FISH FARMING IN SCOTLAND

OPTIMISING ITS CONTRIBUTION TO CLIMATE AND ENVIRONMENTAL POLICIES

Amy McGoohan
Global Academy of Agriculture and Food Security

With Joyce Tait, Alan Raybould, Stuart Parris and Kim Hammond

Innogen Institute

Funded by The Open University in Scotland.
17th August 2021

Cite as:

McGoohan, A., Tait, J., Raybould, A., Parris, S. & Hammond, K. (2021) Fish farming in Scotland: Optimising its contribution to climate and environmental policies.
https://www.innogen.ac.uk/media/304

Contents

Acronym List

AD - Anaerobic Digestion
BSF – Black soldier fly
CED – Cumulative Energy Demand
CW – Carcass Weight
DHA - docosahexaenoic acid
EPA – eicosapentaenoic acid
EU – European Union
GHG – Greenhouse Gasses
GVA – Gross Value Add
GWP – Global Warming Potential
HAB – Harmful Algae Bloom
LCA – Life Cycle Assessment
MSY – Maximum Sustainable Yield
RAS – Recirculating Aquaculture System
SCP – single celled protein
SDG - Sustainable Development Goals
SEPA – Scottish Environmental Protection Agency
SSF – Scottish Sea Farms
UK – United Kingdom
UN – United Nations
USD – United States Dollar

Glossary

Aquaculture	The farming of aquatic organisms which by definition of farming implies some form of intervention in the rearing process to enhance production and also implies individual or corporate ownership of the stock being cultivated.
Capture Fisheries	Commercial harvesting of naturally occurring living resources in both marine and freshwater environments.
Fish/seafood	Finned fish, crustaceans, molluscs and other aquatic animals, excluding aquatic mammals, reptiles, and aquatic plants
Global Warming Potential (GWP)	A measure of the amount of heat absorbed by any greenhouse gas in the atmosphere, as a multiple of the heat that would be absorbed by the same mass of $CO_{2.}$ This is expressed in carbon dioxide equivalents (CO_2-eq) (IPCC, 2018).
Maximum Sustainable Yield (fish stocks)	A theoretical concept which determines the maximum potential annual catch (numbers or mass) that can be removed from a fish stock over a given time period which ensures the stock remains at a level producing maximum growth.
Reduction fisheries	Reduction fisheries are specific wild caught fisheries that catch fish to process into fishmeal or fish oil. They target mainly pelagic species such as anchovies and sardines.

Executive Summary

Aquaculture is a rapidly growing contributor to Scotland's food-related economy, particularly the circular bio-economy that will be more environmentally, economically and societally sustainable. This policy report, funded by the Open University Scotland, demonstrates the role of innovative technologies in contributing to this improved sustainability of aquaculture in Scotland, meeting key government policies on Net Zero carbon emissions, the circular economy, zero waste, marine biodiversity, and improving the nutritional quality of the nation's diet. Where relevant we draw attention to the interactions between meeting climate change targets and contributing to biodiversity targets.

Globally, wild-capture fisheries have little capacity to expand without risking a collapse in fish stocks and seriously damaging marine biodiversity. The capacity of seafood to meet the world's increasing demand for protein will therefore need to come from farmed sources. This highlights the importance of being able sustainably to increase the production of protein foods based on aquaculture, and the role of innovative technologies in meeting that need.

The background research used information from published literature and reports, and from industry and policy contacts, and the report focuses particularly on innovation in fish feed development, fish farming systems, fish processing, and waste and by-product management. It also considers needs for future developments in life cycle analysis (LCA) and animal health and welfare. Given the complexity of the underlying systems, and the limited development and lack of standardisation in greenhouse gas accounting methods, a quantitative comparative analysis of the innovations considered is not yet possible. However, it is possible to judge the relative potential contributions of different innovations to overall climate change and biodiversity targets, as an indication of productive areas for innovation support and for further development.

Innovations and their contributions

The contributions of innovations to sustainable food production will be additional to the baseline climate-change benefits of moving from red meat to seafood-based protein in people's diets. On average, global aquaculture production has significantly lower GHG emissions per kg of edible product (carcass weight): beef production globally averages 45kg CO_2-eq/kg compared to average global aquaculture production at around 5kg CO_2-eq/kg. The potential benefits from the innovations described here would be additional to these baseline numbers, with variation depending on the local context. For example, beef and sheep production in Scotland is already more sustainable than in many other regions of the world and is making progress in further reducing greenhouse gas emissions from those sectors.

Innovation in aqua-feed production

Aqua-feed accounts for over 90% of fish-farm gate GHG emissions and, at 40-75% of total production cost, it is the most expensive component of aquaculture production. Innovation in feed production has the greatest opportunity to contribute to fish farming's climate change mitigation and to improving biodiversity-related impacts. Today's aquafeed has shifted from its previous reliance on fishmeal and fish oil from wild capture fisheries, replacing this with vegetable ingredients such as soya meal and rapeseed oil, so that Scottish fish diets now contain roughly 50% plant based ingredients (contributing 73% of GHG emissions from feed) and roughly 46% marine based ingredients (contributing 24% GHG emissions from feed). Both these feed sources, agricultural land-based and marine, raise biodiversity challenges and today's ingredients have also resulted in a reduction in the omega-3 fatty acid content of farmed fish of around 50% between

2006 and 2015. However, the Scottish salmon industry has retained a higher marine ingredient content in its feed compared to other regions, motivated by the high quality standards of Scottish salmon. The following locally produced innovative sources of protein feedstock will reduce the biodiversity impacts of wild-caught fish ingredients, the climate change impacts of agricultural production and transport, and the biodiversity impacts of plant based ingredients.

Micro-algae

Globally around 16 million tons of fish are captured to produce fish oil and fish meal ingredients for feed, and micro-algae are already being used as a source of both protein and omega-3 oils. One tonne of algae-based oil is estimated to save up to 30 tonnes of wild fish and the use of these oils is estimated to deliver reductions ranging from 45% to 95% in global warming potential of aquafeed. Production and use of algal aquafeed are currently limited by scale-up challenges and cost but these are expected to be resolved soon.

Whisky by-products (pot ale and spent wash) are used as a source of feedstock for algal fermentation in Scotland, contributing to the circular bioeconomy. They could provide enough ingredients to meet the current protein demand in feed for the aquaculture industry, as well as supply future demand from industry growth. However, there will also be demands on this by-product from other industry sectors with circular economy ambitions.

Insect meal

In trials, insect meal from black soldier fly (BSF) larvae has replaced 100% of fishmeal in Atlantic salmon diets, with no difference in nutritional profile, growth rate or feed conversion ratio. They have a low biodiversity impact and energy demand, using no arable land or wild fish stocks and with reduced water use. Insects have negligible levels of omega-3 oils and could substitute for fish meal and vegetable meal, but not the oil-based component of the feed. The food source for the larvae is non-domestic food waste, avoiding competition with human food sources. If only 10% of available by-product streams is redirected to BSF farming it could produce 2.7kt of insect meal for Scotland's salmon farming industry along with an increased economic value. There would be an additional 10% of carbon savings, compared to anaerobic digestion of the waste, saving 69 kg CO_2eq/tonne of input. Using low-grade waste heat to fuel the process, the carbon savings from BSF farming could be increased to 153kg CO_2eq/tonne of input with further savings from future decarbonisation of the electricity grid.

Single celled protein (SCP)

Micro-algae, yeast, bacteria and fungi are highly productive and can be grown using a variety of feedstocks with a focus recently on the use of waste residues and by-products. This would support a more circular economy, potentially reduce the carbon footprint and increase the overall environmental performance of feed production systems.

- Microorganisms are being used to convert methane gas to a product with 71% protein and 9% fat and feeding trials have shown increased growth and improved feed efficiency. As for the other aquafeed innovations, this would reduce the amount of land required compared to soybean meal (1692 km^2 required to produce 40,000 tonnes of usable protein from soy compared to 0.04 km^2 for SCP), along with 77–98% less water needed compared to soy and wheat production (US data). Compared to the USA, the efficiency of the UK electricity grid would amplify the climate change benefits from adoption of SCP and other related aquafeed

inputs and if 100% biogas from waste streams was used to produce the protein, the carbon footprint could be reduced from 5819 kg CO_2eq/tonne to 2274 kg CO_2eq/tonne.
- Micro-organisms are also being used to metabolise CO_2 (a power station by-product) and hydrogen to produce SCP with a comparable nutritional profile to fishmeal with a claimed reduction in carbon footprint of 25%.

New types of production system.

New production systems are being designed to increase production capacity, reduce environmental impacts, meet planning-related challenges, and increase overall control of production systems. There are concerns about the increased energy demand and potentially higher carbon footprint of these technologically advanced systems but some of these could be addressed by using renewable energy sources and advances in decarbonising the electricity grid will also improve their sustainability. There is a lack of LCA-related and other information on these production methods making it difficult to judge the real benefits from technological improvements and to compare different systems.

Offshore high energy systems

These systems could increase the production capacity of fish farming and reduce some sources of environmental concern about current production methods. There are technical challenges in locating farms offshore, and risks related to workforce health and safety but there would also be benefits to fish health, reduced environmental impacts from waste, and scope for the industry to develop higher capacity sites. Cages are 28,000m^3 -125,000m^3 in size and have been designed to alleviate animal health issues caused by sea lice and algal blooms, and to incorporate waste capture technologies. Embedded renewable energy solutions would improve GWP of these facilities. These sites also require smolts to be larger and more robust to withstand the harsher environment, requiring new arrangements to increase the growth size of smolts before transfer to off-shore systems. New inshore closed and semi closed nursery systems and larger land based recirculating aquaculture systems are part of the solution to this issue.

Closed containment aquaculture systems

These systems can be used as nurseries or for salmon on-growing and can be placed in inshore waters or offshore. They benefit from the ability to control and filter the water supply entering the system, and pumping the water from deep levels removes the threat of introducing harmful algae and sea lice into the cages. Adopting closed containment sea pens for all smolt production in Scotland could enable the output from current sea based on-growing sites to be increased by 70%. These systems reduce energy consumption by 75%, increase the feed conversion ratio, and reduce fish mortalities to less than 0.5%.

Recirculating aquaculture systems

These closed containment systems are mainly used for freshwater aquaculture on land, acting as hatcheries and smolt growing systems for salmon. They have been used for many years and the technology is not novel, but there have been improvements in production capacity, smolt mortalities, energy systems, waste recovery, and water cleaning systems that will all contribute to climate change and biodiversity targets.

Food processing

Food processing innovations are also beginning to have an impact on the aquaculture environmental footprint. For example: reusable bulk bins for transport have been introduced with an estimated saving to date of 4,100 tonnes of carbon and considerable scope for expansion; and biodegradable packaging is being developed, based on chitin extracted from shell by-products from farmed crustaceans.

By-product and waste utilisation

Waste and by-product utilisation is an integral part of several of the innovations described, using by-products from other sectors as inputs to fish farming as part of a circular economy approach. There are additional circular economy opportunities using by-products from fish farming as inputs back into the fish farming value chain or beyond fish farming into other sectoral value chains (see Figure below).

- Organic particulates (uneaten fish food and faeces) from land-based RAS systems can be used as biofuel or fertiliser and innovative approaches to capture this resource are being developed for other production systems.
- Fish mortalities, which cannot be used in the human food chain, can be disposed of by incineration, rendering, in vessel composting, or anaerobic digestion at approved plants. The option to use fish oil as a replacement for diesel is being investigated and could contribute to a localised circular economy.
- By-products from food processing can be used to create food grade protein and omega-3 oils for terrestrial livestock feed, pet food and pharmaceuticals, further reducing the reliance on fish meal and fish oil from wild capture fisheries.

Biodiversity and sustainable development goals

A shift in diets from red meat to fish and shellfish consumption, along with adoption of some of the innovations described here, can contribute to sustainable production and consumption (Goal 12), including sufficient, healthy diets (Goals 2 and 3), economic growth and productive employment (Goal 8), fostering innovation (Goal 9), and combatting climate change (Goal 13). In the context of biodiversity, they contribute to sustainable use of marine and terrestrial ecosystems (Goals 14 and 15).

Conclusions

Potentially the greatest contribution to Net Zero and other policy targets will come from shifting a proportion of current diets from red meat, with its high contribution to GHG emissions, to finfish and shellfish consumption. Ensuring that growth in the seafood sector focuses on fish farming rather than wild fish capture, will have little impact on global warming potential but, if managed sustainably, it has the potential to be more beneficial to marine ecosystems and biodiversity. This report has explored how innovation in aquaculture sectors can contribute to meeting multiple government policies and objectives, including Net Zero, a circular economy, zero waste, marine and land biodiversity targets and UN Sustainable Development Goals.

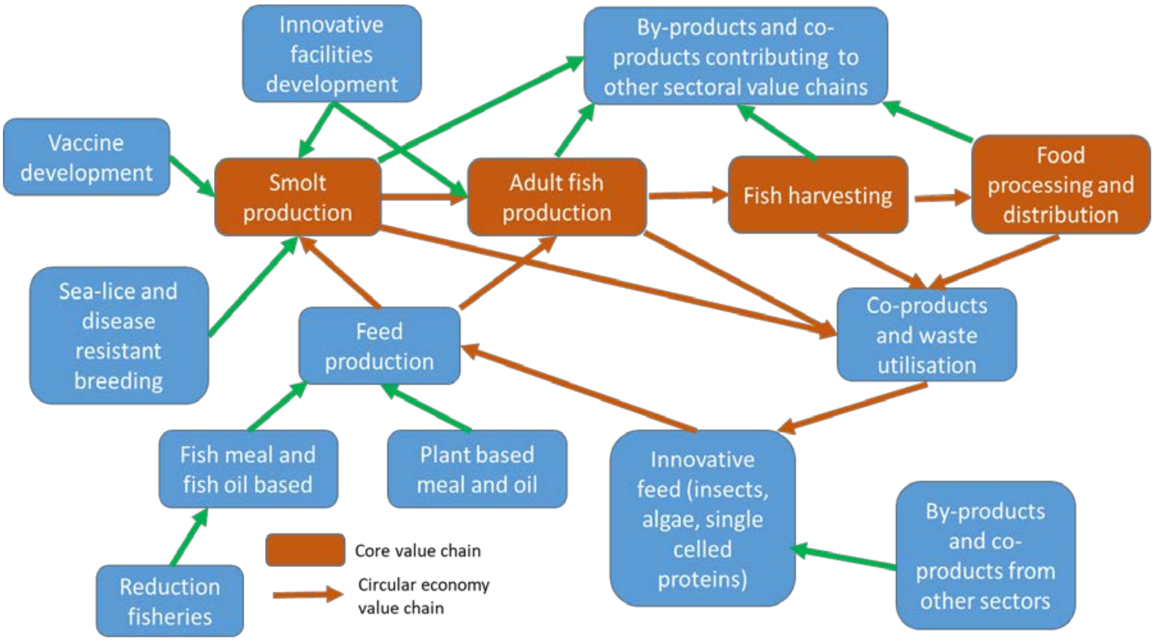
Aquaculture does present recognised environmental challenges involving GHG emissions and biodiversity impacts and continuing to address these issues, and ensuring that the most sustainable, effective and efficient adaptations are promoted, will be an important factor in gaining public acceptance and approval for the sector as a whole and for the roll-out of government policies. The innovative technologies discussed in this report could make significant contributions to these agendas, although there are trade-offs to be considered, for example, where an innovation may improve GHG emissions but have a negative impact on biodiversity or vice versa.

The innovations considered in this report all have a potential to contribute to the relevant policy goals, with varying degrees of impact.

- **Aqua-feed innovations** will have the biggest positive impact on both GHG emissions (Net Zero policies) and aquatic and land biodiversity (SDGs). They will also contribute to several circular economy value chains and zero waste agendas.
- **Innovative production systems** so far seem likely to have greater energy demands, and therefore GHG emissions, than those currently in use, although this could become less relevant as energy systems become less reliant on fossil fuel inputs. They will also contribute to reductions in the impact of pollutants and improvements in fish health, and will be necessary for the expected expansion of the aquaculture sector in Scotland.
- **Fish processing** is a key component of the aquaculture value chain and innovative developments are already contributing to a reduction in GHG emissions. This component of the value chain will also be an important contributor to the circular economy.
- **Waste and by-product management** will also make more modest contributions to reductions in GHG emissions and will be important contributors to several circular economy value chains.

Clearly, some innovations, considered in isolation, will have a greater contribution than others to climate change and biodiversity impacts, but this should not lead to a simplistic approach to prioritising policy initiatives and investment. A systemic approach, taking account of the entire value chain (see figure below) and the interactions among businesses and policies, will be needed to deliver the outcomes that are nationally optimal for Scotland and internationally competitive.

The circular economy value network and the role of innovative technologies for Scottish salmon farming



Recommendations

The policy role is not to pick winners, but to create a supportive innovation ecosystem so that potential winners are not unnecessarily killed off in the early stages of development.

This report helps to identify what needs to be done to fill the research, development and policy gaps that exist in the aquaculture sector and to put Scottish aquaculture on an optimal footing, balancing the sometimes-competing demands of different environmental goals and different sectoral interests. We recommend the following short-list of actions to deliver these outcomes.

1. More investment in the development of life cycle analysis tools for the aquaculture sector is needed, to judge the contributions of innovative technologies to different value chains and to support company investment decision making, and government policy development and implementation. This should cover both the development of effective methodologies and standards for their application to ensure comparability across different analyses.

2. At the national level, a systemic approach is needed, modelling the roles and contributions of the innovations discussed here, of the others that we were not able to include, and of new technologies as they emerge. Also, given the distributed nature of the industry, there are opportunities to build networks of smaller scale local recycling initiatives as contributions to the overall circular economy that is Scotland's ambition.

3. A systemic approach is also needed to understand the interactions between companies, innovators, investors, policy makers and regulators, stakeholders and consumers, that will underlie success or failure of innovations at all levels. The approach should focus on the options with the biggest potential gains and those where synergistic interactions between different innovation initiatives could facilitate development and multiply positive outcomes or minimise negative outcomes.

4. An essential part of this systemic approach will be better communication about innovative technologies and their potential contributions to national environmental, health and economic objectives, particularly in the context of the UN COP 26 meeting in November 2021. There is an important current story to be told about the improvements in sustainability profile that have already been made by Scottish aquaculture and it will be helpful in enabling future innovative developments for the sector if citizens and interested stakeholder groups are more aware of these achievements and of the coming opportunities presented by innovative technologies.

FISH FARMING IN SCOTLAND:
OPTIMISING ITS CONTRIBUTION TO CLIMATE AND ENVIRONMENTAL POLICIES

1. Background

This policy report was funded by the Open University Scotland as part of their contribution to policy engagement with the Scottish Government in the context of the UN COP26 meeting being held in Glasgow in November 2021.

A 2018 report commissioned by the Scottish Parliament Environment, Climate Change and Land Reform Committee (ECCLRC) concluded "There has been a lack of progress in addressing the environmental impacts of salmon farming since they were last highlighted (at the Scottish Parliament) in 2002" and "The Committee is deeply concerned that the development and growth of the sector is taking place without a full understanding of the environmental impacts" (RECC, 2018). This report can be seen as a preliminary contribution to addressing these issues.

It is based on information available in published literature and reports, and from industry and policy contacts. The research was conducted over a short period and with limited resources and the data quoted should be treated as indicative of a general picture, but in need of further confirmation. As well as the time limitations on our ability to cover the field in depth, they are subject to limitations in the development of life cycle analysis and other carbon accounting methodologies in this area.

The report aims to demonstrate (quantitatively where possible) the role of innovative technologies in contributing to the improved sustainability of fish farming in Scotland, meeting key government policies on Net Zero carbon emissions, the circular economy, zero waste and marine biodiversity. It is also relevant to future research needs in this area and to Scottish Government decision making on policies and other support for the aquaculture sector.

1.1 Seafood overview

Global fish production is increasing and was estimated to be approximately 179 million tonnes per year in 2018, worth 401 billion USD. Wild fish production from capture fisheries represents around 96 million tonnes of the total volume, however this production has remained relatively stagnant since the 1980s (**Figure 1**). In comparison, aquaculture production is currently around 82 million tonnes per year, worth 250 billion USD and production has increased significantly over the past 40 years, from contributing 7% of fish production annually to 46% (**Figure 1**). Over the past 60 years, global fish consumption has increased significantly at an average rate of 3.1% (1961-2017). This rate is faster than all other animal protein production and twice as fast as population growth for the same period. Per capita fish consumption globally has increased from 9kg in 1961 to 20.5kg in 2018 and fish consumption currently accounts for 17% of the global human intake of animal protein (FAO, 2020). This increase has been driven by increased consumption of seafood in developing countries, which is partly attributed to the increased globalisation of food systems, increased wealth, production and consumption of seafood across Asia. The predicted growth of the world's population to 9.7 billion people by 2050 will further increase the demand for fish for human diets (United Nations, 2019). It is essential that the increasing demand for fish consumption is achieved through sustainable fish production.

Globally the world's fish stocks are under pressure; 60% of stocks are fished to the maximum sustainable yield (MSY), 30% of stocks are overfished (biologically unsustainable) and 6% are under fished (**Figure 2**) (FAO, 2020). It is therefore sensible to assume that future increases in fish production will need to be met by sustainable aquaculture.

Figure 1 Global capture fisheries and aquaculture production (1950-2018) (FAO, 2020)

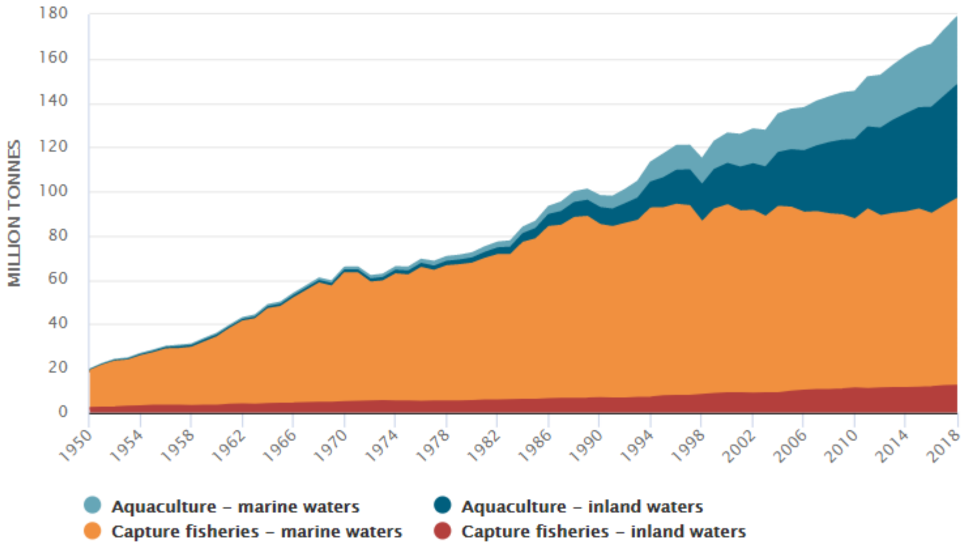
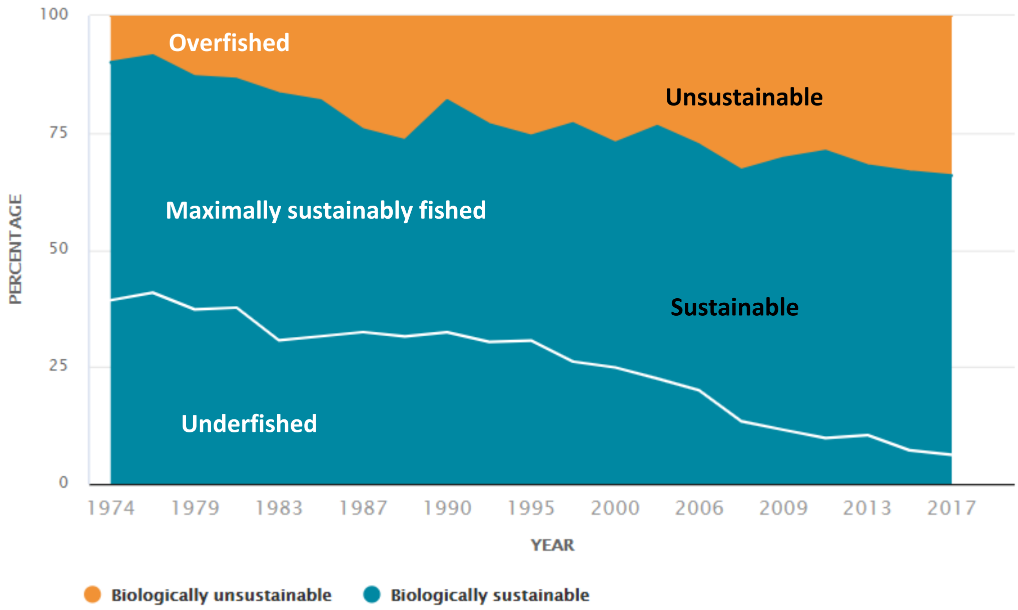


Figure 2 The global state of the world's marine fish stocks (1974-2017) (FAO, 2020)



The term sustainability is difficult to define. Tlusty and Thorsen (2017) outlined how sustainability can never be fully conceptualised as an end-point and instead it should be a process-driven journey with no set path and is actually a behaviour. Defining production as sustainable should therefore enable it to adapt to improvements and innovation in the future. In this report we envisage the concept as being based on the balance of the three pillars of sustainability, environmental, economic and social, as outlined by the United Nations (UN), defined as production which balances socio-economic benefits while maintaining environmental integrity, now and in the future (Tlusty et al, 2019). We focus on sustainable aquaculture in terms of production which is low in greenhouse gas (GHG) emissions while preserving natural resources and biodiversity. We also focus on the social importance of aquaculture as a food source, providing essential nutrients to the global population.

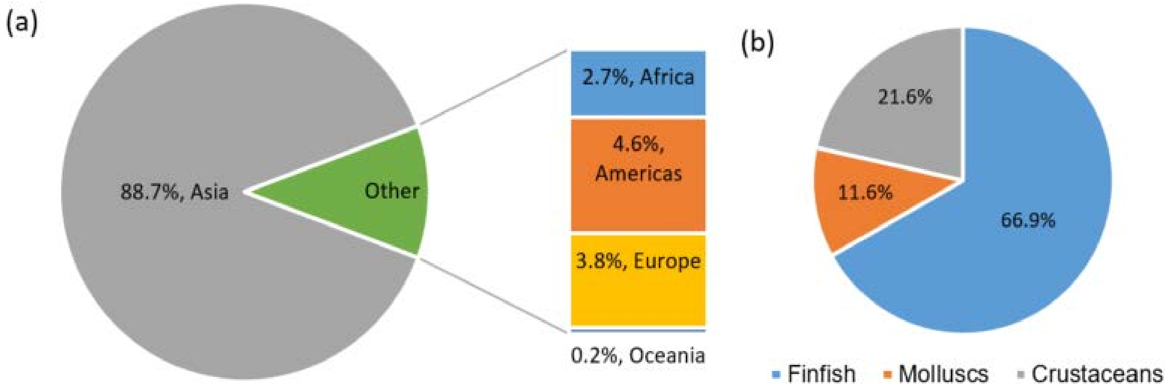
Aquaculture

Aquaculture production globally has grown by 527% over the past 30 years (1990-2018), dominated by Asia which contributed over 88% of global aquaculture production (**Figure 3a**). Of the three main farmed seafood species groups, production is dominated by finfish (e.g. salmon and carp) which accounts for around 67% of produced seafood followed by crustaceans (e.g. shrimp and crab) and molluscs (e.g. mussels and oysters) at 22% and 12% respectively **(Figure 3b)** (FAO, 2020).

Policy goals and targets

In 2015, the United Nations outlined the Paris Agreement with the aim to strengthen the global response to the threat of climate change. The agreement included a target to stop global warming by halting average global temperature rises to below 2°C and ideally below 1.5°C relative to pre-industrial levels. The 195 nations which signed the agreement also agreed to reduce their greenhouse gas (GHG) emissions, so that in the second half of the century the total GHG emissions from human activities is zero (UNFCC, 2015). Since then, several countries and international companies have outlined their own plans to achieve net zero targets. In 2019, the UK was the first country to put legislation in place to achieve the goal of net zero emissions by 2050 as recommended by the UK Committee on Climate Change (CCC, 2019a). Within this target a more ambitious target was set for Scotland, reflecting its greater capacity to reduce emissions to achieve net zero GHG emissions by 2045 and reduce its emissions by 75% by 2030 (CCC, 2019b). Net zero emissions are achieved when anthropogenic emissions of GHG to the atmosphere are balanced by the anthropogenic removals over a specific period (IPCC, 2018).

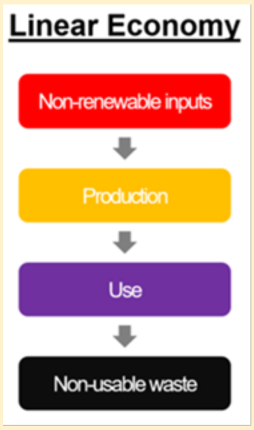
Figure 3 Global percentage of aquaculture production in 2018. (a) Percentage of total global aquaculture production by region (b) Percentage of global aquaculture production by species classification. (Data source FAO, 2020)

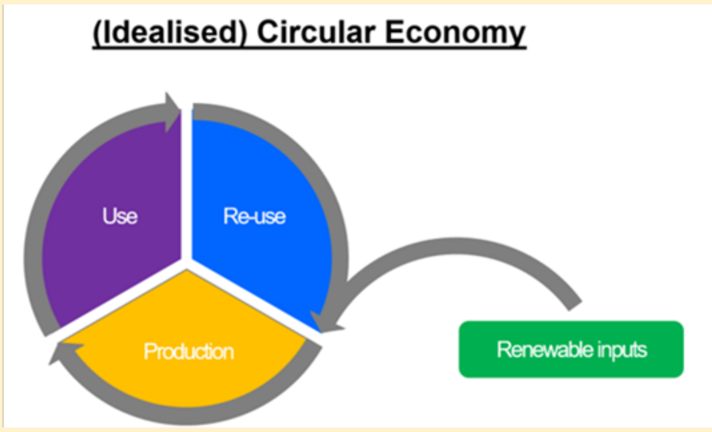


In quantifying emissions targets and policy outcomes, it is important to distinguish between carbon dioxide (CO_2) emissions and other GHGs (Rogelj et al, 2021). In this report we refer to Global Warming Potential (GWP), expressed as CO_2 equivalents (CO_2-eq). CO_2 is the principal anthropogenic GHG and is the main cause of global increased temperatures, remaining in the atmosphere for hundreds of years. It is the reference gas against which other GHGs are measured and therefore has a global warming potential (GWP) of 1 (IPCC, 2018). Other greenhouse gases are shorter lived and remain for years to decades in the atmosphere and some, for example methane, have a more powerful GWP than CO_2. The Paris agreement aims to reduce all GHG emissions, and

Box 1: What is the Circular Economy?

“A circular economy is based on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems.” (Eller MacArthur Foundation)





Diagrams adapted from https://www.government.nl/topics/circular-economy/from-a-linear-to-a-circular-economy

where emissions cannot be eliminated these should be balanced by removal of an equivalent quantity of CO_2 from the atmosphere. GWP (CO_2-eq) is used to measure this amount.

In order for Scotland to achieve its goal of net zero emissions the Scottish Government has also set targets to reduce waste, including plans to reduce food waste by 30% by 2030 and it is also looking to industry to innovate towards a circular economy (Box 1), which will cut waste, reduce emissions and preserve finite resources. A non-governmental organisation (Zero Waste Scotland) estimated that adopting a more circular economy in Scotland by 2050 could reduce carbon emissions by 11 million tonnes per year (Scottish Government, 2016).

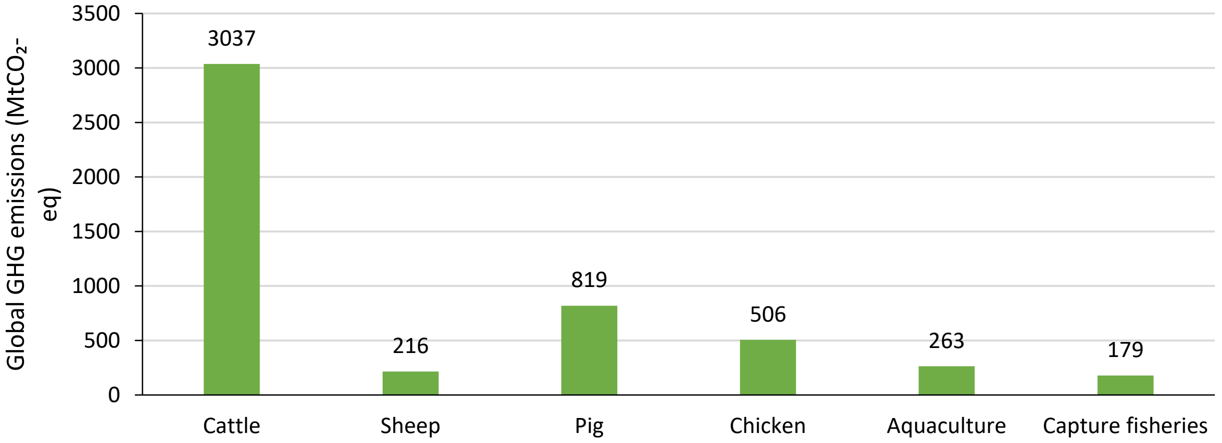
Agriculture is one of the leading contributors to GHG emissions globally, after energy production. A recent study assessed the global contribution of GHG emissions from seafood and compared this with alternative sources of protein based on livestock animal production (**Figure 4**). The study found that globally, aquaculture production contributed less to GHG emissions than beef, pork and chicken production (Macleod et al, 2020), although these data reflect the fact that seafood production worldwide is much lower than terrestrial livestock production. Capture fishery production has the lowest GHG contribution, but global fishery production cannot increase to meet the future protein demand of the world as it relies on fragile natural resources.

When we look at the specific quantity of emissions produced per kg edible product, on average global aquaculture production has significantly lower GHG emissions per kg of edible product (CW: carcass weight); beef production globally averages 45kg CO_2-eq/kg CW compared to average global aquaculture production at ~5kg CO_2-eq/kg CW (Macleod et al, 2020). This highlights the potential reduction in global GHG emissions achievable from a dietary shift that reduces beef consumption and increases seafood consumption, hence the importance of being able sustainably to increase aquaculture production. However, not all fish are similar in terms of carbon footprint, for example, trawler fishery products and farmed catfish and crustaceans can have particularly high carbon footprints (Hallström et al, 2019).

It is also important to consider the Sustainable Development Goals (SDGs) which were launched in 2015 by the United Nations (UN). Seventeen goals were established, split into 169 targets, based on a call to action to end poverty, protect the planet and ensure peace and prosperity to the global population by 2030 (United Nations, 2015).

The SDGs recognised the importance of considering the interlinked pillars of sustainability: society, the economy and the biosphere (the global ecological system) (Nash et al, 2020). The 17 SDGs are integrated in that they recognise that action from one will have an effect on others and therefore development must balance the three pillars of sustainability (United Nations, 2019).

Figure 4 Total global emissions contributed from seafood and terrestrial livestock meat production, from 2010/11 (Macleod et al, 2020; FAO, 2017; Parker et al, 2018).



Sustainable development of aquaculture has the potential to contribute to several of the SDGs, both directly and indirectly:

- **Goal 2**. End hunger, achieve food security and improved nutrition and promote sustainable agriculture.
- **Goal 3**. Ensure healthy lives and promote wellbeing for all at all ages.
- **Goal 8.** Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
- **Goal 9**. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
- **Goal 12**. Ensure sustainable consumption and production patterns.
- **Goal 13.** Take urgent action to combat climate change and its impacts.
- **Goal 14.** Conserve and sustainably use the oceans, seas and marine resources for sustainable development.
- **Goal 15.** Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.

To achieve these goals requires effective policy development and implementation at local, national and international levels. Where the UN SDGs are included in the national policy mix, policy makers could usefully focus on actions and developments that will guide progress towards achieving the SDGs, prevent adverse trade-offs, and work with, and influence, the desires and plans of the relevant industry sectors (Nash et al, 2020). When considering innovative technologies for the aquaculture industry and their ability to mitigate climate change and address sustainability policy objectives it is therefore important also to measure these against their contribution to SDGs.

2. Scottish aquaculture industry overview

The Scottish aquaculture industry has grown significantly over the past 40 years. It is estimated to support around 11,700 jobs in the Scottish economy and, in 2018, to have generated £885 million gross value added (GVA) (Scottish Government, 2020a). There are four main species produced around Scotland: Atlantic salmon, Rainbow trout, Blue mussel and Pacific oyster. Currently Atlantic salmon dominates Scottish aquaculture production (**Table 1)** and the industry supports over 9,000 jobs, being economically and socially important to rural highland and island communities (Scotland Food and Drink, 2016). Scottish aquaculture products are in high demand around the world due to their high quality production and the industry's rigorous standards for the environment, food safety and animal welfare.

The industry has ambitious growth plans to double the economic value of aquaculture by 2030, increasing finfish production to 400,000 tonnes and shellfish production to 21,000 tonnes per annum (Scotland Food and Drink, 2016). The industry is on its way to achieving this target for salmon. A preliminary target was set of 200,000 tonnes by 2020, and the industry achieved this by 2019, the highest recorded production of salmon in Scotland since aquaculture began (Marine Scotland Science, 2019a). The industry's growth needs to be sustainable in that it promotes increased environmental preservation, protects natural resources, provides high quality nutritious food and ensures that high standards of fish health and welfare are maintained. To achieve this the industry is investing heavily in innovations that can increase capacity while reducing environmental impacts such as new closed containment production systems and scoping for optimum aquaculture sites whether offshore or on land.

Table 1 Production volumes and economic value for the four main farmed aquatic species produced in Scotland and beef as a comparison. (Sources: for finfish, Marine Scotland Science (2019a); for shellfish (mussels and oysters), Marine Scotland Science (2019b); for beef Scottish Government (2020b); GVA data for aquatic species, Scottish Government (2020a); GVA for beef, Moxey (2016). *Rainbow trout includes all finfish production in Scotland that is not Atlantic salmon.)

	Atlantic salmon (*Salmo Salar*)	**Rainbow trout** (*Oncorhynchus mykiss*)	**Blue mussel** (*Mytilus edulis*)	**Pacific oyster** (*Crassostrea gigas*)	**Beef** (as comparison)
Production volume (tonnes)	203,881	7405	6699	369	185,000
GVA (£millions)	585	21*	10		452

2.1 Salmonid Production

The Scottish salmon industry has been very successful since its inception during the 1970s. It is currently the second largest producer of salmon in the EU and the third largest producer in the world (following Norway and Chile). The industry has a large export market, exporting to over 60 countries worldwide and is currently the UK's largest food export by value (Scotland Food and Drink, 2016; SSPO, 2021).

Atlantic salmon are anadromous fish which means they live the early stages of their life cycle in freshwater and spend the main growth phase in seawater. Once they reach maturity wild salmon would then naturally return to freshwater to reproduce. Salmon farming therefore occurs in both freshwater and seawater, and in Scotland this is predominantly carried out on the West Coast and across the Highlands and Islands of the country, where the topography of the seashore provides numerous sheltered lochs with reliable flows of cold, well oxygenated water, ideal for aquaculture. At the beginning of their life cycle, brood-stock for salmon are selected and then fertilised and the fertilised ova are then grown in freshwater hatcheries where they develop into fry, during which time they feed off their yolk sac. Fry then develop into parr which are moved to freshwater nurseries where they undergo smoltificication, a physiological process that adapts the fish to seawater. The smolts are then grown to the preferred size for transfer to seawater. Once at sea, the fish are produced in floating seawater pens which have large underwater nets enclosing the salmon. Generally, salmon will spend between 18-24 months at sea (Kenyon and Davies, 2018). The industry has been reducing the time salmon spend at sea by advancing their technology for optimum feeding and growth and more recently by increasing the size of smolts prior to seawater transfer. This trend in reducing salmon time at sea will most likely advance as new technologies and larger freshwater hatcheries are developed and this will help reduce the localised environmental issues surrounding open cage salmon farming (See Appendix A for overview of Scottish salmon sector).

The Salmon farming industry in Scotland has gone through a significant consolidation and approximately 95% of Scottish farmed salmon is now produced by a few large companies (SARF, 2019). This shift in industry structure, which has resulted in fewer small companies has been beneficial in increasing capital investment and standardising the industry.

2.2 Shellfish production

Production of shellfish in Scotland is predominantly based on the farming of Blue mussels and Pacific oysters. Native oysters and scallops are also produced but production volumes are low. There are currently 165 shellfish sites in operation around Scotland. Scotland produces a large amount of shellfish for the UK, and a significant amount is consumed locally through the service sector and value added products supplied to supermarkets. The estimated value of shellfish production is around £7.9 million (Marine Scotland Science, 2019b).

Blue mussel farming dominates the industry and production has increased by 72.3% between 2006 and 2015 (Marine Scotland, 2017). Mussels are mainly cultivated on suspended rope systems in sheltered coastal areas, where wild mussel spat is settled onto ropes and grown for up to 3 years until they are market size. Similarly to salmon, the production of mussels is based around the shores of the Highlands and Islands of Scotland with 79% of production based in Shetland (Marine Scotland Science, 2019b).

Pacific oyster production is relatively low, mainly due to challenges faced by the industry including; disease, spat availability, algal toxins and adverse weather. Oyster production is an important sector for Scotland and demand is increasing in local and export markets. Demand for Scottish oysters is high and research is attempting to address these constraints with the aim to increase production in the future. Production is already growing; there was a 14% increase in volume between 2018/19. Oysters are mainly produced on the intertidal zone in mesh bags fixed to trestles. Oyster seed from hatcheries is placed into the bags and grown for up to 3 years until market size. Production is mainly situated on the West Coast of Scotland in the Strathclyde area where 53% of production takes place (Marine Scotland Science, 2019b).

Unlike the salmon and trout industry the shellfish sector is predominantly based on several small holding farms with a few larger operations. A large proportion of the industry forms part of a cooperative called the Scottish Shellfish Marketing Group which has consolidated the processing, packaging and marketing for much of the industry, creating a level of standardisation within the industry and increasing assess to markets for Scottish shellfish produce.

2.3 Current environmental performance of Scottish aquaculture

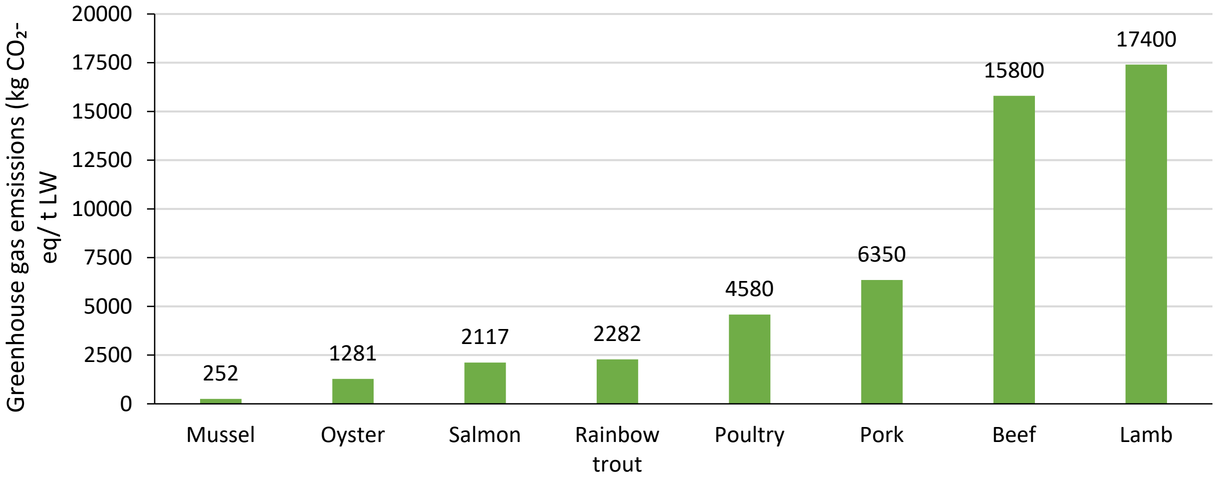
Since aquaculture on a global commercial scale began, there have been concerns about its environmental impacts, including: use of land and freshwater resources, biodiversity impacts, release of medicines and chemicals, spread of disease and parasites, dilution of wild fish populations though interbreeding by escapees, destruction of coastal habitats and land use change, dependency on wild fish populations for feed, climate change emissions and localised eutrophication effects (Folke and Klautsky, 1992; Fernandes et al, 2001; Martinez-Porchas and Martinez-Cordova, 2012; Samuel-Fitwi et al, 2012; Henriksson et al, 2012; Poore and Nemecek, 2018). Not all research agrees with these concerns and different production methods and aquaculture species around the world can have markedly different associated environmental impacts. Mussel and oyster production in Scotland is a good example of aquaculture production that has a low environmental footprint (**Figure 6)** and can also provide beneficial ecosystem services.

Traditionally environmental assessments of aquaculture production have focused on release of nutrients and suspended solids into water bodies, on a local or regional scale (Aubin et al, 2006). However, following in the footsteps of agriculture and with concerns rising over the contribution of food production to climate change, there has been increased interest in the potential global impacts of aquaculture production (for example GHG emissions), including the increased application of life cycle assessments (LCA) to aquaculture production systems. LCA (Box 2) was first used to assess agricultural food systems in the 1990s and in 2004 the first aquaculture assessment was carried out on the feed cycle of Rainbow trout, quickly followed by assessments on Atlantic salmon and other species (Henriksson et al, 2012). To date around 25 species have been assessed across 30 different countries, with more assessments seen across Europe than anywhere else. In Scotland, three studies have assessed salmon aquaculture using a variety of different impact categories. Results show that on average 1 tonne live weight of salmon produces 2117 Kg CO_2-eq and this is lower than for any terrestrial livestock production system (**Figure 5).** Scottish salmon is also low in freshwater use, land use and acidification potential when compared to livestock production **(Table 3).** One of the studies included primary processing of salmon (Newton and Little, 2018) but no studies to date have looked at the full life cycle of salmon to retail market. There have been no studies carried out on Scottish or UK based trout production, so results for **Figure 5** have been taken from a study of French aquaculture, and results were found to be close to but slightly higher than those of salmon.

Globally there has been much less research on shellfish systems and only one LCA study has been carried out in Scotland, looking at the whole life cycle of Blue mussel and Pacific oyster cultivation, including processing and packaging, assessing only the carbon footprint. The results showed that mussel and oyster production both have low carbon emissions compared with other animal protein sources (**Figure 5),** although the impact of oyster production (1281 Kg CO_2-eq) was found to be higher than that of mussels (252 Kg CO_2-eq). One reason for this difference, is depuration of the oysters which accounted for 310 Kg CO_2-eq (Fry, 2012). Depuration is the process of placing shellfish in a tank of clean seawater to allow their natural filtering activity to expel any contaminants. This method effectively ensures that shellfish are safe for human consumption, but it can be energy intensive and is not always required to meet food standards. If shellfish are harvested from good quality waters (Class A), as is the case for a large proportion of shellfish production in Scotland, there is no need to depurate the products. The GHG emissions for oyster production in Scotland could therefore be lower (971 Kg CO_2-eq).

Further LCA assessments are needed for trout and shellfish production and for the full supply chain of Scottish aquaculture up to edible portions supplied through supermarkets, to help identify potential mitigation measures within domestic trade to increase our knowledge of potential impacts across the value chain beyond the farm gate or primary processing. New LCA research by the Universities of Edinburgh and Stirling on the environmental performance of UK shellfish production aims to address some of these gaps and deliver a recent, thorough analysis of environmental emissions from shellfish production.

Figure 5. Average GHG emissions of UK based livestock and seafood production. Results include all processes up to farm gate. Sources: mussel and oyster (Fry, 2012), salmon (Boissy et al, 2011; Newton and Little, 2018), Rainbow trout* (Boissy et al, 2011; Chen et al, 2015), poultry, pork, beef and lamb (Williams, Audsley and Sandars, 2006). *No studies have been conducted on Rainbow trout in the UK, data has been used from French studies.



Box. 2: Life cycle assessments

Life cycle assessment (LCA) is an International Standard Organisation accredited environmental impact assessment method which can be used to perform comprehensive assessments of the environmental impacts associated with a product or process throughout the whole life cycle of the system ('cradle to grave') (ISO 14044, 2006). The LCA process involves estimating all abiotic and biotic inputs into a system along the whole supply chain and uses this to estimate the potential outputs emitted into the environment during all stages of the life cycle. Taking farmed salmon as an example this would include all stages of the process from feed production, egg production, freshwater and marine growing stages, harvesting and slaughter, processing, packaging, transport, retail, consumption and finally disposal. Due to the complexity and specificity of the whole supply chain, most LCA studies focus on quantifying impacts up to the harvest and slaughter of animals, this is referred to as "cradle to farm gate". A LCA can be used to quantify several environmental outcomes both on a global or local scale and more models are frequently being developed. The main uses currently are to quantify: (1) global warming potential, (2) acidification potential, (3) eutrophication potential, (4) energy demand (5) land use, and (6) water use.

Table.2 Common Life Cycle Assessment impact categories used and description of metric.

Impact category	Description of impacts quantified
Global Warming Potential	Contribution of atmospheric absorption of infrared radiation
Acidification potential	Contribution to acid rain
Eutrophication Potential	Contribution of excess nutrients
Cumulative Energy Demand	Contribution to depletion of non-renewable energy sources
Land use	Contribution of land used
Water use	Contribution of water used

Therefore, in its basic form, assessing aquaculture products using LCA allows the estimation of greenhouse gas emissions, potential for excess nutrient loading, energy used from non-renewable sources and the land and water used throughout the whole supply chain of the seafood product. The application of LCA also allows the comparison of different products, production systems or methodologies and therefore it can be used to identify areas for improvement and provide evidence based support for alternative options which have lower environmental footprints.

2.4 Nutritional performance

Around the world an estimated 820 million people (~15% of the world's population) lack sufficient food and even more suffer from nutritional inadequacy (Willet et al, 2019). Seafood products not only provide a good source of low calorie high-quality protein, they are also a major source of long chain poly unsaturated fatty acids (omega-3), and have a balanced amino acid profile, containing high proportions of Vitamin D, Vitamin B12, choline, taurine, and the minerals selenium, iodine, phosphorus and calcium (Tilami and Sampels, 2018). Increased fish production and consumption will play an important role in meeting the demand for nutritious food for an increasing world population and hence in meeting UN Sustainable Development Goal 2, 'zero hunger across the world'.

One of the main health benefits associated with salmon consumption is the high level of omega-3 oils they provide. Omega-3 oils include several fatty acids; of particular importance are eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). Humans are unable to produce EPA and DHA other than at low levels from consumption of some plant sources, but this is not sufficient to meet the physiological demand of the human body and therefore human diets require additional intake of EPA and DHA from food for optimum nutrition (Tocher et al, 2019). Marine organisms are the only major food sources that contain a naturally high amount of these fatty acids. Health benefits from consumption of EPA and DHA include improved cardiac function (reducing the risk of coronary heart disease and ischemic stroke), lower blood pressure, neural development (particularly in infants) and normal blood triacylglycerols (Tilami and Sampels, 2018).

Table 3 Life cycle assessment emission results for 1 tonne of live weight Scottish salmon up to the farm gate. (Newton and Little, 2018; Boissy et al, 2011)

Environmental Impacts from 1 tonne LW Scottish Salmon	
Global Warming Potential (Kg CO_2-eq)	2117
Acidification potential (Kg SO_2-eq)	13.25
Eutrophication potential (Kg SO_2-eq)	57.45
Cumulative Energy Demand (MJ)	32159
Water dependency (m^3)	30
Land use (m^2)	932

The importance of the inclusion of omega-3 oils in a balanced diet has resulted in several countries implementing recommended intake levels for adults, ranging between 250mg-650mg of EPA and DHA daily. There is also further guidance on increased intake levels for those suffering with heart problems and pregnant women, based on the benefits of omega-3s. Globally, less than 20% of the world's population consume the minimum guidance of ≥ 250 mg per day of omega-3s. The UK government recommends at least two portions of fish per week equating to roughly 450mg of EPA and DHA daily (Micha et al, 2014). The UK population like many others consume low levels of fish with average intake levels at just 100mg/day of EPA and DHA (SACN, 2004). Therefore, from a nutritional standpoint, both within the UK and globally, increasing fish consumption has the potential to contribute to balanced diets including higher levels of EPA and DHA.

Not all fish are equally nutritious and several variables can affect the nutritional profile of seafood, most notably the variation across species, fish diets, and production location and method. Oily fish are much higher in omega-3 oils and this includes farmed salmon and trout in Scotland. Although less widely noted, bivalves such as oysters and mussels are also a good source of omega-3s along with a variety of other vitamins and minerals (**Table 4)**. Compared with livestock animal protein, salmon and trout are comparable in protein content and significantly higher in omega-3s, Vitamin D and Vitamin B-12. Shellfish (oysters and mussels) have slightly less protein content (lower than that of livestock animal protein) but are higher in omega-3 content and are excellent sources of Vitamin B-12, Zinc and Iron **(Table 4)**.

As seafood is such an important aspect of a healthy diet it is important always to consider the contribution of fish products to dietary nutritional outcomes and helping achieve these societal goals.

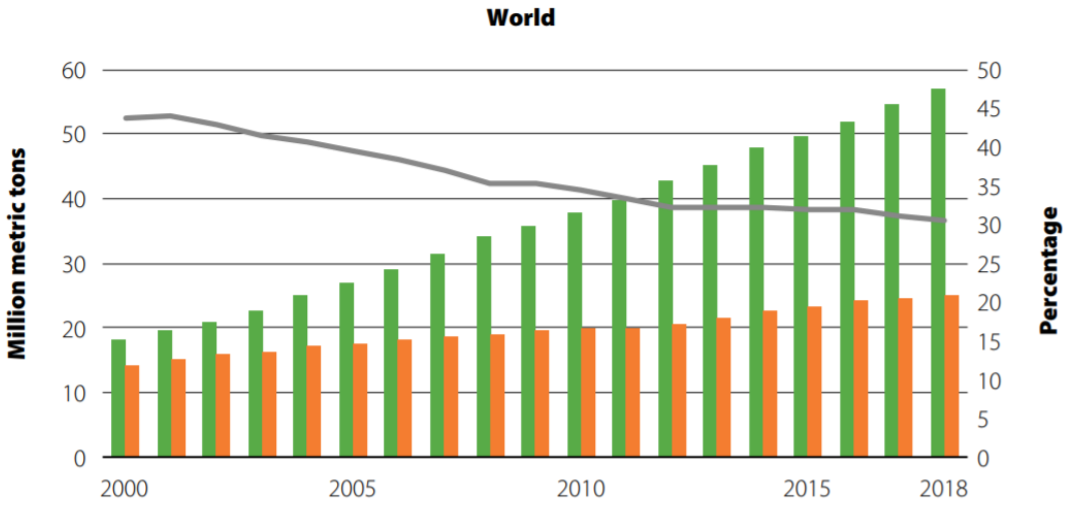
Table 4 Nutritional composition of 100g (wet weight) of UK animal protein foods. (Data source: FAO/INFOODS, 2016)

	Protein (g)	Omega-3 (DHA & EPA) (g)	Vitamin D (µg)	VitaminB-12 (µg)	Zinc (mg)	Iron (mg)
Beef	22.5	0	0.5	2	4.1	2.7
Chicken	22.3	0	0.1	TR	2.1	0.7
Pork	21.8	TR	0.5	1	0.7	1.6
Salmon	20.4	2.21	4.7	4.4	0.4	0.33
Trout	19.9	1.03	7.9	2.8	0.5	0.28
Mussels	12.1	0.4	TR	19	2.5	2.53
Oysters	10.8	0.3	1	17	59.2	5.7

3. Aquaculture feed

Aquaculture systems can be categorised into two groups: fed and non-fed. Fed aquaculture production requires the input of feed for the growth of fish, for example salmon and trout. Non-fed aquaculture production in comparison are systems which do not require feed input, for example shellfish such as mussels and oysters. Some freshwater systems such as carp grown in extensive pond systems without feed are also in this category. The production of non-fed aquaculture has declined from 44% to 30.5% (2000-2018) (**Figure 6)** (FAO, 2020), largely due to the increased consumer demand for fed aquaculture species such as salmon and shrimp. Feed is the most expensive component of aquaculture production, representing 40-75% of total production costs and the current aquafeed market is predicted to increase by 8-10% per annum and reach 73 million tonne (Mt) by 2025 (Sarker et al, 2020).

Figure 6. Global production and contribution of fed (green bars) and non-fed (orange bars) aquaculture production (2000-2018). (Marwana, Beveridge and Phillips (2020); modified from FAO, 2020).



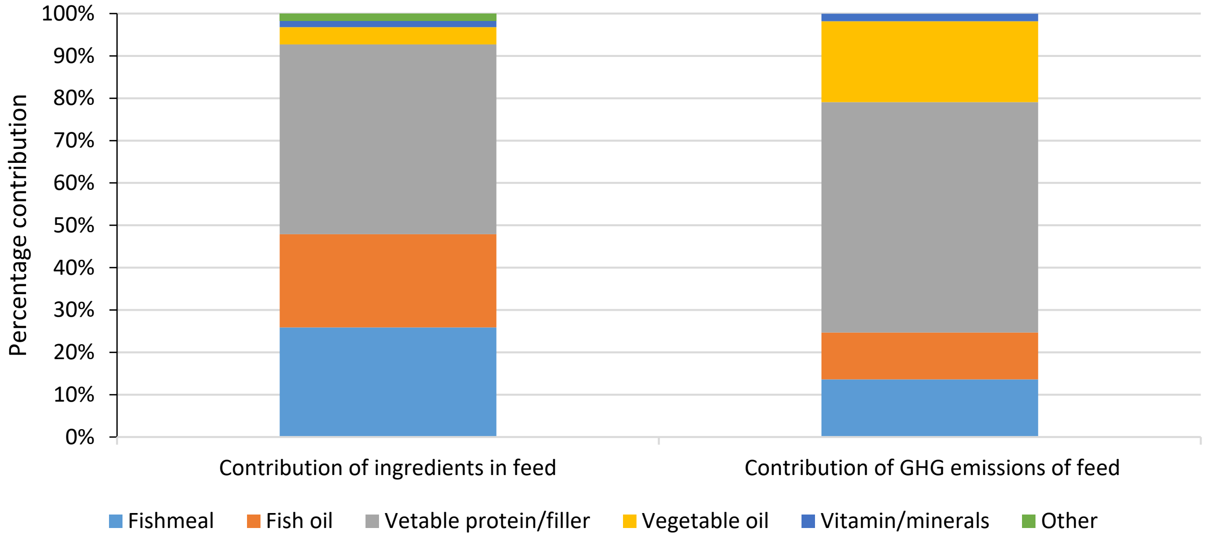
In the Scottish aquaculture sector, salmon and trout production require large amounts of feed. This is not only the most expensive part of production but LCA research has shown it is also the highest contributor to environmental impacts. Throughout the farming stage of Scottish salmon production, feed accounts for over 90% of GHG emissions, land use, water use and energy use (Newton and Little, 2018).

Traditionally the two most important ingredients in salmon feed were fishmeal and fish oil derived from wild capture reduction fisheries. However, the decline in the sustainability of wild fish stocks **(Figure 2)** has caused concern over the future supply of marine ingredients to support aquaculture growth and also over the amount of wild fish used for non-direct human consumption, with impacts on marine biodiversity. Feed companies have been searching for protein and oil substitutes for marine ingredients, leading initially to increased use of vegetable based ingredients such as soybean meal and rapeseed oil. In Norway in 1990 salmon feed contained 90% fishmeal and fish oil and only 10% was from plant ingredients; in 2013 this had changed to around 70% plant based ingredients and less than 30% marine based ingredients. This resulted in reduced reliance on wild fish for feed with a significant reduction in the forage fish dependency ratio (FFDR) which for fishmeal decreased from 4.4 to 1.1 in the Norwegian salmon industry (Ytrestøyl et al, 2014).

Although this shift has decreased the percentage of fishmeal and fish oil used in feeds, it has caused concerns over the environmental impacts of feed production and also its nutritional profile. Aquaculture LCA study results indicate that vegetable based ingredients have a higher impact on GHG emissions than marine ingredients. In the average Scottish salmon feed, around half of the ingredients are from marine origin (fishmeal and fish oil) and the other half from terrestrial origin (vegetable oil and meal).

The contribution to GHG emissions from feed ingredients shows marine ingredients represent roughly 24% of GHG contribution compared to 73% from terrestrial based ingredients (**Figure 7**) (Newton and Little, 2018). While moving to vegetable based ingredients is argued to have beneficial impacts on global fish stocks and therefore potentially marine biodiversity, the majority of crop ingredients such as soybean come from South America and some soya bean production in this region has been associated with deforestation and a loss of biodiversity. The contribution of transport over long distances to bring these ingredients to the UK can also be seen as a cause of environmental inefficiencies, but studies to date have shown that this has little overall impact on emissions as they are transported by sea.

Figure 7 Percentage contribution of ingredients in Scottish salmon feed and the corresponding contribution of those ingredients to total GHG emissions of feed production. (Data source: Newton and Little, 2018).



Another trade-off from this dietary ingredient shift has been alterations to the nutritional profile of salmon. Unlike wild captured fish which bio-accumulate omega-3 through the food chain by eating smaller fish that have consumed algae, fed aquaculture species such as salmon rely on feed which has been formulated to contain these essential fatty acids, along with other important nutrients needed for optimum human and fish health. Vegetable oils used to replace fish oil are high in omega-6 oils rather than omega-3, and although omega-6 is an important part of the human diet, average UK diets already contain large amounts of omega-6 oils and it is the omega-3 component that is failing to meet the recommended dietary guidelines. Studies have shown that DHA and EPA levels decreased in Scottish salmon by around 50% between 2006 and 2015 (Sprague et al, 2016). There has also been a decrease in other nutrients, including iodine, zinc, copper, selenium and Vitamin D (Roos et al, 2017). However, on average, the Scottish salmon industry has maintained a higher marine ingredient content in its feed compared to other regions such as Norway and subsequently its salmon are seen to have a higher nutritional profile, contributing to the premium product branding around Scottish salmon which the industry is keen to maintain. Although Scottish salmon feeds have reduced their marine ingredient content and therefore the levels of EPA and DHA, farmed salmon are still an excellent source of omega-3s for healthy human diets **(see Table 4)**. Furthermore, some studies have shown that farmed salmon has higher EPA and DHA content than wild salmon due to research-based formulation and nutritional performance monitoring of aquafeeds, resulting in standardised levels of nutrients in fed farmed species (Sprague et al, 2016).

It is clear that the environmental impact of aquafeed is heavily dependent on the composition of ingredients in the feed. The industry is conscious of the current trade-offs from the use of different feed ingredients and as neither vegetable based ingredients nor marine based ingredients appear to be fully sustainable in the future, the industry is investing heavily in finding new alternative feed ingredients to solve these problems.

4. Innovation in the aquaculture industry sectors

4.1 Analysing innovation systems

There is currently strong interest in Scotland from government, industry, non-government organisations and the public to better understand and support the development of innovative technologies that can minimize environmental impacts associated with Scottish aquaculture, while supporting the continued economic, employment, food security and human nutrition benefits provided by this industry.

This section identifies a number of innovations currently being used (or with the potential to be used) in the Scottish aquaculture industry to promote its sustainable growth. The Innogen Institute's systemic approach to the analysis of innovation systems (**Figure 8)** takes account of the interactions between researchers/innovators, policy makers/regulators, and stakeholders/ citizens (Strategic Analysis of Advanced Technology Innovation Systems (STRATIS)) (Wield et al, 2017). These interactions will determine which innovations will successfully make the journey from proof of concept as a novel idea to availability and use in the market place.

This section considers the value chain itself, the core of **Figure 8**, looking at the innovations relevant to incumbent or new companies and business models. All innovations will either have to find a place in an existing value chain or, a much more challenging option, create a new value chain capable of out-competing the incumbent companies. The first requirement of any innovative product or process is that it should be economically viable and this will be determined by the properties of the innovation itself and by factors included in the innovation ecosystem in **Figure 8** (stakeholder and market perspectives, regulatory systems, and government innovation support policies). These factors are considered in Sections 4.2 – 4.7.

Figure 9 summarises the elements of the existing aquaculture value chain that are relevant to this analysis, based on the more detailed description in **Appendix A**. Potentially, each of the sub-sectors in **Figure 9** could be populated by a number of different companies but, as the fish farming sector in Scotland has consolidated, a few large companies have increasingly extended their reach to cover more of the overall value chain. Where possible this section refers to LCA and quantitative information to evaluate the contribution of an innovation to climate change and biodiversity policies.

As described in Section 3, feed production is currently the most expensive part of aquaculture and also the highest contributor to total GHG emissions. There is therefore a strong incentive for industry to find innovative technologies for new aquafeed ingredients to address these issues and to increase the sustainability of supply to meet the demand to increase aquaculture production in the future. Sustainable innovation in the area of feed will most likely be able to provide the greatest impact on the carbon footprint of aquaculture production and will be pivotal in the industry's capacity to achieve net zero carbon emissions by 2045.

Figure 8 Innogen STRATIS approach

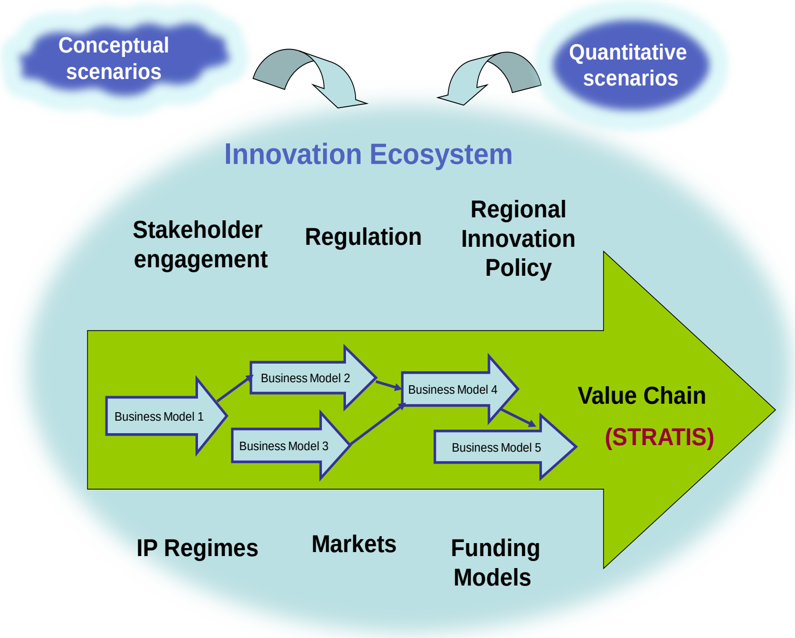
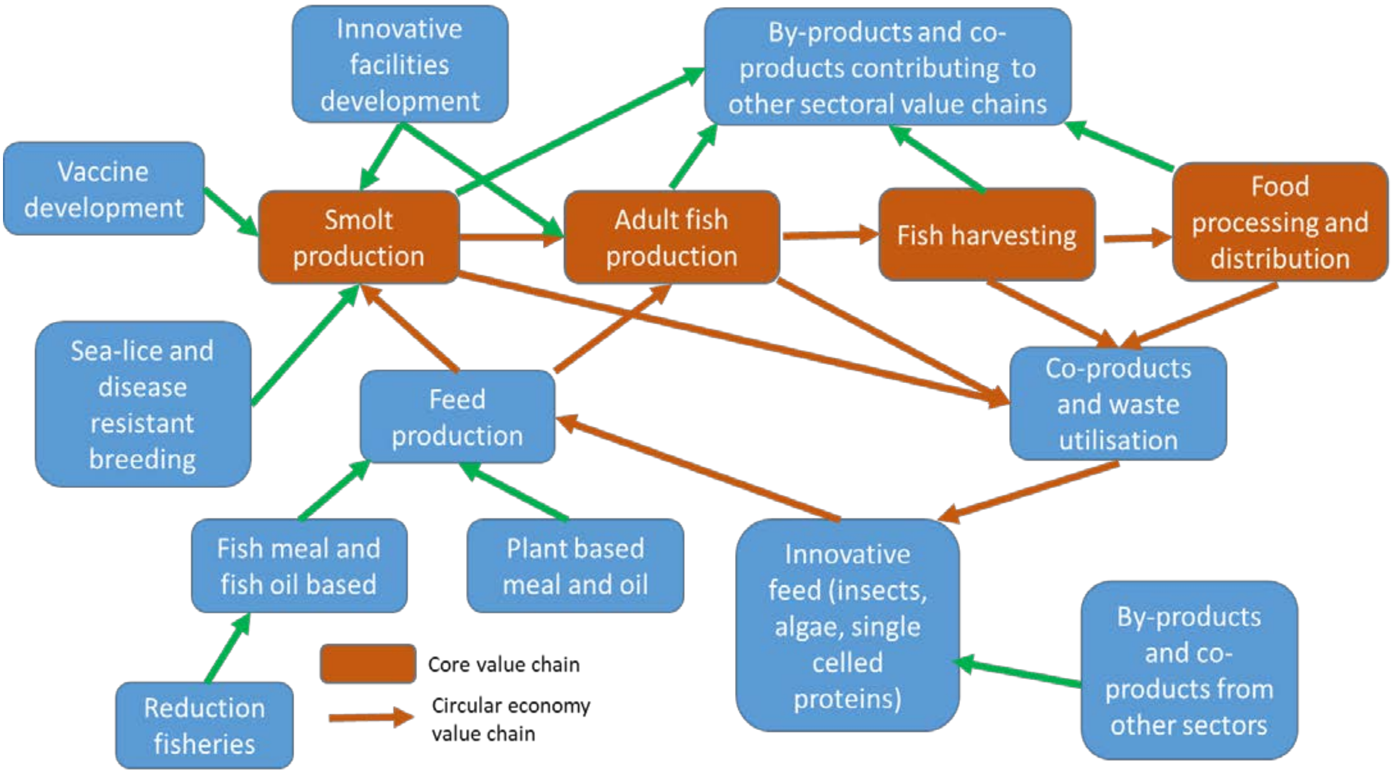


Figure 9. The circular economy value network and the role of innovative technologies for Scottish salmon farming



4.2 Feed innovations

Within Scotland, aquaculture feed innovation is mainly directed to the production of Atlantic salmon and Rainbow trout. There are several novel feed ingredients in development with the potential to be used in the Scottish aquaculture industry including algae based ingredients, insect meal and single celled proteins, covered in this report. One of the many benefits of these innovative technologies in aquafeed development is that the supply of the ingredients is not limited to certain regions of the world as is currently the case. Currently over 50% of Scottish salmon feed ingredients come from outside of the UK (Newton and Little, 2018), and novel ingredients can be based on local sources. Furthermore, several of these new technologies are components of circular economy systems, reusing waste from other sectors. This provides an opportunity for Scottish supply chains to adopt circular economy based solutions to advance the goals of zero waste and net zero carbon emissions across supply chains. Here we will outline some of the current innovations in the feed value chain and discuss both benefits and disadvantages of these novel feed ingredients.

Algal ingredients

Algae are primary producers at the base of the aquatic food chain and can be high in protein and omega-3 oils so they present a promising alternative source of proteins and lipids in fish feed (see Case Study 1). Micro-algae that can synthesise omega-3 fatty acids could reduce reliance on marine and plant based ingredients. The nutritional quality of micro-algae is high, with a crude protein content of up to 71% and lipid content of up to 40%, which makes it comparable to marine and terrestrial ingredients currently used in feed (Hua et al, 2019). Depending on the organism involved, micro-algae can be used in fish diets as either biomass with the potential to replace vegetable and fish meal protein content or as algal oil which could replace fish oil and vegetable oil in current formulations. Although there is great promise in the use of algae in aquafeed, production so far has been limited by biological, technical and economic constraints. The price of micro-algae is several times higher than that of soybean meal, but as scale up of production continues, algae could become more competitively priced.

Currently algal ingredients are used in aquafeed products across several European countries, particularly Norway. BioMar, one of the largest aquafeed producers in the world and a major supplier to the Scottish industry, has been using algal oil in its salmon feed in Norway (BioMar, 2019). There is clearly an increased appetite for its use and this has been supported by several UK supermarkets encouraging development and giving approval for the use of these novel ingredients in seafood products (TESCO, 2019).

The most common algal strain used to produce micro-algal oil is *Schizochytrium* which can be produced heterotrophically through fermentation. This technology has been advancing, but scalability has been a constraint to its development. A limitation of this method for producing microalgae is that it generally produces only DHA and not EPA and therefore most microalgae products provide a source of DHA only, such as AlgalPrimeDHA^{TM} which has been used in salmon feed (BioMar, 2019).

The company Veramaris (https://www.veramaris.com/home.html) has begun researching and producing algal oil using a strain of *Schizochytrium* which produces both DHA and EPA and the product is a better algal oil for use in aquafeed to replace current fish oil or plant based oils (Tocher et al, 2019). The main production site for Veramaris is in Nebraska, and the Veramaris oil process involves using sugar from corn, beet or wheat as fermentation feedstock. During fermentation, the algal cells convert dextrose from the sugar to omega-3 fatty acids, which accumulate in oil vesicles.

The cell wall of the algae is then broken and the oil vesicles are separated from the aqueous phase. The residual water is removed by centrifugation, leaving algal oil with 50% EPA and DHA and a liquid co-product. The liquid co-product is high in protein and can be used in cattle feed or converted to biogas to contribute to the national electricity grid. Veramaris therefore report their process is waste free. The company also claims that including 1 ton of their product is equivalent to using 60 ton of wild fish to produce fish oil. With the current production capacity of Veramaris this means they have the ability to replace the oil extracted from a total of 1.2 million wild forage fish. It is estimated that around 16.9 million tonnes of forage fish are used globally to produce fish meal and oil (Cottrell et al, 2020).

The company became the first algal oil producer to achieve certification to the ASC-MSC Seaweed (Algae) standard. It aims to produce roughly 45% of the global supply of MSC certified EPA and DHA omega-3 and a total of 15% of the global requirement for EPA and DHA for use in salmon feed (Veramaris, 2021). The oil is now available at scale and is already widely used in Norway (around one third of Norwegian salmon are raised on feed containing the algal oil) and also in the USA and Chile.

There is little research on the environmental performance of algal based ingredients, however most micro-algal fermentations rely on organic carbon feedstock (e.g. dextrose/corn syrup in the Veramaris process), obtained from corn or sugar production. These products are thus linked to the terrestrial farming of these crops with the associated sustainability issues (SAMS, 2018). Fermentation is also an energy intensive process and this might also be a source of environmental impact inefficiencies, requiring further research on the environmental footprint of these feeds.

Veramaris have reported on a LCA study they conducted on their process, using alternative categories to traditional LCA which they believe are more relevant to assessing the impacts of products on the marine environment. Their results indicated that the current commercial salmon diet requires 59 tons of carbon to be converted by photosynthesis to produce 1 ton of salmon. However, by replacing just the fish oil content of feed with Veramaris algal oil (fish meal and plant based ingredients remaining the same), the photosynthetic carbon requirement is reduced by 45%. Furthermore, the amount of wild fish required to be caught for the use in feed is reduced by 83% (DSM, 2019).

Increasing numbers of companies are aiming to adopt circular economy supply chains to produce high value products from industry waste streams. AlgaePro (https://www.algaepro.no/) is a Norwegian company founded in 2018 with an aim to use fermented organic waste from household food waste and potentially sludge collected from aquaculture systems to create organic fertiliser (nitrates and phosphates). They also plan to utilise CO_2 and warm spill water from industry, together with the organic fertiliser, as the raw materials to produce micro-algal biomass as a component of aquaculture feed diets to replace fishmeal and vegetable meal. As well as providing high value nutritious aquaculture feed for future food production, using organic waste could reduce GHG emissions released from landfill and capture CO_2 from industry, reducing carbon dioxide emissions from waste sites.

Case Study 1: Converting whisky Industry waste to aquafeed ingredients

Three UK based companies have teamed up to explore the potential of using whisky production by-products to produce aquaculture feed ingredients. The Whisky Project which is led by the Industrial Biotechnology Innovation Centre and co-funded by Zero Waste Scotland and the Scotch Whisky Research Institute aims to explore potential new sustainable applications for whisky co-products. These include draff, husk residue left over from the fermentation process and pot ale, the remaining liquid after distillation. The companies involved have already been successful in utilising co-products from the whisky production process and this collaborative project plans to further develop these efforts.

This circular economy project aims to aid the Scotch whisky industry in achieving its sustainability goals by identifying economically valuable sustainable end uses for co-products within the industry. It could also help the aquaculture industry reach its sustainable goals by providing locally sourced nutritionally viable aquafeed ingredients, reducing the industries' reliance on marine and plant based ingredients (Fish Farming Expert, 2020a).

Bio-based wastes and by-products of the whisky industry are estimated to be 4,371,000 tonnes each year.

MiAlgae (https://www.mialgae.com/) has developed a technology to use nitrates and phosphates from whisky production wastewater to produce microalgae that they claim are high in omega-3 and could replace the fish oil used in current aquafeed. The process also saves the distillery from having to clean waste water and the clean water is recycled in the process. MiAlgae claims that 1 tonne of its algae saves up to 30 tonnes of wild fish. This is half the savings in wild fish inputs reported by Veramaris, and is probably linked to the EPA and DHA content of the algal oil. Although this is less for MiAlgae, the proposal to use whisky waste as a feedstock for algae fermentation would be an improvement compared to using agricultural crops. The company currently has a small 1000 litre pilot plant and have just secured funding for a 30,000 litre demonstrator plant to allow them to carry out commercial trials (Fish farming Expert, 2020a).

Horizon Proteins have created a technology to recover the proteins and macromolecules present in pot ale which can be used as ingredients in animal feed. These proteins can be used as a substitute for fishmeal and soybean meal present in aquafeeds. The company is now fully commercialised and has already run three successful process scale trials and a feed trial with salmon in Scotland. It has gained EU approval for commercial use in several feeds and is currently awaiting construction of a full scale processing plant (IBioIC, 2020).

Zero Waste Scotland estimates the whisky industry produces 528,000 tonnes of draff and 885,000 tonnes of pot ale per year. Pot ale, the liquid residue from the first distillation stage, contains protein from the yeast and grain, roughly 8 litres of pot ale being produced for every litre of alcohol in the whisky, containing approximately 2% protein on a wet weight basis. Draff, the spent grain residue from malt whiskey production, is high in digestible fibre, protein and carbohydrates (Zero Waste Scotland, 2015). This Zero Waste Scotland analysis estimated the potential value of aquafeed protein produced using the Horizon protein method, based on the amount of pot ale produced by the whisky industry. Updating the study's calculation to reflect current production levels, the protein requirement for Scottish salmon farming is 120,000 tonnes per year, based on 2019 production volumes of 200,000 tonnes (**Table. 1)**, an average feed conversion ratio of 1.2 and 50% protein content required in feed. The amount of protein that in theory could be extracted from all of Scotland's whisky sector, using the Horizon Proteins process, could be as much as 181,000 tonnes per year, a third more than is currently required by the Scottish salmon industry. This is based on the total amount of pot ale and spent wash produced at source, 9 million tonnes per year. (Zero Waste Scotland, 2015).

Insect meal

There has been significant research on the cultivation and use of insects for aquaculture feed. Insects are highly productive with very short life cycles and can be produced on a variety of substances in any location (Hua et al, 2019). Insects also have a very good feed conversion ratio; 1 kg of insect biomass can be produced from 2kg of feed biomass (often food waste) (Makkar et al, 2014). The ease of production coupled with a relatively good nutritional profile has resulted in increasing attention to the use of insect ingredients in feed. Advantages are that the production of insects does not compete with human food sources or production, helping to alleviate concerns over the use of arable crop ingredients and marine ingredients in feed, some of which instead could be used for direct human consumption (Hua et al, 2019). Of particular interest is the ability of insects to convert low quality organic waste into high value nutritious products which can be used in feed supply chains (Bacchetti et al, 2020; Henry et al, 2015)

The potential for the use of insects in aquaculture feed was recently increased when the European Commission changed the regulatory system to allow the use of insect meal in feed for aquaculture (Regulation (EU) 2017/893) in 2017 (Bacchetti et al, 2020). This legislation followed similar changes in Canada and the US, where insect meal is now present in aquafeed, replacing fishmeal in the salmon industry. Although insects are not currently used in aquafeed for the UK, this change to legislation suggests that substitution of fishmeal or vegetable meal with insect meal in aquaculture diets will be a reality in the near future (**Case study 2**).

Most interest is focused on black soldier fly (*Hermetia illucens*), common housefly (*Musca domestica*) and yellow mealworm (*Tenebrio molito*). The crude protein content of insects is between 42-63% and their lipid content ranges from 8.5-36% depending on the species (Hua et al, 2019). Insects have negligible levels of EPA and DHA and similarly to vegetable ingredients, they contain more omega-6 oils, and therefore their substitution with current feed ingredients is best placed to replace fishmeal and vegetable meal rather than fish oil and vegetable oil.

Studies have found that the palatability of insect meal as an alternative ingredient for fish feed is very good and some research shows that insect meal could replace 25-100% of fishmeal and soymeal, depending on the farmed species (Makkar et al, 2014). The current focus for many companies is the use of insects to replace fishmeal and this is mainly driven by concerns over the future supply of marine ingredients and the much higher cost of insect based ingredients when compared to vegetable ingredients (e.g. soymeal). One of the constraints on the use of insects in feed has been price competiveness with other raw materials and production levels are still relatively low (Hua et al, 2019). With increased production and enhanced integrated supply chains insect meal is expected to become more economically viable as a feed source.

Black soldier fly larvae (*Hermetia illucens*) have proved successful in replacing 100% of fishmeal in Atlantic salmon diets. The trial showed no difference in nutritional profiles, growth rates or feed conversion ratios of fish feed compared with insect meal (Belghit et al, 2019). A study on Rainbow trout actually showed an increase in growth rate and feed conversion ratio on farmed trout fed 100% replacement of fishmeal with yellow mealworm (*Tenebrio molitor*) (Rema et al, 2019).

Insect production has a small ecological footprint and therefore could be a sustainable option for reducing environmental concerns of current fish feed ingredients. When used as a substitute for vegetable ingredients they reduce arable land used, lower energy demand and reduce water use (Henry et al, 2015). They also have the potential to reduce fishmeal content in feeds and therefore reduce reliance on wild fish stocks.

Optimising the use of food waste as a substrate for insect farming as an aquafeed ingredient aligns with several UN SDGs: (1) Goal 12: Responsible Consumption and Production, aiming to half food waste by 2030, (2) Climate Action, (3) Life Below Water and (4) Zero Hunger. It will also help to support the Scottish Government goals of developing circular economy supply chains along with aiding in the target to achieve net zero carbon by 2045 and promoting a zero waste economy (Scottish Government, 2016; CCC, 2019b).

Single Celled Proteins

Single cell protein (SCP), produced by a variety of microbial sources including micro-algae, yeast, bacteria and fungi are highly productive and can be grown using a variety of feedstocks. Traditionally the focus was on producing SCPs using agriculture based feedstocks such as sugar cane or corn, and these methods have had proven success. More recently, innovative use of waste residues and by-products as feedstocks is likely to support a more circular economy, increase economic yield and potentially reduce carbon footprint and overall environmental outcomes of production systems (Jones et al, 2020) (see **Case Study 3**).

An example of an SCP product is Feedkind Protein, created through fermentation using methanotrophic microorganisms (microorganisms which metabolise methane gas as their source of carbon and energy). The protein has a good nutritional profile with 71% crude protein and 9% fat and feeding trials on salmon and trout have shown that substitution of Feedkind for other proteins results in increased growth and improved feed efficiency. It can therefore be used as a replacement for fishmeal or vegetable protein in aquafeed. A LCA was carried out on the production of Feedkind protein and, compared with current feed sources (fishmeal and vegetable meal), it reduced the amount of land required for production compared to crop ingredients such as soybean meal: 1692 km^2 are required to produce 40,000 tonnes of usable protein from soy, compared to just 0.04km^2 for Feedkind protein. The study also highlighted significant reductions in water use for production with 77-98% less water used compared to soy and wheat production (Carbon Trust, 2016).

The Feedkind production process is being scaled up in the USA. Currently the carbon footprint of the protein is not better than traditional feed sources, however scaling up production and using alternative energy sources could improve this. The US electricity grid is less carbon efficient than in Europe, so improvements could be made by using alternative electricity sources or through production in countries that have lower carbon footprint electricity grids. The study found that if 100% biogas from waste streams was used to produce the protein, the carbon footprint could be halved from 5819 kg CO_2–eq/tonne to 2274 kg CO_2–eq/tonne (Carbon Trust, 2016). There has been interest in the use of Feedkind protein in Scottish aquaculture feeds and if a processing facility could be build closer to production, this would further enhance the sustainability of this alternative feed.

Investigating innovative developments in the aquafeed sector has highlighted the importance of developing new feed ingredients for aquaculture. It has also highlighted the constraints and challenges associated with many novel ingredients and also their great potential to address environmental concerns associated with aquaculture feed production.

Case Study 2: Utilising food or other waste/by-products to cultivate insects as protein substitutes in aquafeed

Entoycle (https://www.entocycle.com/) is a UK based start-up company producing insect based protein for use in animal feed. They are using a circular economy approach to farm black soldier fly (BSF) with locally sourced food waste. The pre-consumer food waste will include surplus fruits and vegatables from retail as well as grain by-products from the brewing industry and coffee grounds.

Black soldier fly larvae are used to produce insect meal, high in protein, amino acids and other minerals. The process also extacts lipids from the larvae which can be used in animal feed (e.g. pet food) or the bio-fuel industry. The frass created by larval farming contains organic substrate and chitin which can be used as a soil enhancer; it also enhances growth of microganisms in soil, potentially reducing plant pathogens. The full utilisation of the process offers a zero waste alternative feed ingredient which can be produced locally to the site of use.

Entocycle have teamed up with several partners on a UK Government Industrial Strategy Challenge Funded project including Sustainable Aquaculture Innovation Centre, University of Stirling Institute of Aquaculture and Cooke Aquaculture Scotland. The consortium aims to demonstrate the use of BSF farming to convert food waste into insect based animal feeds and biofertilisers. It will investigate the economic viability and scalability of the process as well as validating it as a low carbon process and ensuring the safety of products. The 10 million pound project has ambitious aims to make the UK a centre of excellence for the farming of BSF and plans to deliver more than 100 BSF farming sites internationally, creating 3,300 jobs in the UK and saving an estimated 50 million kg CO_2-e over the next 20 years (SAIC, 2020).

Zero Waste Scotland investigated the economic and environmental potential of BSF farming as a circular economy solution to produce animal feed ingredients using pre-consumer food waste as a feedstock. The study found that BSF larvae are a low carbon, high value alternative to conventional food waste streams and current protein feed production processes. They highlighted that BSF do not carry human or livestock diseases and they were able to convert large quantities of food waste very quickly into high quality protein, while the insect frass (leftover insect manure) could be used as a soil enhancer for agriculture. (Riera and Lenaghan, 2018).

Scotland produces around 0.74Mt of pre-consumer (non-household) waste each year and currently the most carbon efficient way of treating this waste is Anaerobic Digestion (AD). In 2017, Scotland produced 500kt of unused or landfilled agriculture feedstock and if as little as 10% of this was redirected to BSF farming it could produce 2.7kt of insect meal for Scotland's salmon farming industry while also increasing economic value of this waste. The LCA results of the study showed that although the current treatment of food waste using AD results in net carbon savings, using this waste for BSF farming resulted in an additional 10% of carbon savings (per tonne of input: AD generated savings of 69 kg/CO_2-eq and BSF farming 76 kg/CO_2-eq). Furthermore, scenario analysis showed that by using low grade waste heat (a technology currently available and supported by policy in Scotland) the carbon savings from BSF farming could be doubled to -153kg CO_2-eq per tonne of input. Savings could also be made by decarbonisation of the electricity grid, a target already set by the Scottish Government (Riera and Lenaghan, 2018).

Research does not yet provide a clear picture of the potential for these innovations to be produced at scale and to reduce GHG emissions in practice. Many are still in the early stages of development and we have highlighted several promising options which could result in improvements in GHG emissions, biodiversity, reductions in land use, freshwater dependency, reliance on wild fish stocks, and potentially improving the nutritional status of seafood products, all in the near future. Of particular interest, many of these technologies are part of circular economy systems that use waste streams from aquaculture and other sectors, improving environmental impacts of aquaculture and re-using waste. Further research is needed to quantify the environmental profiles of these alternative ingredients and to highlight the areas where support for expansion should be focused.

4.3 Production system innovation

Within the Scottish aquaculture industry there is a strong interest in new production technologies and a move to alternative production locations from traditional sites in sheltered bays. This has been driven by the desire to increase production capacity and reduce environmental impacts and also by planning-related challenges and the need to increase the overall control of production systems. As discussed in **Section 2** the aquaculture industry has ambitious goals to double its production, and to achieve this it needs to develop new sites or to increase the capacity at existing sites. Marine fish farm sites are licensed by the Scottish Environmental Protection Agency (SEPA) who place restrictions on the permitted biomass of sites, based on environmental modelling of organic waste released and how this is dispersed in the marine environment, taking into account the environment and at any given time is roughly 2,500 t and this limits the ability to increase capacity (SARF, 2019). The process of licensing new sites is costly, time consuming and not guaranteed and therefore companies are very selective about where they choose to develop new farms. At the same time, the industry is increasingly anticipating future sites and production methods which can maximise biosecurity by reducing localised environmental issues such as sea lice, harmful algal blooms and seal attacks. There is also pressure on the industry to adapt current sea cage farming in the lochs around Scotland due to growing concern over the environmental impacts from these systems. These include localised pollution from the release of feed waste and fish faeces from cages, release of chemicals and medicines from sites and fish escapes, all with the potential to cause environmental impacts. The aquaculture industry globally has begun to use new production methods which could avoid these limitations (**Table 5**) and their use in Scotland is likely to increase in future.

Offshore and high energy site farming

Moving production offshore to higher-energy sites where ocean currents are stronger than in sheltered inshore areas benefits from reduced competition for space and less conflict with other operations in a confined area, both of which will allow expansion of the industry (Black and Hughes, 2017). The term “offshore” implies some distance from inshore, but does not distinguish where the boundary between inshore and offshore lies. Offshore aquaculture has been defined as production in exposed sites usually >2km from shore (Buck et al, 2018).

Offshore systems were trialled in Canada in the 1990s but these early attempts failed. Designs have now greatly improved and successful production trials have been undertaken (Fisheries and Oceans Canada, 2019). The growing interest in production in these environments has resulted in research to produce solutions that address the challenges of farming in these harsher more exposed environments, including the need for tougher construction materials, safety of the workforce and fish survival.

Case Study 3: Capturing CO_2 to produce protein for aquafeed

Deep Branch Biotechnology (https://deepbranch.com/) founded in 2018 and operating in the UK and Netherlands set out to tackle two big issues we face globally, the need to reduce CO_2 emissions and to produce more sustainable food for the growing population by using waste carbon dioxide to produce food. The company set up the REACT-FIRST project to pave the way to developing the UK's first scalable route to sustainable protein production. The project, involving an end to end value chain consortium of 10 industry and academic partners with the aim to transform the UK's food production systems through feed innovation, is funded by the UKRI Innovate UK and the Sustainable Aquaculture Innovation Centre.

Deep Branch Biotechnology have developed a fermentation process using microbes to convert carbon dioxide from industrial emissions into a high value single-celled protein product (Proton^{TM}). The proprietary gas fermentation process is fuelled by CO_2 and hydrogen from bioenergy power generation, rather than using sugar feedstock as in other microbial fermentation processes. The aim is for the protein to be used as a partial or complete substitute for conventional sources of animal protein such as fish meal and vegetable meal. Using waste CO_2 and hydrogen as feedstock, rather than sugars from crops removes the reliance on agriculture products for their process.

The pilot project for the technology is partnered with the Drax power station which has provided a location for the pilot Deep Branch Biotechnology site and they are providing CO_2 for the fermentation process captured using their own pioneering capture technology. Drax has set out goals to be carbon negative by 2030 and this project would help them achieve this target.

This innovation is an example of industry collaborating to achieve net zero carbon emissions and also adopting circular economy value chains using waste from other industries to produce high value products.

Proton^{TM} is undergoing trials to test its nutritional profile. It could provide biodiversity benefits from the replacement of fishmeal in aquafeed, reducing the reliance on fragile wild fish stock populations. Alternative proteins could also provide greater stability in the supply of protein as their production is not dependent on weather or season in the same way that plant based and marine ingredients can be. Furthermore, this technology allows for the production of protein in any location and could therefore further benefit the aquafeed environmental footprint from reduced global transport of ingredients such as soybean, which predominantly comes from South America. It therefore has the potential to provide a locally produced, low carbon alternative protein for use in the Scottish aquaculture industry.

During salmon production, 30% of the carbon dioxide equivalents are associated with the protein used for feed and Deep Branch Biotechnology claims that replacing fishmeal in the diets of salmon with Proton^{TM} has the potential to reduce the total carbon footprint of a salmon fillet (including transport and packaging) by over 25%. On the basis of a production facility that could produce 100,000 tons of Proton^{TM} per year, this would be able to produce dramatically more protein using much less land area than a traditional soya bean plantation in South America, and therefore the land use profile of this technology is much more sustainable.

The industry and academic partners working on the REACT-FIRST project include BioMar, who will be developing the formulations for the inclusion of Proton^{TM} in aquafeed, the Institute of Aquaculture who will be trialling these feeds for the use in salmon aquaculture, including assessing the nutritional quality, digestibility and the performance and health status of the fish involved.

Table 5 Overview of different salmon aquaculture production systems.

Location	Land based	Inshore (sheltered)	Inshore (exposed)	Offshore
Fish production	• Smolts • Post-smolts • Harvest size	• Post-smolts • Harvest size	• Post-smolts • Harvest size	• Harvest size
Design	• Closed recirculating aquaculture systems • Flow through aquaculture systems	• Closed/semi-closed containment • Open systems	• Closed/semi-closed containment • Open systems	• Closed/semi-closed containment • Open systems

The adoption of offshore and high-energy site farming is also a priority for the Scottish Government, as highlighted in the Rural Economy and Connectivity Committee (RECC) report published in 2018 from the inquiry into Scottish salmon farming. "The Committee recommends that work to examine the scope for siting salmon farms in suitable offshore and other locations where there are higher energy water flows should also be treated as a high priority by the industry. It acknowledges that there are significant technological challenges associated with locating farms in these areas, as well as risks in terms of workforce health and safety. However, it also notes the benefits this could bring in terms of addressing fish health issues, reducing the environmental impact of waste and providing scope for the industry to develop higher capacity sites" (RECC, 2018).

In Scotland, the move to high-energy sites is already underway, with a site currently being tested 2.5km off the coast of Orkney. The Skelwick Skerry site which is owned by Cooke Aquaculture is the first of its kind in Scotland and already has four cages installed out of a planned eight cages at the location, with a similar sized site also planned close by. These cages are 130m circumference, 50m deep and around 28,000m^3 in size and were designed specifically to cope with the increased wave action in these areas. The testing site project is being supported by Marine Scotland and the Sustainable Aquaculture Innovation Centre (SAIC). The site has already succeeded in growing salmon to harvest weight, although this first attempt used fish transferred at an average size of 2.5kg, which is much larger than the average smolt size currently transferred to sea cages. However, from this initial trial, fish health, growth rates and mortality have showed positive signs and there is optimism for increased production in high-energy sites in the future (Houston, 2019).

Another promising development in this area for Scotland is the 'Impact 9' (https://www.impact-9.com/) offshore production systems, funded to carry out a feasibility study in Scotland using an offshore submersible cage for salmon farming called Net9^{TM}. The concept cage is larger than those at Skelwick Skerry, at around 282m in circumference, with a volume of 125,000m^3 and will be placed in deeper water (65-90m). The cages have been specifically designed with welfare in mind; they will be at least 6 metres below the surface which should alleviate health issues caused by sea lice and algal blooms. These are already reduced the further offshore cages move (Fish Farming

Expert, 2019a). The company also plans to introduce waste capture technologies into the systems along with renewable energy solutions with options to integrate the cages at offshore renewable energy sites.

The successful implementation of these high energy production systems could greatly increase the production capacity of farming while also help reduce environmental concerns about current production methods in the near future.

Norway has already developed offshore fish farms. In 2017 SalMar introduced Ocean Farm 1, the world's first offshore fish farm as a pilot structure to test research and develop the offshore structure technology with a focus on fish health and welfare (SalMar, 2020). The system, located 5km off the coast of Norway, is 110m in diameter, over 40m deep and has a volume of 250,000m^3 potentially holding 1.5 million Atlantic salmon. The company states that the first production results from the system were very positive, showing high survival, good quality and low levels of sea lice (Evans, 2020).

Due to the links between the Norwegian and Scottish salmon industries, with Norwegian companies being the majority owners of several enterprises operating in Scotland, it would be reasonable to expect that offshore, high energy systems will soon be adopted in Scotland, provided they continue to prove successful and are supported by Scottish licensing and regulation. Scottish Sea farms announced in 2020 that it hopes to trial Scotland's first open ocean farm similar to the Ocean Farm 1 (Fish Farming Expert, 2020b).

The shellfish production industry is also interested in offshore farming. In 2019, Offshore Shellfish ltd (https://offshoreshellfish.com/) opened the UK's first large scale offshore mussel farm, around 6 miles off the coast of South Devon, and plans to have three sites in the area, covering a total area of 15 square km with the potential to produce 10,000 tonnes per year. This site could produce more mussels than the entire Scottish mussel industry, which currently produces around 6700 tonnes annually over several different sites (Marine Scotland Science, 2019b). The success of this operation provides a real opportunity for increased shellfish production through offshore systems in Scotland.

Research on the ability of offshore farms to reduce negative environmental impacts from nutrient release compared to conventional systems has given varied results. Some studies have reported that waste release can be reduced or minimised by ensuring good site location and farm management; others have reported that nutrients might become concentrated due to a lack of dispersion in areas potentially far from the site of release at the fish farm, highlighting the importance of modelling the potential trajectory of nutrient mixing and dispersal from these systems prior to giving consent (Buck et al, 2018).

One of the challenges to farming fish offshore or in higher energy sites is the need for their population with larger more robust smolts that can withstand the harsher environments at these locations. Therefore, in parallel with the development of high energy farming systems the industry is also developing technologies to increase the growth size of smolts prior to transfer to open cage marine systems, including the use of inshore closed and semi closed nursery systems and larger land based recirculating aquaculture systems (SARF, 2019; Evans, 2020).

Closed containment aquaculture systems

The industry is also interested in the use of closed containment aquaculture systems, either as nurseries or for full salmon on-growing, in inshore waters and offshore. Closed systems benefit from the ability to control and filter the water supply entering the system and in some cases this can be pumped from a greater depth to remove the threat of harmful algae and sea lice being introduced into the cages. Early prototypes were developed in the 1990s but high capital investment and operational costs led to failure in competition with traditional open net cage systems.

When used as nurseries closed systems offer the opportunity to increase the size of smolts for transfer to high-energy/offshore sites, increasing the survival rate. A recent technical report commissioned by SARF (Scottish Aquaculture Research Forum) and carried out by the Institute of Aquaculture at Stirling University, looked at the feasibility of adopting closed containment sea pens for smolt production in Scotland. The report calculated that if the whole Scottish industry adopted this strategy the output from current sea-based on-growing sites could be increased by 70% (SARF, 2019).

Benefits from adoption of this system include:

- Increased optimisation of current biomass limits from existing farm sites
- Reduced time of smolts at sea, thereby reducing the impact of environmental health challenges
- The ability to collect, treat and dispose of fish faeces and feed waste

Norway aims to use closed containment to produce large post-smolts (up to 1kg) prior to transfer to open pen systems. Mowi, a Norwegian company and the largest producer of Atlantic salmon in Scotland, have begun developing a closed aquaculture system with Huage Aqua, resulting in a prototype called ‘the Egg’.

Other successful examples include the Neptun system designed by Aquafarm Equipment (https://aquafarm.no/) which has been tested since 2013 to grow salmon to 1kg prior to transfer to open marine cages. The system can hold up to 1 million fish and has a sophisticated pumping system able to source water from 30m deep, filter it, treat it with UV light and oxygenated it. The system also allows for the capture and utilisation of 60-70% of fish waste, with the goal to increase this to 80-90%, contributing to circular value chains for waste re-use while also decreasing the nutrient loading impacts of open farming systems (SARF, 2019). Compared to land-based RAS systems the company state these systems reduce energy consumption by 75%. Trials have also showed that fish mortalities are less than 0.5% and the feed conversion ratio is increased to 0.85. Mowi have reported they plan to use these systems in Scotland in the near future (The Fish Site, 2019).

Closed containment systems can also be used to grow salmonids to full harvest weight and this is the goal of the Inverness based company Aqua Innovation (https://aquainnovations.co.uk/) who are developing a closed containment aquaculture system, the SeaCap6000, for use in the Scottish aquaculture industry. The system has been designed with Scottish environmental conditions in mind and can either be floating or attached to the seabed and constructed at local oil rig fabrication facilities using local labour and materials. The prototype will be 6000m^3 and will grow salmon to harvest weight with the system designed to provide optimum environmental control and fish health. Waste will also be captured and utilised within the proposed system. The system is being designed for the use of salmon and trout production in the UK to grow fish from 100g to 5kg (market size).

Recirculating Aquaculture Systems (RAS)

Re-circulating aquaculture systems (RAS) are closed containment systems mainly used for freshwater aquaculture on land. For salmon these systems mainly act as nurseries and smolt growing systems during the freshwater stage of production, prior to the transfer of juvenile fish to open sea based production systems. The technology can also be adapted to salt water and used to grow market size salmon, but to date challenges including high energy demand have prevented full growth of salmon species on land as a sustainable option. As discussed above there has been growing interest in the production of larger smolts to reduce the time salmon spend at sea, which can reduce localised environmental impacts from open cage systems, reduce the risk of adverse health impacts and improve smolt transfer mortalities. This practice will also become more important if the industry begins to farm offshore or in higher energy sites.

As for offshore farming, the use of RAS production methods is also a priority for the Scottish Government, as highlighted in the Rural Economy and Connectivity Committee (RECC) final report published in 2018 from the inquiry into Scottish salmon farming. The report noted “The Committee endorses the ECCLR Committee’s recommendation for urgent research on the subject and the consideration of ways to incentivise the industry to explore further use of the technology. However, it is aware that RAS is not the only closed containment option and would encourage wider research on alternative technologies” (RECC, 2018). RAS systems have been used for many years and the technology is not necessarily novel, but there has been significant improvement in the scale, sophistication and waste utilisation potentials of the systems.

There has been increased research and some successful examples of the use of RAS to grow harvest size salmon and with this comes some environmental benefits as the system is contained and prevents waste, chemicals and diseases being transferred to the marine environment from production systems. However, significant improvements will be required for this to be sustainable. Unlike closed containment sea based systems and offshore methods, RAS systems have been subjected to environmental impact assessments and these will enable us to understand the benefits and pitfalls of these systems and to address them. **Table 6** summarises the results of LCA research on RAS production systems for salmon and trout farming across the world, showing marked differences between studies, potentially due to the energy mix, methods of calculation, the fish diet, and feeding efficiency of the system. This variation is to be expected, given that this production method is not yet widely used and there is a lack of standardisation in the methods of production. These LCA studies did show that all the RAS systems reported higher GWP and cumulative energy demand (CED) than the average of all studies on traditional open sea based cage farming, which is currently used for the majority of salmon production.

Several studies have modelled the potential to reduce RAS emissions and energy demand by altering the energy mix used to power them. Phillis et al (2019) reviewed salmon aquaculture LCAs, demonstrating that using an alternative renewable energy mix can significantly reduce GHG emissions for RAS systems. Also, using wind power has the potential to reduce RAS GHG emissions by a factor of 10 and there was a 50% reduction in GHG emissions from RAS systems fuelled on a 90% hydropower mix in the US (Lui et al 2016).

Research on the environmental impacts of these fish farming production technologies has not kept pace with their development. It is clear that there are benefits from offshore farming, land based aquaculture and closed and semi closed marine systems, but it is difficult to quantify the potential environmental emissions reduction from these systems compared to conventional fish farming systems. Further research is needed to bridge this gap and ensure that new production systems support the industry and government targets such as net zero carbon emissions.

Table 6 Global Warming Potential and Cumulative Energy Demand from LCA studies of RAS and open sea based systems, from cradle to farm gate using each production method.

LCA studies	System	Global Warming Potential (Kg CO_2-eq)	Cumulative Energy Demand (MJ)
Wilfart et al, 2013 (France)	Land based RAS	3137	105,800
Lui et al, 2016 (US)	Land based RAS	5370	-
Ayer et al, 2009 (Canada)	Land based RAS	10300	233000
Song et al, 2019 (China)	Land based RAS	16757	203257
Avg all studies (global)	Land based RAS	8891	180685
Avg all studies (global) (*Phillis et al, 2019)	Sea open based pen	2933	37913

* Average results for open sea based pen sourced from LCA literature review (Phillis et al, 2019)

4.4 Fish Processing

Reusable bulk bin packaging

For the export of products, despite considerable research, single use polystyrene boxes remain the only viable packaging option. Recyclable cardboard boxes have been trialled but there were problems with the integrity of the boxes and their ability to maintain the necessary chilled temperature.

There are other options for the large proportion of Scottish salmon that goes to commercial processing sites in the UK, destined for UK supermarket chains. In 2017, Scottish Sea Farms, in collaboration with their processing company Dawnfresh Seafood ltd., developed a reusable bulk bin packaging for domestic transport that can hold significantly more fish than a polystyrene box and holds the fish in an ice slurry to maintain temperatures. The bulk bins containing fish are sent to the processing site, cleaned and returned to collect the next load of fish. A study by the Caledonia Environment Centre found that the innovation had replaced 780,000 EPS single use boxes with a saving of 4,100 tonnes of carbon (Fish Farming Expert, 2019b). If other companies adopt this approach for domestic fish sales it could result in further carbon savings.

Biodegradable food packaging from shellfish waste

There is growing interest in the use of shellfish by-products (shells) as a novel source of packaging materials. Currently the market for shell by-products is relatively small as our bivalve products are sold with shell on or exported and therefore there is little potential to capture these by-products prior to export or going into household/hospitality waste.

The company CaunTec is developing biodegradable novel packaging from langoustine shells, a by-product from the fisheries industry. The process uses fermentation to extract chitin from the shells to create a film similar to the current plastic packaging that can be disposed of in a compost bin.

Although this is not yet a use of aquaculture waste, the company have partnered with Waitrose who hope to use it in all seafood packaging, beginning with trials in salmon (Cauntec, 2019).

This is an example of how companies are developing innovative technologies with circular economy approaches and helping to advance zero waste targets. Although the technology is still in early development, it would also be reasonable to suggest that this innovation will have carbon reduction benefits from repurposing landfill waste and reducing plastic production required for packaging.

Case Study 4: Innovations in Freshwater RAS Hatcheries

The advancement in freshwater RAS technology is already being utilised in Scotland. In 2017 Scottish Sea Farms (SSF) opened their new state of the art RAS facility in Barcaldine, Oban. The facility which cost £58 million was designed to allow the company to double its smolt production capacity to 10 million per year and also increase the size of their smolts prior to the transfer to open sea cages. The first smolts grown on the site had an average weight of 178g, which is more than double the weight SSF would expect of smolts grown through conventional hatchery methods. These first smolts were then harvested from sea fully grown in 2020, requiring two months less time at sea to reach market size (Scottish Sea farms, 2020).

The RAS facility will allow SSF to increase their production capacity, reduce the time salmon spend in open environments as well as potentially provide a stepping stone to farming fish further offshore and reducing mortalities at smolts transfer.

As well as these benefits the facility has been designed with environmental sustainability and bio-security in mind. The site has been designed to be waste free and to optimise value streams by capturing and repurposing waste.

Water is supplied to the hatchery from a private reservoir, and 99% of this water is re-circulated, providing an estimated 20% saving on traditional hatcheries. This water is cleaned via filters and UV light, avoiding the need for chemicals (Scottish Sea Farms, 2020).

Maintaining water temperature is achieved through heat pumps and exchangers which use less energy than conventional kerosene boilers and electric chillers. The rest of the site is heated through a biomass system run on locally sourced wood chip, which has been reported to save 683 tonnes of carbon per year compared to using oil (Salmon Business, 2021).

The hatchery also has a system for collecting sludge, which is bound into larger particles and repurposed as an agricultural fertiliser. This system can be further optimised to remove the remaining water content and convert the sludge to dry pellets, which would reduce the volume of waste being transported and further improve environmental footprint.

4.5 Waste and by-product management

Solid organic waste and by-product outputs from Scottish finfish aquaculture include:

- Organic particulates (mainly uneaten food and fish faeces), from all stages of fish production (freshwater hatcheries (RAS) and freshwater and marine cages);

- Fish mortalities from all stages of fish production (freshwater hatcheries (RAS) and freshwater and marine cages);
- Cleaner fish (e.g. wrasse and lumpsuckers); including mortalities and fish at the end of the harvest cycle when they are euthanized; and
- By-products produced during processing including all non-fillet parts of the fish (heads, frames, viscera, blood, skin and trimmings)

Organic (sludge) waste

There is increasing concern over the environmental release of organic waste from open net based systems, including fish faeces and uneaten food (Keeley, 2014). This is particularly an issue where water currents are slow and wave action is low, reducing the dispersal of waste away from the cage. SEPA notes that "the discharge of a pollutant to the environment will cause harm if the quantity of the pollutant discharged (the load) is greater than the quantity of the pollutant that the environment is able to assimilate" (SEPA, 2019). Where organic matter particulates sink to the seafloor they increase the biological oxygen demand as they degrade, in severe cases causing anoxic environments with a smothering effect on benthic marine life, habitat degradation and a loss or change to local biodiversity (Keeley, 2014).

SEPA is the regulatory authority ensuring that discharge of pollutants is kept within safe limits by calculating the pollutant load that will be generated and using modelling software (DEPOMOD) to predict the solid accumulation that will deposit on the seabed from the farm and the potential benthic faunal impacts from this (Cromey et al, 2002; SEPA, 2019). SEPA sets biomass limits (Maximum Allowable Biomass) on sites and monitors these limits to ensure they are being adhered to, noting what impact if any on the local benthic ecosystem. SEPA is now considering a new method for allocating site licenses based on total weight of feed used rather than total weight of fish (biomass) and they are consulting with industry to decide on the future limits (SEPA, 2019).

The area covered by this organic matter can be 0.5 km^2 around a 1500t biomass farm (SAMS, 2018) and further research is required to understand the scale of waste from aquaculture in sea lochs and the environmental impact on local biodiversity. This organic matter along with chemicals from treatments and therapeutics can also increase eutrophication in the lochs causing increased phytoplankton growth which in turn can have negative impacts on fish health.

As discussed in **Section 4.3**, modelling the waste dispersal capability for new site developments is important to avoid locating cages in areas where waste will accumulate, another reason why the industry is increasingly considering moving to offshore and higher energy locations. Aquaculture companies also operate sites on a rotational basis, known as fallowing, where sites have periods where no fish is produced to allow the area to recover. Recovery is mostly dependant on wave and current energy and substantial recovery around areas of fish farming in Scottish lochs has been reported within 1-2 years after production stops.

Organic waste is a natural product of animal production and is also present in terrestrial farming systems; for example in 2016, nitrogenous waste from Scotland's total sheep production was twice that of salmon while delivering only a quarter as much edible food (SAMS, 2018).

New sites in high energy or offshore locations, or producing fish in semi-closed sea cages are potential solutions to avoid impacts from organic waste build up around fish farming (**Section 4.3)**. Sludge from these systems can also be captured, treated to produce dry solid matter and then used as fertiliser or bio-fuel.

In open water cages there is no method for collecting organic waste and this is why biomass limits exist. However, there is some exploratory work on waste capture systems integrated beneath a traditional salmon pen which can capture the organic waste and could be retrofitted to farms in low energy areas that could become in breach of the SEPA site licensing regulations. Aqua Innovations Ltd. located in Scotland have been developing a Waste Capture System that acts like a funnel under the cage to collect organic waste and pump it to the surface where it can be collected and recycled into fertiliser or bio-fuel. This could allow operators to increase their production and still adhere to regulations, helping the industry to meet its targets for aquaculture growth while also contributing to zero waste and circular economy agendas. The first pilot system was installed in Ardessie, North West Scotland in July 2020, with initial results on waste recovery being positive (Seafood Innovation, 2020).

A similar innovation is being trialled in the Norwegian salmon industry. The company Lift Up began developing their sludge capture system in 2012 as an evolution of its fish mortality collection system. It uses a combi-cone which pumps both sludge and fish mortalities up to the barge, the waste water is then filtered producing 10% dry matter. They are also looking into the value of producing biogas from the waste captured. Their pilot system deployed in 2020 has shown promising results: for every tonne of feed delivered into the cage, 650kg of sludge was captured and the company plans to improve the technology to increase further the feed to sludge ratio.

These waste removal innovations align with the Scottish Government's recommendations to address environmental concerns from Scottish salmon farming as highlighted in the Rural Economy and Connectivity Committee (RECC) report: "The Committee believe that it is essential that the issue of waste collection and removal is given a high priority by the industry, the Scottish Government and relevant agencies. It is clearly one of the main impacts on the environment and needs to be addressed as a matter of urgency." (RECC, 2018, Recommendation 29). The capture of fish farm cage waste will also contribute to the SDG 14, to prevent and significantly reduce marine pollution of all kinds from land based activities, including marine debris and nutrient pollution, by 2025 (United Nations, 2015).

Fish mortalities

Producers strive to reduce fish mortalities (often referred to as 'morts') but a consistent low volume of mortality is inevitable, e.g. from disease or sea lice infestations. Mass mortality events can also occur due to disease, harmful algal blooms (HABs), jellyfish blooms, predator attacks, severe sea lice infestations or extreme weather, and on rare occasions this could result in the culling of an entire cage of fish (Newton et al, 2013).

Fish morts are classified as Category 2 animal by-products and cannot be used in the human food chain. They must be disposed of safely, in an environmentally responsible way as outlined in the Animal By-Product (Enforcement) (Scotland) regulations 2013 (ABP(E)(S)). Suitable disposal includes incineration, rendering, in vessel composting, or anaerobic digestion at approved plants (Zero Waste Scotland, 2016). Disposal of morts was permitted via landfill in remote areas (where most fish farms are located), but the Scottish Government amended this regulation in 2016. Many operators are still investigating the most valuable and feasible options for the disposal of fish morts and this presents an opportunity to optimise value streams from fish mortalities, similarly to other organic waste from industry (Zero Waste Scotland, 2016). The disposal of morts can be costly, especially in areas that are remote such as Scottish islands and so there are both economic and welfare incentives to reduce the level of morts.

The fish farming industry in 2019 produced over 200,000 tonnes of finfish and in 2020 the Salmon industry reported an annual average mortality rate of 14.5% (SSPO, 2021). Using these data, processing all the industry morts through anaerobic digestion could produce 2,900 tonnes of oil.

The industry sets a high priority on reducing mortalities by improving health and welfare of fish through technology such as vaccines and sea lice interventions, environmental monitoring systems to detect and mitigate events that could affect fish health, closed containment systems, and increasing smolt size of fish transferred to sea cages.

The company SEM (**Case Study 5)** have developed a biodiesel production facility for fish mortalities and are at the same time trying to reduce fish mortalities. They have developed an algae monitoring system that detects potentially toxic levels of organic matter build-up such as detritus or harmful algal blooms in the areas surrounding fish farms and can alert operators to a potentially harmful event so they can take action to protect the fish stocks.

In fish farming there will always be some level of mortality and increasing the value of these by-products and recycling waste back into usable materials is also an important avenue for investment. Anaerobic digestion to produce biogas was identified as the permitted disposal method for morts which could produce the highest value product (Newton et al, 2013). However, biodiesel production, a novel method in the sector, can produce even higher value products and was highlighted as a potentially better solution for the treatment of morts (Zero Waste Scotland, 2016).

A common thread throughout our research and communications with industry was the need for aquaculture companies across Scotland to come together to invest in, and implement, new waste and by-product innovations to make them more feasible and reduce the carbon footprint of fish processing. Collaboration between companies and other industry bodies to develop disposal and processing centres around the country to deal with morts could enhance progress on optimisation of waste stream treatments and also produce cost savings (Newton et al, 2013; Zero Waste Scotland, 2016). This was also the opinion of the company SEM who have already developed a biodiesel production site in Shetland which takes waste from multiple companies and they hope to further expand this model into mainland Scotland to service the West Coast and Highlands aquaculture enterprises (SEM, Personal Communication, March 2021).

Further research including cost benefit analysis and environmental assessments should be carried out on these by-product processing operations in consultation with the aquaculture industry to understand better the potential capacity for higher value products to be produced and the potential environmental footprint of these value chains.

4.6 Environmental impact calculating tools

Understanding the environmental impacts of fish farming is key to making informed decisions on how to achieve sustainability of the sector, driving evidence based policy decision making (Samuel-Fitwi et al, 2012). There has been increasing interest in the quantification and modelling of environmental metrics for food products to provide clarity on the environmental performance of food systems and to encourage the adoption of mitigation measures which could improve their performance. Such accounting tools have been in development for many years and several are being used across agricultural industry sectors. The focus is predominantly on calculating GHG emissions of farms or food systems, but they are also being developed to include biodiversity, land and water use. Examples of carbon accounting tools used across the UK agriculture industry include the Cool Farm Tool, AgRE Calc and Farm Carbon Calculator.

Case Study 5: Optimising value chains from fish mortalities and by-products

The company SEM (https://sem.world/), based in Aberdeen, Scotland, is developing innovative solutions for industry with the goal of aiding the evolution of zero-waste, the circular economy and securing the planet's health and wealth for future generations. The focus is on developing innovations to repurpose waste, recovering resources and nutrients for re-use.

The company is working on several aquaculture based innovations spanning the production value chain. One of these is the PLUTUS technology, producing high value by-products based on waste from fish processing such as Category 2 fish mortalities, separating the raw material into suspended solids, oils and water. These are high value by-products: the solid matter can be sold as fertiliser and the oil can be processed to create biodiesel for fishing vessels or for public transport. Fish oil can replace fuel in unmodified diesel engines, and oily fish such as salmon and trout produce high yields (Newton et al, 2013).

This process can also take Category 3 waste from fish processing to create food grade protein and omega-3 oils used in, for example, terrestrial livestock feed, pet food and pharmaceuticals, reducing reliance on fish meal and fish oil from wild capture fisheries.

A working harbour based biodiesel plant in Shetland has a capacity of 10,000 tonnes and can take whole morts or macerated morts This is particularly beneficial for mass mortality events where large volumes of Category 2 waste is required to be treated urgently. The partnership with the operators who supply the feedstock is an example of a circular economy operation in that the waste from the operator's production is being re-purposed to produce cleaner biodiesel for local fishing vessels. Previously the fish morts were transported by lorry to Fife where they were processed at an anaerobic digestion plant.

A carbon assessment of this process, comparing it with the previous process, showed that the biodiesel produced in the new plant is a higher value product than biogas and could achieve a 96% reduction in carbon emissions compared to the previous operation (36,545 kg CO_2-eq. compared to 1,011,638 kg CO_2-eq per year). The majority of the emission savings were attributed to the reduction in transport-related emissions. The system had a higher electricity power demand and CO_2 emissions than the previous AD operation, but the savings in other areas mean that the operation is still more environmentally efficient. The energy demand is an area where the industry should focus its attention, to improve its carbon footprint further (SEM, Personal Communication, March 2021).

The company's goal was to achieve the 60% reduction in carbon emissions required to qualify for a Renewable Transport Fuel Certificate, a scheme implemented by the Renewable Transport Fuel Obligation outlined by the Scottish Government, to reduce greenhouse gas emissions from vehicles by encouraging the production of biofuels which do not damage the environment. Under the certification, companies producing biofuels from wastes rather than agricultural products are favoured to diminish undesirable impacts from agricultural production.

A great deal of work is required to optimise the benefits of these tools (CIEL, 2020). The Cool Farm Tool started as a carbon accounting tool for crop production and later included livestock production. More recently it has been developed into a multi-impact tool incorporating sustainability indicators for water and biodiversity (Cool Farm Alliance, 2020). This tool, as for the others, uses empirical models to estimate the full farm life cycle emissions from agriculture products and allows farmers to explore alternative management choices and potential mitigation options that could help to reduce their environmental impact (Hillier et al, 2011). The tool is now used by several large food and feed production companies across the world.

Case studies on the use of these tools have highlighted their ability to reduce GHG emissions. Egg farmers who used the Cool Farm Tool to quantify their GHG emissions and investigate different mitigation options, implemented changes that resulted in decreasing their emissions by 25% over three years (Vetter et al, 2018). A case study using the AgRE Calc tool on a dairy farm, resulted in the farmer reducing carbon emissions by 16% over four years (2014-2018), by implementing mitigation options provided through the online tool (AgRE Calc, 2021).

Currently no tools like those used in agriculture are available for aquaculture systems. They could provide information on the current environmental performance of aquaculture systems and products and also highlight the beneficial impacts of innovative products and processes, for example new feed ingredients and production systems. There is growing interest in the development of such tools for use in the aquaculture industry and we recommended further research is targeted to advance these developments. One of the biggest challenges in using such tools is the lack of comparability across the outputs of different tools, highlighting the importance of having standards available that would ensure comparability, and encouraging user compliance with the standard.

4.7 Animal Health and Welfare

Although not directly within the scope of this project, it is important to note that the Scottish aquaculture industry has invested in addressing health issues of farmed fish and ensuring optimal fish welfare throughout production. The industry faces health challenges from disease and pathogens that are difficult to control, given the nature of farming in open water. Important health challenges for the finfish industry are sea lice and gill health issues, and for shellfish, pathogens and viruses remain a challenge (Jones et al, 2016). Health issues have fish welfare implications, and also limit production therefore detection, prevention and treatment is a top priority for the industry. Addressing health challenges was highlighted as a high priority area for innovation by the Sustainable Aquaculture Innovation Centre, forming one of their five key innovation areas. The challenge requires collaboration across the industry and was seen as a barrier to growth if not addressed (SAIC, 2017). The Scottish Salmon Producer’s Organisation states that “Health and welfare is the Scottish salmon farming sector's number one priority” (SSPO, 2021).

Sea lice infestation is the most immediate challenge to the salmon industry, and was rated as the most important pathogen for sustainable development of the finfish sector (Jones et al, 2016). Sea lice are caligid copepods that attach themselves to the skin of salmon and feed on mucus, blood and skin. Infections can be low to severe and if not treated can lead to skin lesions, causing secondary infections, immunosuppression and stress (Overton et al, 2018). Interventions to control sea lice in salmonid production are long established, requiring labour and investment. The cost of interventions was calculated to be around 9% of farm revenue in the Norwegian salmon industry (Abolofia, Asche & Wilen, 2017).

Traditional treatments for sea lice include in-feed anti-parasitic drugs or medicinal bath treatments applied to sea cages. Resistance to these treatments and concerns over the environmental impacts from the release of chemicals and medicines into the local ecosystem has resulted in the industry looking for alternative innovations to treat the parasites (Shephard and Little, 2014).

Alternative methods to combat sea lice include: thermal treatments, where fish are placed in warm water for a short time (e.g. Thermolicer®); mechanical removal, through the use of water jets (e.g. Hydrolicer®); and biological control using 'cleaner fish' such as Ballan wrasse and Lumpsuckers (Overton et al, 2018; Shephard and Little, 2014). With regards to cleaner fish, the industry has had great success with using these fish to control infections, but the use of wild populations of wrasse to be used in the industry has been criticised. In response, the industry has carried out research on the farming of cleaner fish, and a consortium of industry partners has succeeded in rearing wrasse for commercial use (SAIC, 2021). The industry is still innovating in this area, for example using underwater lasers to shoot lice off the fish (Optical Delousing™, Stingray Marine Solutions AS, Norway) and further innovative solutions to dealing with this critical health issue are expected.

As already outlined, closed containment production systems, increased size of smolts and farming in high energy sites are other methods the industry is considering which could reduce the impact from sea lice as well as other biological threats to fish health.

It is clear from the amount of innovation and research in this field that the industry is determined to optimise health and welfare of fish production. The finfish industry in Scotland prides itself on its high welfare standards and most companies subscribe to the RSPCA welfare standards.

5. Conclusions

There is strong policy support in Scotland for expansion of the aquaculture sector with an emphasis on sustainable development, contributing to the Net Zero, circular economy/zero waste and biodiversity policy agendas, and UN Sustainable Development Goals.

It is also clear that a shift in human diets from beef and sheep meat to fish would, in itself, have a major impact on global warming. However, wild-capture fisheries have little capacity to expand without risking a collapse in fish stocks and seriously damaging marine biodiversity so the capacity of seafood to meet the world's (and Scotland's) increasing demand for protein will need to come from farmed sources. This highlights the importance of being able sustainably to increase the production of protein foods based on aquaculture, and the role of innovative technologies in meeting that need.

This is a very dynamic area with strong innovation activity and moving policy targets. For example, there are plans for major reductions in GHG emissions from cattle production in Scotland (Suckler Beef Climate Group, 2020), potentially reducing, but not eliminating, the disparity between the GWP potential of beef and fish consumption. Also, on 20th April 2021 the UK Government announced a reduction in the timescale to meet Net Zero targets and there is a new emphasis on the biodiversity losses being caused by wild capture fisheries. The issues discussed in this report are therefore likely to remain salient for the foreseeable future.

The innovations considered in this report all have a potential to contribute to the relevant policy goals, with varying degrees of impact (**Table 7**).

- **Aqua-feed innovations** will have the biggest positive impact on both GHG emissions (Net Zero policies) and aquatic and land biodiversity (SDGs). They will also contribute to several circular economy value chains and zero waste agendas.

- **Innovative production systems** so far seem likely to have greater energy demands, and therefore GHG emissions, than those currently in use, although this could change as energy systems become less reliant on fossil fuel inputs. On the other hand, they will contribute to reductions in the impact of pollutants and improvements in fish health, and will be necessary for the expected expansion of the aquaculture sector in Scotland.
- **Fish processing** is a key component of the aquaculture value chain and innovative developments are already contributing to a reduction in GHG emissions. This component of the value chain will also be an important contributor to the circular economy.
- **Waste and by-product management** will also make modest contributions to reductions in GHG emissions and will be important contributors to several circular economy value chains.

Factors that should be included in future analyses but are not dealt with here are:

- The geographically distributed nature of the aquaculture sector, making transport costs an important factor to include in all LCAs, potentially favouring innovations that can be part of localised circular economy developments;
- Opportunities for data capture from distributed facilities to enable improved learning and uptake of innovations across the sector;
- Opportunities from genetic research to enable development of disease resistant fish and (potentially) more productive variants; and
- Given the differences in GWP between finfish and shellfish, evaluation of policy and other supports directed to increasing the role of shellfish in our diets.

Clearly, some innovations, considered in isolation, will have a greater contribution than others to climate change and biodiversity impacts, but this should not lead to a simplistic approach to prioritising policy initiatives and investment. A systemic approach, taking account of the entire value chain and the interactions between businesses and between policies (**Figures 8 and 9**) will be needed to deliver the outcomes that are nationally optimal for Scotland and internationally competitive.

Table 7. Environmental and related issues for the Scottish aquaculture industry and relevant innovations.

Concerns relevant to Scottish aquaculture	**Innovations included in study**					
	Closed/semi production systems	Sea lice controls	Environmental monitoring (e.g. HABs, sea lice)	Alternative feed ingredients	By-product /waste capture and utilisation	Packaging innovations
Feed ingredient sustainability				🟩	🟩	
GHG emissions from food production	🟩	🟩		🟩	🟩	🟩
Sea lice	🟩	🟩	🟩			
Disease transfer to wild populations	🟩	🟩				
Organic waste from sea cages	🟩		🟩		🟩	
Eutrophication of water bodies	🟩		🟩		🟩	
Medicines and chemicals used in cages harming local organisms	🟩	🟩	🟩			
Fish escapes (genetics dilution of wild populations)	🟩					
Predator control	🟩		🟩			
Exploitation of wild wrasse populations	🟩	🟩	🟩			

6. Recommendations

This report helps to identify what needs to be done to fill the research, development and policy gaps that exist in the aquaculture sector and to put Scottish aquaculture on an optimal footing, balancing the sometimes-competing demands of different environmental goals and different sectoral interests.

Specific gaps identified in this project include:

- Fermentation, to produce innovative feed or to re-use waste materials and by-products, is an energy intensive process and could be a source of environmental impact inefficiencies, and further research is needed on its effect on the environmental footprint of aqua-feed.
- For offshore, closed containment and recirculating aquaculture systems there is a need for greater scrutiny of their environmental and economic performance.
- The areas of waste capture and optimising the development of high value product streams from closed and open systems requires additional analysis to help offset their environmental footprint and to understand their capacity to deliver higher value products.

More investment in the development of life cycle analysis tools for the aquaculture sector will be needed, to judge the contributions of innovative technologies to different value chains and to support company investment decision making, and government policy development and implementation. This should cover both the development of effective methodologies and standards for their application to ensure comparability across different analyses.

At the national level, a systemic approach is needed, modelling the roles and contributions of the innovations discussed here, of the others that we were not able to include, and of new technologies as they emerge (**Figures 8 and 9 and Annex A**). Also, given the distributed nature of the industry, there are opportunities to build networks of smaller scale local recycling initiatives (e.g. **Case Study 5**) as contributions to the overall circular economy that is Scotland's ambition.

The policy role here is not to pick winners, but to create a supportive innovation ecosystem so that potential winners are not unnecessarily rejected in the early stages of development.

The systemic approach will help to understand the interactions between companies, innovators, investors, policy makers and regulators, and stakeholders and consumers, that will underlie success or failure at all levels. The approach should focus on the options with the biggest potential gains and those where synergistic interactions between different innovation initiatives could facilitate development and multiply positive outcomes or minimise negative outcomes.

Another important part of this systemic approach will be better communication about innovative technologies and their potential contributions to national environmental, health and economic objectives, particularly in the context of the UN COP 26 meeting in November 2021. There is an important current story to be told about the improvements in sustainability profile that have already been made by Scottish aquaculture and it will be helpful in enabling future innovative developments for the sector if citizens and interested stakeholder groups are more aware of these achievements.

7. References

Abolofia J, Asche F and Wilen JE (2017). The Cost of Lice: Quantifying the Impacts of Parasitic Sea Lice on Farmed Salmon. *Marine Resource Economics.* 32(3). http://dx.doi.org/10.1086/691981

AgRE Calc (2021). *Case study: Grosvenor Farms Limited.* AgRE Calc. Edinburgh. Available at: https://www.agrecalc.com/#casestudies

Aubin J, Papatryphon E, Van der Werf HMG, Petit J and Morvan YJM (2006). Characterisation of the environmental impact of a turbot (*Scophthalmus maximus*) re-circulating production system using Life Cycle Assessment. *Aquaculture*. 261(4): 1259-1268. https://doi.org/10.1016/j.aquaculture.2006.09.008

Ayer NW, and Tyedmers PH (2009). Assessing alternative aquaculture technologies: life cycle assessment of salmonid culture systems in Canada. *Journal of Cleaner Production*. 17(3): 362-373. https://doi.org/10.1016/j.jclepro.2008.08.002

Bacchetti T, Annibaldi A, Comitini F, Ciani M, Damiani E, Norici A, Tiano L, Truzzi C and Olivotto I (2020). Alternative ingredients for feed and food. In: Longhi S et al (eds). *The First Outstanding 50 years of "Università Politecnica delle Marche".* Springer. Switzerland. 529-545. https://doi.org/10.1007/978-3-030-33832-9_34

Belghit I, Liland NS, Gjesdal P, Biancarosa I, Menchetti E, Li Y, Waagbø R, Krogdahl A and Lock EJ (2019). Black soldier fly larvae meal can replace fish meal in diets of sea-water phase Atlantic salmon (Salmo salar). *Aquaculture.* 503: 609-619. https://doi.org/10.1016/j.aquaculture.2018.12.032

BioMar (2019). *Growing adoption of Algaprime™ dha is improving omega-3 content of farmed fish and accelerating sustainable aquaculture.* [Press release] Available at: https://www.biomar.com/en/global/articles/news/algae-as-a-replacement-for-marine-resources-is-gaining-market-acceptance/

Black K and Hughes A (2017). *Foresight - Future of the Sea: Trends in Aquaculture.* UK Government. London. https://www.gov.uk/government/publications/future-of-the-sea-trends-in-aquaculture

Boissy J, Aubin J, Drissi A, van der Werf HMG, Bell GJ and Kaushik SJ (2011). Environmental impacts of plant-based salmonid diets at feed and farm scales. *Aquaculture*. 321(1-2): 61-70. https://doi.org/10.1016/j.aquaculture.2011.08.033

Buck BH, Troell MF, Krausse G, Angel DL, Grote B and Chopin T (2018). State of the art and challenges for offshore integrated multi-trophic aquaculture (IMTA). *Frontiers in Marine Science.* 5(165). https://doi.org/10.3389/fmars.2018.00165

Carbon Trust (2016). *Assessment of environmental impact of FeedKind protein*. Carbon trust. London. Available at: https://www.carbontrust.com/resources/assessment-of-environmental-footprint-of-feedkind-protein

Centre for Innovation Excellence in Livestock (CIEL) (2020). *Net Zero Carbon and UK Livestock.* CIEL. York. Available at: https://www.cielivestock.co.uk/net-zero-carbon-and-uk-livestock/

Chen X, Samson E, Tocqueville A, and Aubin J (2015). Environmental assessment of trout farming in France by life cycle assessment: using bootstrapped principal component analysis to better define system classification. *Journal of Cleaner Production.* 87: 87-95. https://doi.org/10.1016/j.jclepro.2014.09.021

Committee on Climate Change (CCC) (2019a). *Net Zero: The UK's contribution to stopping global warming.* Committee on Climate Change. London. Available at: https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

Committee on Climate Change (CCC) (2019b). Reducing emissions in Scotland – 2019 Progress Report to Parliament. Committee on Climate Change. London. Available at: https://www.theccc.org.uk/publication/reducing-emissions-in-scotland-2019-progress-report-to-parliament/

Cool Farm Alliance (2020). *Cool Farm Impact Report.* Cool Farm Alliance. Lincolnshire. Available at: https://coolfarmtool.org/2020/10/cool-farm-impact-report/

Cottrell RS, Blanchard JL, Halpern BS, Metian M and Froehlich HE (2020). Global adoption of novel aquaculture feeds could substantially reduce forage fish demand by 2030. *Nature Food*. 1:301-308. https://doi.org/10.1038/s43016-020-0078-x

Cromey CJ, Nickell TD and Black KD (2002). DEPOMOD—modelling the deposition and biological effects of waste solids from marine cage farms. *Aquaculture*. 214(1-4):211-239. https://doi.org/10.1016/S0044-8486(02)00368-X

Cauntec (2019). *Cauntec Partners with Waitrose.* [Press release]. Cauntec. Scotland. Available at: https://www.cuantec.com/post/cuantec-partners-with-waitrose

DSM (2019). *Reducing our reliance on marine resources.* DSM. Netherlands. Available at: https://www.dsm.com/anh/en_US/feedtalks/feedtalks/reducing-our-reliance.html

Evans O (2020). Scottish Sea Farms to make Scotland's first 'ocean farm'. *Salmon Business.* 3rd March 2020. Available at: https://salmonbusiness.com/scottish-sea-farms-to-make-scotlands-first-ocean-farm-a-huge-rig-that-can-produce-up-to-20000t-of-salmon-per-year-in-exposed-waters/

Fernandes T, Eleftheriou A, Ackefors H, Eleftheriou M, Ervik A, Sanchez-Mata A and Pearson TJ (2001). The scientific principles underlying the monitoring of the environmental impacts of aquaculture. *Journal of Applied Ichthyology*. 17(4): 181-193. https://doi.org/10.1046/j.1439-0426.2001.00315.x

Fisheries and Oceans Canada (2019). *State of Salmon Aquaculture Technologies*. Government of Canada. Available at: https://www.dfo-mpo.gc.ca/aquaculture/publications/ssat-ets-eng.html

Fish Farming Expert (2019a). Taking the plunge: a submersible cage designed for Scotland. *Fish Farming Expert*. 17th September 2019. Available at: https://www.fishfarmingexpert.com/article/taking-the-plunge-a-submersible-cage-for-scotland/

Fish Farming Expert (2019b). M&S rewards Scottish Sea Farms for polystyrene purge. *Fish Farming Expert*. 20th June 2019. Available at: https://www.fishfarmingexpert.com/article/mands-rewards-scottish-sea-farms-for-polystyrene-purge/

Fish Farming Expert (2020a). Feed pioneers seek to get more out of whisky. *Fish Farming Expert.* 17th December 2020. Available at: https://www.fishfarmingexpert.com/article/omega-3-producer-seeks-to-squeeze-more-out-of-whisky-waste/

Fish Farming Expert (2020b). Scottish Sea Farms plans an ocean farm in Scotland. *Fish farming Expert.* 2nd March 2020. Available at: https://www.fishfarmingexpert.com/article/scottish-sea-farms-plans-an-ocean-farm-in-scotland/

Folke C and Kautsky N (1992). Aquaculture with its environment: prospects for sustainability. *Ocean and Coastal Management.* 17(1): 5-24. https://doi.org/10.1016/0964-5691(92)90059-T

Food and Agriculture Organization of the United Nations (FAO/INFOODS) (2016). *FAO/INFOODS Global Food Composition Database for Fish and Shellfish Version 1.0- uFiSh1.0.* Rome. Available at: http://www.fao.org/infoods/infoods/tables-and-databases/faoinfoods-databases/en/

Food and Agriculture Organisation of the United Nations (FAO) (2017). Global Livestock Environmental Assessment Model (GLEAM). Rome. Available at: www.fao.org/gleam/en/

Food and Agriculture Organisation of the United Nations (FAO) (2020). The State of World Fisheries and Aquaculture 2020 – Sustainability in action. Rome. Available at: http://www.fao.org/3/ca9229en/CA9229EN.pdf

Fry (2012). *Carbon Footprint of Scottish Suspended Mussels and Intertidal Oysters.* Scottish Aquaculture Research Forum. Oxford. http://www.sarf.org.uk/

Hallström E, Bergman K, Mifflin K, Parker R, Tyedmers P, Troell M and Ziegler F (2019). Combined climate and nutritional performance of seafoods. *Journal of Cleaner Production.* 230:402-411. https://doi.org/10.1016/j.jclepro.2019.04.229

Henriksson PJ, Guinée JB, Kleijn R and de Snoo GR (2012). Life cycle assessment of aquaculture systems—a review of methodologies. *International Journal of Life Cycle Assessment*. 17(3): 304-313. https://doi.org/10.1007/s11367-011-0369-4

Henry M, Gasco G, Piccolo E and Fountoulaki E (2015). Review on the use of insects in the diet of farmed fish: Past and future. *Animal Feed Science and Technology.* 203: 1-22. https://doi.org/10.1016/j.anifeedsci.2015.03.001

Hillier J, Walter C, Malin D, Garcia-Suarez T, Mila-i-Canals L, and Smith P (2011). A farm-focused calculator for emissions from crop and livestock production. *Environmental Modelling & Software*. 26(9): 1070-1078. https://doi.org/10.1016/j.envsoft.2011.03.014

Houston S (2019). *Blueprint for Aquaculture in Scotland*. Institute of food Science and technology (IFST). Scotland. Available at: https://ifst.onlinelibrary.wiley.com/doi/full/10.1002/fsat.3303_15.x

Hua K, Cobcroft JM, Cole A, Condon K, Jerry DR, Mangott A, Praeger C, Vucko MJ, Zeng C, Zenger K and Strugnell JM (2019). The Future of Aquatic Protein: Implications for Protein Sources in Aquaculture Diets. *One Earth.* 1(3):316-329. https://doi.org/10.1016/j.oneear.2019.10.018

Industrial Biotechnology Innovation Centre (IBioIC) (2020). *Addressing the global need for protein using next generation by-products*. IBioIC. Glasgow. Available at: https://www.ibioic.com/case-study-database/addressing-the-global-need-for-protein-using-next-generation-by-products?rq=aquaculture

International Panel on Climate Change (IPCC) (2018). *Annex 1: Glossary* [Matthews JBR (ed.)]. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte VP, Zhai HO, Pörtner D, Roberts J, Skea PR, Shukla A, Pirani W, Moufouma-Okia C, Péan R, Pidcock S, Connors JBR, Matthews Y, Chen X Zhou MI, Gomis E, Lonnoy T, Maycock M, Tignor and Waterfield T (eds.)]. Available at: https://www.ipcc.ch/sr15/chapter/glossary/

ISO 14044 (2006). Environmental management — Life cycle assessment — Requirements and guidelines. ISO. Geneva, Switzerland. Available at: https://www.iso.org/standard/38498.html

Jones AC, Mead A, Kaiser MJ, Austen MCV, Adrian AW, Auchterlonie NA, Black KD, Blow LR, Bury C, Brown JH, Burnell GM, Connolly E, Dingwall A, Derrick S, Eno NC, Gautier DJH, Green KA, Gubbins M, Hart PR, Holmyard JM, Immink AJ, Jarrad DL, Katoh E, Langley JCR, Lee DO, Le Vay L, Leftwich CP, Mitchell M, Moore A, Murray AG, McLaren EMR, Norbury H, Parker D, Parry SO, Purchase D, Rahman A, Sanver F, Siggs M, Simpson SD, Slaski RJ, Smith K, Syvret MLQ, Tibbott C, Thomas PC, Turnbull J, Whiteley R, Whittles M, Wilcockson MJ, Wilson J, Dicks LV and Sutherland WJ (2015). Prioritization of knowledge needs for sustainable aquaculture: a national and global perspective. *Fish and Fisheries.* 16: 668-683. https://doi.org/10.1111/faf.12086

Jones SW, Karpol A, Friedman S, Maru BT and Tracy BP (2020). Recent advances in single cell protein use as a feed ingredient in aquaculture. *Current Opinion in Biotechnology.* 61: 189-197. https://doi.org/10.1016/j.copbio.2019.12.026

Keeley NB, Macleod CK, Hopkins GA and Forrest BM (2014). Spatial and temporal dynamics in macrobenthos during recovery from salmon farm induced organic enrichment: When is recovery complete?. *Marine Pollution Bulletin.* 80(1-2):250-262. https://doi.org/10.1016/j.marpolbul.2013.12.008

Kenyon and Davies (2018). *SPICe Briefing – Salmon farming in Scotland.* The Scottish Parliament. Scotland. Available at: https://sp-bpr-en-prod-cdnep.azureedge.net/published/2018/2/13/Salmon-Farming-in-Scotland/SB%2018-12%20rev.pdf

Liu Y, Rosten TW, Henriksen K, Hognes ES, Summerfelt S, and Vinci B (2016). Comparative economic performance and carbon footprint of two farming models for producing Atlantic salmon (Salmo salar): Land-based closed containment system in freshwater and open net pen in seawater. *Aquacultural Engineering*. 71: 1-12. https://doi.org/10.1016/j.aquaeng.2016.01.001

MacLeod MJ, Hasan MR, Robb DHF and Mammun-Ur-Rashid M (2020). Quantifying greenhouse gas emissions from global aquaculture. *Scientific reports.* 10:11679. https://doi.org/10.1038/s41598-020-68231-8

Makkar HPS, Tran G, Heuzé V and Ankers P (2014). State-of-the-art on use of insects as animal feed. *Animal Feed Science and Technology.* 197: 1-33. https://doi.org/10.1016/j.anifeedsci.2014.07.008

Marine Scotland Science (2019a). *Scottish Fish Farm Production Survey 2019*. The Scottish Government. Edinburgh. Available at: https://www.gov.scot/publications/scottish-fish-farm-production-survey-2019/.

Marine Scotland Science (2019b). *Scottish Shellfish Farm Production Survey 2019*. The Scottish Government. Edinburgh. Available at: https://www.gov.scot/publications/scottish-shellfish-farm-production-survey-2019/

Martinez-Porchas M and Martinez-Cordova LR (2012). World aquaculture: environmental impacts and troubleshooting alternatives. *Scientific World Journal*. 2012: 389623. https://doi.org/10.1100/2012/389623

Marwaha N, Beveridge MCM, Phillips MJ, Komugisha BR, Boso D, Chan YC, Kabir KA, Sulster TB and Wiebe K (2020) *Alternative seafood: Assessing food, nutrition and livelihood futures of plant-based and cell-based seafood.* Penang, Malaysia. WorldFish. Program Report: 2020-42. Available at: https://hdl.handle.net/20.500.12348/4428

Micha R, Khatibzadeh S, Shi P, Fahimi S, Lim S, Andrews KG, Engell RE, Powles J, Ezzati M and Mozaffarian D (2014). Global, regional, and national consumption levels of dietary fats and oils in 1990 and 2010: a systematic analysis including 266 country-specific nutrition surveys. *BMG.* 348: g2272. https://doi.org/10.1136/bmj.g2272

Moxey A (2016). *An Assessment of the Economic Contribution of Scotland's Red Meat Supply Chain.* Quality Meat Scotland. Scotland. Available at: https://www.qmscotland.co.uk/sites/default/files/economic-contribution-of-scotlands-red-meat-supply-chain.pdf

Nash KL, Blythe JL, Cvitanovic C, Fulton EA, Halpern BS, Milner-gulland EJ, Addison PFE, Pecl GT, Watson RA and Blanchard JL (2020). To achieve a sustainable blue future, progress assessments must include interdependencies between the sustainable development goals. *One Earth*. 2:161-173. https://doi.org/10.1016/j.oneear.2020.01.008

Newton RW, Telfer T and Little DC (2013). Perspectives on the Utilization of Aquaculture Coproduct in Europe and Asia: Prospects for Value Addition and Improved Resource Efficiency. *Critical reviews in Food science and Nutrition.* 54(4): 495-510. https://doi.org/10.1080/10408398.2011.588349

Newton RW and Little DC (2018) Mapping the impacts of farmed Scottish salmon from a life cycle perspective. *International Journal of Life Cycle Assess*ment 23: 1018–1029. https://doi.org/10.1007/s11367-017-1386-8

Overton K, Dempster T, Oppedal F, Kristiansen TS, Gismervik K and Stien LH (2018). Salmon lice treatments and salmon mortality in Norwegian aquaculture: a review. *Reviews in Aquaculture.* 11(4): 1398-1417 https://doi.org/10.1111/raq.12299

Parker RWR, Blanchard JL, Gardner C, Green BS, Hartmann K, Tyedmers PH and Watson RA (2018). Fuel use and greenhouse gas emissions of world fisheries. *Nature Climate Change*. 8**:** 333–337. https://doi.org/10.1038/s41558-018-0117-x

Philis G, Ziegler F, Gansel LC, Jansen MD, Gracey EO, and Stene A (2019). Comparing Life Cycle Assessment (LCA) of Salmonid Aquaculture Production Systems: Status and Perspectives. *Sustainability.* 11(9): 2517. https://doi.org/10.3390/su11092517

Poore J and Nemecek T (2018). Reducing food's environmental impacts through producers and consumers*. Science*. 60(6392): 987-992. https://doi.org/10.1126/science.aaq0216

Rema P, Saravanan S, Armenjon B, Motte C and Dias J (2019). Graded Incorporation of Defatted Yellow Mealworm (Tenebrio molitor) in Rainbow Trout (Oncorhynchus mykiss) Diet Improves Growth Performance and Nutrient Retention. *Animals.* 9(4) 187. https://doi.org/10.3390/ani9040187

Riera A and Lenaghan M (2018). *Black soldier fly: A circular economy solution for Scotland.* Zero Waste Scotland. Available at: https://www.zerowastescotland.org.uk/content/insect-farming-scotland

Rogelj J, Geden O, Cowie A and Reisinger A (2021). Three ways to improve net zero emissions targets. *Nature.* 591:365-368. https://doi.org/10.1038/d41586-021-00662-3

Roos Bd, Sneddon AA, Sprague M, Horgan GW and Brouwer IA (2017). The potential impact of compositional changes in farmed fish on its health-giving properties: is it time to reconsider current dietary recommendations? *Public Health Nutrition*. 20(11): 2042-2049. https://doi.org/10.1017/s1368980017000696

Rural Economy and Connectivity Committee (RECC) (2018). *Salmon Farming in Scotland (SPP432).* The Scottish Parliament. Scotland. Available at: https://sp-bpr-en-prod-cdnep.azureedge.net/published/REC/2018/11/27/Salmon-farming-in-Scotland/REC-S5-18-09.pdf

SalMar (2020). *Offshore Fish Farming in Scotland*. SalMar. Norway. Available at: https://www.salmar.no/en/offshore-fish-farming-a-new-era/

Salmon Business (2021). *"Accelerating decarbonisation" UK Government Minister for Scotland visits Scottish sea Farms' £58 million Barcaldine Hatchery.* Salmon Business. 18th June 2021. Available at: https://salmonbusiness.com/accelerating-decarbonisation-uk-government-minister-for-scotland-visits-scottish-sea-farms-58-million-barcaldine-hatchery/

Samuel-Fitwi B, Wuertz S, Schroeder JP, and Schulz C (2012). Sustainability assessment tools to support aquaculture development. *Journal of Cleaner Production*. 32: 183-192. https://doi.org/10.1016/j.jclepro.2012.03.037

Sarker PK, Kapuscinski AR, McKuin B, Fitzgerald DS, Nash HM and Greenwood C (2020). Microalgae-blend tilapia feed eliminates fishmeal and fish oil, improves growth, and is cost viable. *Scientific Reports*. 10:19328. https://doi.org/10.1038/s41598-020-75289-x

Scientific Advisory Committee on Nutrition (SACN) (2004). *Advice on Fish Consumption: Benefits and Risks*. London. Available at: https://www.gov.uk/government/publications/sacn-advice-on-fish-consumption

Scotland Food and Drink (2016). *Aquaculture Growth to 2030 – A Strategic Plan for Farming Scotland's seas*. Edinburgh. Available at: https://aquaculture.scot/wpcontent/uploads/2017/11/Aquaculture_Growth_2030.pdf.

Scottish Aquaculture Research Forum (SARF) (2019). *Technical considerations of closed containment sea pen production for some life stages of salmonids.* University of Stirling. Stirling. Available at: https://dspace.stir.ac.uk/handle/1893/29642#.YPX-lehKg2w

Scottish Association for Marine Sciences (SAMS) (2018). *Review of the environmental impacts of salmon farming in Scotland.* The Scottish Parliament. Oban. Available at: https://archive2021.parliament.scot/parliamentarybusiness/currentcommittees/107588.aspx

Scottish Environmental Protection Agency (SEPA) (2019). *Consultation: The use of biomass or feed to regulate the organic output from marine pen fish farming to the environment.* SEPA. Stirling. Available at: https://consultation.sepa.org.uk/regulatory-services/biomassfeed/

Scottish Government (2016). *Making Things Last: A Circular Economy Strategy for Scotland.* The Scottish Government. Edinburgh. Available at: https://www.gov.scot/publications/making-things-last-circular-economy-strategy-scotland/

Scottish Government (2020a). *Estimation of the Wider Economic Impacts of the Aquaculture Sector in Scotland.* The Scottish Government. Edinburgh. Available at: https://www.gov.scot/publications/estimation-wider-economic-impacts-aquaculture-sector-scotland/documents/

Scottish Government (2020b). *Beef 2020 Report – A vision for the beef Industry in Scotland.* The Scottish Government. Edinburgh. Available at: https://www.gov.scot/binaries/content/documents/govscot/publications/advice-and-guidance/2014/08/beef-2020-review-report/documents/00457906-pdf/00457906-pdf/govscot%3Adocument/00457906.pdf

Scottish Sea Farms (2020). *Milestone for Barcaldine as first RAS fish reach market*. Scottish Sea Farms. Scotland. Available at: https://www.scottishseafarms.com/news/2020/december-2020/milestone-for-barcaldine-as-first-ras-grown-fish-reach-market/

Scottish Salmon Producers Organisation (SSPO) (2021). *Did you know? Health and welfare standards of Scottish farmed salmon.* SSPO. Edinburgh. Available at: https://www.scottishsalmon.co.uk/facts/fish-health-welfare/did-you-know-health-and-welfare-standards-of-scottish-farmed-salmon

Scottish Salmon Producers Organisation (SSPO) (2021). Reports. Available at: https://www.scottishsalmon.co.uk/reports

Seafood Innovation (2020). *Project updates from two aquaculture #SEAFOODINNOVATORS*. UK Seafood Innovation Fund. 13th November 2020. Available at: https://www.seafoodinnovation.fund/project-updates-from-two-aquaculture-seafoodinnovators/

Shepherd CJ, and Little DC (2014). Aquaculture: are the criticisms justified? II – Aquaculture's environmental impact and use of resources, with specific reference to farming Atlantic salmon. *World Agriculture* 4(2): 37-52. Available at: http://www.world-agriculture.net/article/aquaculture-are-the-criticisms-justified-ii-aquaculture-s-environmental-impact-and-use-of-resources-with-special-reference-to-fa

Song X, Liu Y, Pettersen JB, Brandão M, Ma X, Røberg S, and Frostell B (2019). Life cycle assessment of recirculating aquaculture systems: A case of Atlantic salmon farming in China. *Journal of Industrial Ecology.* 23(5): 1077-1086. https://doi.org/10.1111/jiec.12845

Sprague M, Dick JR and Tocher DR (2016). Impact of sustainable feeds on omega-3 long-chain fatty acid levels in farmed Atlantic salmon, 2006–2015. *Scientific Reports*. 6: 21892. https://doi.org/10.1038/srep21892

Suckler Beef Climate Group (2020) *Suckler Beef Climate Scheme: Final Report*. The Scottish Government. Edinburgh. Available at: https://www.gov.scot/publications/suckler-beef-climate-scheme-final-report-2/pages/18/

Sustainable Aquaculture Innovation Centre (SAIC) (2017). *Scottish Aquaculture a view towards 2030.* SAIC. Stirling. Available at: https://www.sustainableaquaculture.com/resources/

Sustainable Aquaculture Innovation Centre (SAIC) (2020). £10 million insect farm funding a boon for aquaculture sector. [Press release]. SAIC. Scotland. Available at: https://www.sustainableaquaculture.com/news-events/10-million-insect-farm-funding-a-boon-for-aquaculture-sector/

Sustainable Aquaculture Innovation Centre (SAIC) (2021). *Completed Project Case Study: Scaling up production and implementation of farmed cleaner fish in the Scottish salmon industry.* SAIC. Stirling. Available at: https://www.sustainableaquaculture.com/projects/finfish-health-welfare/details/scaling-up-the-use-of-cleaner-fish/

TESCO (2019). *Encouraging sustainable feeding practices in the aquaculture industry*. [Press release] Available at: https://www.tescoplc.com/updates/2019/encouraging-sustainable-feeding-practices-in-the-aquaculture-industry/

The Fish Site (2019). Mowi bids to install novel-closed containment salmon farms. *The Fish Site.* Ireland. 19th November 2020. Available at: https://thefishsite.com/articles/mowi-bids-to-install-novel-closed-containment-salmon-farms

Tilami SK and Sampels S (2018). Nutritional Value of Fish: Lipids, Proteins, Vitamins, and Minerals. *Reviews in Fisheries Science & Aquaculture.* 26(2): 243-253. https://doi.org/10.1080/23308249.2017.1399104

Tlusty MF and Thorsen O (2017). Claiming seafood is sustainable risks limiting improvements. *Fish and Fisheries*. 18:340-346. https://doi.org/10.1111/faf.12170

Tlusty MF, Tyedmers P, Bailey M, Ziegler F, Henriksson PJG, Béné C, Bush S, Newton R, Asche F, Little DC, Troell M and Jonell M (2019). Reframing the sustainable seafood narrative. *Global Environmental Change.* 59. https://doi.org/10.1016/j.gloenvcha.2019.101991

Tocher DR, Betancor MB, Sprague M, Olsen RE and Napier JA (2019). Omega-3 Long-Chain Polyunsaturated Fatty Acids, EPA and DHA: Bridging the Gap between Supply and Demand. *Nutrients*. 11(1): 89. https://dx.doi.org/10.3390%2Fnu11010089

United Nations Framework Convention on Climate Change (UNFCC) (2015). *Paris Agreement*. United Nations. Paris. Available at: https://unfccc.int/sites/default/files/english_paris_agreement.pdf

United Nations (2015). *Transforming our world: the 2030 Agenda for Sustainable Development*. United Nations General Assembly 25th October 2015. A/RES/70/1. Available at: https://www.un.org/sustainabledevelopment/sustainable-development-goals/

United Nations (2019). *World Population Prospects 2019: Highlights*. Department of Economic and Social Affairs, Population Division: New York. Available at: https://population.un.org/wpp/Publications/Files/WPP2019_Highlights.pdf

Veramaris (2021). Veramaris becomes first ASC-MSC certified microalgae for feed. [Press release] Available at: https://www.veramaris.com/press-releases-detail/veramaris-becomes-first-asc-msc-certified-microalgae-for-feed.html

Vetter SH, Malin D, Smith P, and Hillier J (2018). The potential to reduce GHG emissions in egg production using a GHG calculator – A Cool Farm Tool case study. *Journal of Cleaner Production*. 202: 1068-1076. https://doi.org/10.1016/j.jclepro.2018.08.199

Wield D, Tait J, Chataway C, Mittra J, and Mastroeni M (2017). Conceptualising and practising multiple knowledge interactions in the life sciences. *Technological Forecasting and Social Change*. 116(3): 308-315 http://dx.doi.org/10.1016/j.techfore.2016.09.025.

Wilfart A, Prudhomme J, Blancheton J-P, and Aubin J (2013). LCA and emergy accounting of aquaculture systems: Towards ecological intensification. *Journal of Environmental Management.* 121: 96-109. https://doi.org/10.1016/j.jenvman.2013.01.031

Williams AG, Audsley E, Sandars DL (2006). *Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities*. Main Report. Defra Research Project IS0205. Cranfield University and DEFRA, Bedford. Available at: http://randd.defra.gov.uk/Default.aspx?Module=More&Location=None&ProjectID=11442

Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, Garnett T, Tilman D, DeClerck F, Wood A, Jonell M, Clark M, Gordon LJ, Fanzo J, Hawkes C, Zurayk R, Rivera JA, De Vries W, Majele Sibanda L, Afshin A, Chaudhary A, Herrero M, Agustina R, Branca F, Lartey A, Fan S, Crona B, Fox E, Bignet V, Troell M, Lindahl T, Singh S, Cornell SE, Srinath Reddy K, Narain S, Nishtar S, and Murray CJL (2019). Food in the Anthropocene: the EAT Lancet Commission on healthy diets from sustainable food systems. *The Lancet*. 393(10170): 447-492. https://doi.org/10.1016/S0140-6736(18)31788-4

Ytrestøyl T, Aas TS and Åasgård T (2014). Resource utilisation of Norwegian salmon farming in 2012-2013. NOFIMA report no. 36/2014. *The Norwegian Institute of Food, Fisheries, and Aquaculture Research*, Tromsø. Available at: https://nofima.no/wp-content/uploads/2014/11/Nofima_report_resource_utilisation_Oct_2014.pdf

Zero Waste Scotland (2015). *Circular Economy: Sector study on beer, whisky and fish.* The Scottish Government. Scotland. Available at: https://www.zerowastescotland.org.uk/content/sector-study-beer-whisky-and-fish-0

Zero Waste Scotland (2016). *Finfish Mortalities in Scotland.* The Scottish Government. Scotland. Available at: https://www.gov.scot/publications/zero-waste-report-finfish-mortalities-in-scotland-2/

Appendix A: Figure A.1: Overview of Scottish Salmon industry product and process flows