical in an environmental sample, generally of air or water.

Epiphytes: An epiphyte is an organism that grows on the surface of a plant, and which derives nutrients from the surrounding environment.

Eutrophication: Defined by the Urban Waste Water Treatment Directive (91/271/EEC, article 2) as "*... the enrichment of water by nutrients, especially compounds of nitrogen and/or phosphorus, causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned*". An expansion was drafted by a European expert group in 2009 (Ferreira *et al.*, 2011): "*Eutrophication is a process driven by*

enrichment of water by nutrients, especially compounds of nitrogen and/or phosphorus, leading to: increased growth, primary production and biomass of algae; changes in the balance of organisms; and water quality degradation. The consequences of eutrophication are undesirable if they appreciably degrade ecosystem health and/or the sustainable provision of goods and services."

Flagellate: Refers to any single-celled organisms (not a bacterium) with the organ of motility called a flagellum, a long thin motile external process used to move the organism through water.

Food Conversion Ratio (FCR): Term used in animal husbandry; FCR is a ratio or rate measuring of the efficiency with which the bodies of livestock convert animal feed into the desired output.

Forage Fisheries: Fisheries where the target species are those which are the prey of the important commercial species. Although there are some directed fisheries for these species, for the most part they are too small or otherwise of no interest.

Fjords: Refer to the definition provided for sea-lochs.

Fucoid: Seaweeds include the brown wracks of the sea-shore

Good Environmental Status: The main goal of the EU Marine Directive is to achieve Good Environmental Status of marine waters by 2020. The Directive defines GES as *"The environmental status of marine waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy and productive"*. GES means that the different uses made of the marine resources are conducted at a sustainable level, ensuring their continuity for future generations. Annex I of the Directive set out 11 qualitative descriptors of what the environment will look like when GES has been achieved:

- | | |
|----------------|---|
| Descriptor 1. | Biodiversity is maintained |
| Descriptor 2. | Non-indigenous species do not adversely alter the ecosystem |
| Descriptor 3. | The population of commercial fish species is healthy |
| Descriptor 4. | Elements of food webs ensure long-term abundance and reproduction |
| Descriptor 5. | Eutrophication is minimised |
| Descriptor 6. | The sea floor integrity ensures functioning of the ecosystem |
| Descriptor 7. | Permanent alteration of hydrographical conditions does not adversely affect the ecosystem |
| Descriptor 8. | Concentrations of contaminants give no effects |
| Descriptor 9. | Contaminants in seafood are below safe levels |
| Descriptor 10. | Marine litter does not cause harm |
| Descriptor 11. | Introduction of energy (including underwater noise) does not adversely affect the ecosystem |

HA and HAB: stands for 'Harmful Algae' and Harmful Algal Blooms'. A rapid increase or accumulation in the population of algae in freshwater or marine water systems, which causes negative impacts to other organisms via production of natural toxins, mechanical damage to other organisms, or by other means. HABs are often associated with large-scale marine mortality events and have been associated with various types of shellfish poisonings (ASP, DSP, PSP).

Heterotrophic: Mode of nutrition in which organisms depends on other organisms to survive. All animals and non-green plants are heterotrophic. Heterotrophic organisms have to acquire and take in all the organic substances they need to survive.

Hypoxia: Deficiency in the amount of oxygen within the environment or within biological tissues.

Integrated Multitrophic Aquaculture (IMTA): Integrated Multi-Trophic Aquaculture, the synergistic growing of different kinds of cultivated organisms together. In the present case it describes systems in which seaweeds are grown in the same water-bodies as salmon-farms, to absorb some of the nutrients, and mussels or similar shellfish cultivated to remove some of the phytoplankton produced with these nutrients.

Lipid: Substance of biological origin that is soluble in non-polar solvents. It comprises of a group of molecules that include fats, waxes, and sterols amongst others. Although the term "lipid" is sometimes used as a synonym for fats, fats are a subgroup of lipids called triglycerides. Lipids also encompass molecules such as fatty acids and their derivatives. Although humans and other mammals use various biosynthetic pathways both to break down and to synthesize lipids, some essential lipids cannot be made this way and must be obtained from the diet.

Locational Guidelines: Introduced to facilitate the transfer of authorisation to permit marine fish farm developments from the Crown Estate (CEC) to Scottish local authorities following the announcement in 1997 that. The purpose of the Locational Guidelines was to facilitate this transfer by providing guidance to local authorities, other regulatory bodies and the industry on the future location of marine fish farms.

Macrobenthic, Macrobenthos: Classification of marine benthic organisms defined by body size, visible to the naked eye. Depending on classification scheme, it may refer to all organisms larger to 1mm, or 0.5 mm.

Macrophyte: Translates as 'large plant'. It is used of aquatic photosynthetic organisms that are large enough to be seen with the naked eye. In the present case these are seaweeds (macro-algae) and sea-grasses. The former include brown, red and green algae, which are seen by taxonomists as different from each other as they are from Animals and Fungi. Sea-grasses are true plants: indeed they are monocotyledons, like terrestrial grasses, but within this category they are only distantly related to those grasses. Some call them eel-grass.

Marine Spatial Planning (MSP): Is a process that brings together multiple users of the ocean – including energy, industry, government, conservation and recreation – to make informed and coordinated decisions about how to use marine resources sustainably.

Maximum Residue Limit (MRL): The maximum concentration of residue accepted by the European Union (EU) in a food product obtained from an animal that has received a veterinary medicine or that has been exposed to a biocidal product for use in animal husbandry.

Mesozooplankton: Middle-sized animal Plankton.

Micro-algae: Single celled Algae,

Mixotroph (-ic, -y) or Myxotroph (-ic, -y): An organism that can use particulate or dissolved organic matter (POM or DOM) as a source of energy and nutrients, whilst retaining the ability to photosynthesise. In the case of marine pelagic mixotrophs the POM might be non-living, or in the form of bacteria or other algae or protozoa. A familiar example of a mixotroph is a sundew, a small plant growing in nutrient-poor boggy soils that trap insects as a source of nitrogen. Mixotrophic is the adjective, mixotrophy refers to the mode of nutrition. Given the derivation from (classical Greek), the terms are sometimes spelt myxotroph.

Morbidity: Refers to the condition of being diseased and the rate of disease in a population.

Nutrients: Defined by the Urban Waste Water Treatment Directive as "... especially compounds of nitrogen and/or phosphorus, [capable of] causing an accelerated growth of algae and higher forms of plant life"; the main compounds are dissolved and ionic, i.e. nitrate (NO_3^-), ammonium (NH_4^+) and phosphate (PO_4^{3-}). In solid form they correspond to compounds such as ammonium nitrate or calcium phosphate in artificial fertiliser. The elements nitrogen (N) and phosphorus (P) are essential components of living matter, but are often in short supply in the environment in forms that can be assimilated; it is because of this that their enrichment can stimulate plant or algal growth. Aquatic ecosystems tend towards a ratio of 16 atoms of (available) nitrogen to one atom of (available) phosphorus; disturbances to this ratio may lead to disturbances to the 'balance of organisms' (Tett, Hydes & Sanders, 2003). The element silicon (Si), usually in the form of dissolved silica, is an essential nutrient for the growth of the type of phytoplankton called Diatoms, which use it to strengthen their cell walls, which are characteristic of temperate coastal seas during much of the year, and which provide much of the input to marine food webs. Increase in N relative to Si may stimulate other kinds of phytoplankton, with undesirable consequences for the food webs.

Oligotrophic: Refers to waters that are literally those poor in food for fish, people etc. The reason for this is great scarcity of nutrients for phytoplankton and their production of organic matter subsequently used in marine food webs.

OSPAR: The mechanism by which 15 Governments and the EU cooperate to protect the marine environment of the North-East Atlantic; OSPAR is so named because of the original Oslo and Paris Conventions ("OS" for Oslo and "PAR" for Paris). It has for several decades co-ordinated member states in a 'Strategy to Combat Eutrophication' in the seas and coastal waters of N-W Europe.

Oxic: (of a process or environment) in which oxygen is involved or present.

Phytobenthos: The community of photosynthetic organisms living on the seabed, within the reach of light penetrating from the sea-surface. It includes seaweeds and seagrasses (see Macrophytes) and single-celled micro-algae.

Plankton, Phyto- and Zoo-: The (mostly small) 'plants' and 'animals' of the sea, found most abundantly in its illuminated upper waters and unable to swim against currents. Strictly, the term Plankton applies to the community of organisms, while Plankter denotes an individual or a species. The Phytoplankton consists of micro-algae such as diatoms and dinoflagellates and photosynthetic blue-green bacteria, all of which are functionally plants (in that they photosynthesise with the aid of the green pigment chlorophyll) but most of which unrelated to the taxonomic entity called 'Plants' which includes ferns, grasses and trees. The exceptions are green micro-algae, the group from which the land plants evolved, and the blue-green bacteria, which gave rise, through symbiosis, to the chloroplasts (containing chlorophyll) found in all algae and Plants. The Zooplankton are notionally animal, in the functional sense of being unable to photosynthesise, and some are taxonomically animal, in that they are multicellular creatures (from jellyfish to small crustaceans) with muscles and a nervous system. However, the functional grouping also includes many single-celled creatures, the Protozoa, which (it is becoming increasingly apparent) are often the main feeders on micro-algae. The term Mesozooplankton (middle-sized zooplankton) is used here to refer to the small animal section of the zooplankton, i.e. excluding both the smaller Protozoa and the larger jellyfish.

Phototrophic: Using light energy to obtain a source of organic carbon, usually from DIC, also DOC of photosynthesis

Phytoplankton: see Plankton.

Pressure: A result of a driver-initiated mechanism (human activity/natural process) causing an effect on any part of an ecosystem that may alter the environmental state.

Priority Marine Feature (PMF): A list of 81 marine features that represent habitats and species of conservation concern that are considered important components of the biodiversity of Scottish seas.

Protected Habitat: A habitat which is forbidden by law to harm or destroy.

Protected Species: A species of animal or plant which is forbidden by law to harm or destroy.

Protozoa: Biological classification of organisms; mostly used informally to designate single-celled, non-photosynthetic protists, such as the ciliates, amoebae and flagellates.

Paralytic Shellfish Poisoning (PSP): Caused by consumption of shellfish in which neurotoxins (principally saxitoxin) have accumulated in high levels. The toxins are produced naturally by marine phytoplankton. Symptoms include nausea, vomiting, diarrhoea, abdominal pain, tingling or burning lips, gums, tongue, face, neck, arms, legs, and toes. Shortness of breath, dry mouth, a choking feeling, confused or slurred speech, and loss of coordination are also possible. PSP can be fatal in extreme cases.

Recirculating Aquaculture Systems (RAS): Are used in home aquaria and for fish production where water exchange is limited and the use of biofiltration is required to

reduce ammonia toxicity. Other types of filtration and environmental control are often also necessary to maintain clean water and provide a suitable habitat for fish.

Seagrass: Flowering plants (angiosperms) that grow in marine, fully saline environments. They grow in sheltered waters such as inlets, bays, estuaries and saltwater lagoons, and have long thin leaves. Seagrass beds are regarded as Priority Marine Features in Scottish Waters.

Sea-Lochs (Fjords): Glacially over-deepened river valleys now flooded by the sea; characteristically long and thin, with most freshwater arriving near the heads, they include surprisingly deep basins partly isolated from the sea by a shallow entrance sill. This sill may result in stagnation of basin deep water for weeks or months; the upper layers of sea-lochs, however, usually exchange vigorously with the sea as a result of tidal flows and a fresh-water driven circulation. Many Scottish Firths (such as those of Clyde and Lorn) are also fjords, but have more complex circulations because of their width.

The Scottish Environment Protection Agency (SEPA): A non-departmental public body accountable to Scottish ministers, and one of four main consultees for marine aquaculture planning applications (Anonymous, 2010); in particular, it applies the Controlled Activities Regulations to licence and monitor aquaculture activities (<https://www.sepa.org.uk/environment/water/aquaculture/>).

Simpson's Evenness: This is a measure of the evenness of the abundance distribution of different taxa within an assemblage.

Smolts: A young salmon (or trout) after the parr stage, when it becomes silvery and migrates to the sea for the first time.

Scottish Natural Heritage (SNH): A non-departmental public body accountable to Scottish ministers; it "... promotes, cares for and improves Scotland's nature and landscapes" <https://www.snh.scot/about-snh>; it is one of four main consultees for marine aquaculture planning applications (Anonymous, 2010), its main role being to protect biodiversity, especially in relation to species and habitats identified as of conservation value.

State: The actual condition of the ecosystem and its components established in a certain area at a specific time frame, that can be quantitatively-qualitatively described based on physical (e.g. temperature, light), biological (e.g. genetic-, species-, community- habitat levels), and chemical (e.g. nitrogen level, atmospheric gas concentration) characteristics.

Water Framework Directive (WFD): Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy, adopted on October 23rd 2000. It is a European Union directive which commits European Union member states to achieve good qualitative and quantitative status of all water bodies.

Zooplankton: see Plankton