The Scottish Government
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Marine Scotland

MGSA Science & Research Working Group

Aquaculture Science & Research Strategy

Produced on behalf of the Scottish Government Ministerial Group for Sustainable Aquaculture (MGSA)

May 2014

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REPORT REFERENCE

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Foreword

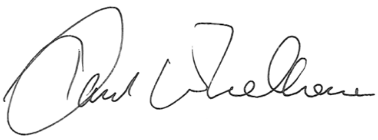
Aquaculture is an increasingly important sector to Scotland, contributing up to £1.4 billion per annum to the Scottish economy and 8,000 jobs. It underpins sustainable economic growth that supports employment and economic wellbeing of many fragile rural communities across the country. Scotland is internationally recognised for the high calibre of its aquaculture research which is strengthened through strong collaboration. Improved co-ordination of research activity coupled to effective collaboration between those that support aquaculture-related research will be imperative to ensure that the aquaculture sector continues to thrive.

Through the auspices of my Ministerial Group for Sustainable Aquaculture, I tasked the Science and Research Working Group with producing a comprehensive research strategy to define research requirements to help contribute to the sustainable growth of Scotland's aquaculture industry by 2020 and beyond, with due regard to the marine environment.

I welcome this comprehensive document. In addition to highlighting some of the cogent research required to help underpin the industry's sustainable production targets articulated in Scotland's National Marine Plan consultation, this document also identifies a range of science and research which could contribute to the future sustainability of the aquaculture in Scotland and internationally. The document is primarily designed to inform those public and private bodies that fund aquaculture research and development and is based on a combination of review and analysis of historic research, expert opinion and broad stakeholder consultation.

The sector has great potential. If industry's 2020 sustainable production targets are met – this could mean a turn-over value of £2 billion to the Scottish economy every year and the on-going support of 10,000 jobs. For this to be fully realised, the sector must continue to demonstrate its commitment to

improved environmental performance and sustainable growth; aided by a research and academic community that is well positioned to underpin that development. The Scottish Government wants to see aquaculture continue to thrive, growing sustainably, led by world-leading science and research.



Paul Wheelhouse MSP
Minister for Environment and Climate Change

Executive Summary

This research strategy and requirements document has been produced by the Scottish Government's Ministerial Group for Sustainable Aquaculture – Science and Research Working Group (MGSA-S&R WG). Expert Task Groups were established and charged with providing an authoritative set of research requirements which should inter alia: be aware of other cognate research strategies; demonstrate understanding and robust knowledge of current and historic aquaculture-related research and: provide evidence that each group has engaged in broad consultation with key stakeholders, including policy, regulation, industry and relevant NGOs. The MGSA will be expected to assess the impact of research in relation to its contribution to achieving sustainable growth in the aquaculture sector in Scotland.

In addition to providing a general context for the stated research requirements, each expert Task Group has, where possible, ranked and prioritised the research requirements with respect to their importance in achieving the aquaculture sectors sustainable growth targets by 2020, as set out in the consultation draft of the National Marine Plan, with due regard to the marine environment:

Support the industry and other stakeholders to increase sustainable production by 2020 (from a 2011/2012 baseline) of:

- Marine finfish to 210,000 tonnes (159,269 t in 2011)
- Shellfish, especially mussels, to 13,000 tonnes (6525 t in 2012)

Research requirements have been brigaded according to the following topic areas – there is no priority to the order in which these topics area listed:

- Nutrition
- Stock Improvement
- Health & Welfare
- Food Safety & Hygiene
- Technology & Engineering
- Wild-Farmed Interactions
- Markets, Economics & Social Science
- Capacity
- Blue Biotechnology & Growth

This document is designed to help inform potential sponsors of aquaculture related research of key research priorities. It is intended that the MGSA-S&R WG will revisit this document on an approximately annual basis to review what progress has been made in addressing these research priorities.

The overriding theme running though all of the research requirements is the need for improved understanding of, and development of applied commercially relevant solutions to, measures to increase capacity for aquaculture expansion without detriment to the marine and coastal environments and conflicting with other legitimate interests. This is a cross cutting issue for all the topic areas listed above.

An immediate and ongoing priority for the largest and most profitable sector – salmon, is the effective management of sea lice. For the shellfish sector issues of hygiene related to water quality remain paramount if the industry is to secure the investment required for expansion. The physical space in which aquaculture is permitted to operate has a current and significant future bearing upon the ability of the sector to expand to meet the 2020 targets.

Climate change is likely to have an increasing impact on many aspects of aquaculture. New strategies, innovation and tools will be needed to ensure that the industry has both the resilience and the flexibility to respond to such changes.

The research requirements outlined in this document suggest that Scotland has the potential to use its natural resources, existing research and industry capacity to be a recognized world leader in pure and applied research. The expected demand for aquaculture products and services including those derived from emerging Blue Biotechnology*/Growth is assured – simply as a function of increases in human population and per capita consumption. But to exploit this

* Blue Biotechnology is a term that has been used to describe the marine and aquatic applications of biotechnology. Biotechnology is defined by the American Chemical Society as the application of biological organisms, systems, or processes by various industries to learning about the science of life and the improvement of the value of materials and organisms such as pharmaceuticals, crops, and livestock.

potential, industry, academia and Government will need to explore new models of working together – established norms in the public funding of research, academic progression and training, industry investment and in translating basic and applied research into commercially relevant solutions will need to be challenged. Government and Research Councils should take a strong lead in this regard.

KEY RESEARCH PRIORITIES

This document provides an assessment of research requirements which have been subject to a broad range of Task Group and Stakeholder scrutiny. A common strand emerging from the consultation process has been the need to provide additional focus to identify which of the research areas should be recognised as being of the highest priority. The priority has been assessed on the respective contribution to informing the sustainable economic growth of the Scottish aquaculture industry and the potential impacts of the 2020 production targets as detailed in the draft consultation Scottish Marine Plan in 2013.

The following research requirements reflect the need for research activity which may be additional to that known to be in progress:

FINFISH

The effective control of sea lice on salmon farms is highlighted as being of the highest priority and is reflected in the following research requirements:

- Between farm transmission mechanisms – Health & Welfare
- Within Farm management practices – Health & Welfare
- Health and welfare of cleaner fish – Health & Welfare
- Non-chemical treatment of sea lice – Technology & Engineering
- Selective Breeding (focusing on resistance to sea lice) – Stock Improvement – Health & Welfare

Understanding and managing interactions with wild salmonids particularly with respect to sea lice is also highlighted as being of the highest priority and reflected in the following research requirements:

- Greater understanding of sea lice dynamics – Wild-Farmed Interactions
- The dispersal patterns of sea trout and salmon and subsequent distribution in relation to the Scottish Coast – Wild-Farmed Interactions
- The effects of sea lice at a population level on wild salmonids – Wild-Farmed Interactions

One of the highest priority areas within the research strategy is replacing scarce, marine-sourced components of aquaculture feeds with sustainable, alternative ingredients that will not adversely affect stock health and welfare or product quality:

- Replacement of marine resources within aquaculture feeds – Nutrition

SHELLFISH

Food safety and hygiene is the highest research priority for the shellfish sector, specifically:

- Norovirus detection and management – Food Safety & Hygiene
- Detection, quantification and management of algal biotoxins in shellfish production – Food Safety & Hygiene

GENERIC

Identifying additional areas to increase production capacity in support of the 2020 production target aspirations is also of the highest priority:

- Integration of aquaculture into marine spatial plans which identify areas for increased capacity – Carrying Capacity
- Improved estimates of assimilative and biological carrying capacity for fish and shellfish farms in inshore and offshore marine ecosystems – Carrying Capacity

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Preface

CONTEXT

Aquaculture is the world's fastest growing food producing sector (6-8% per year over the past 10 years) and now accounts for over half of the world's fish supply for human consumption. Projected population growth and per capita increases in seafood consumption coupled to plateauing and possible decline of capture fishery production dictates that future demand will need to be met by aquaculture. Globally, it has been estimated that aquaculture will provide approximately two thirds of global food fish consumption by 2030 as catches from wild capture fisheries level off and demand from an emerging middle class increases substantially[1].

Despite Scotland experiencing growth in recent years, the aquaculture industry as a whole across Europe has stagnated which has led to an increased reliance on importing fish products from outside the EU. Aquaculture is therefore being promoted strongly in the Blue Growth Strategy, the Atlantic Strategy and the reformed Common Fisheries Policy (CFP).

Scotland is the largest producer of farmed Atlantic salmon in the EU and 3rd globally behind Norway and

Chile (2012). Using DCF and FAO data, it has been estimated that the aquaculture sector production in the EU27 accounted for 1.32 million tonnes, with a turnover estimated at 3.99 billion Euros, in 2011. Spain, with 21% of the total EU production in volume, is the largest aquaculture producer in the EU, followed by France (18%), United Kingdom (14%), Italy (13%) and Greece (11%). These five countries account for more than 75% of the total EU aquaculture production in weight. In terms of value, the United Kingdom is the largest EU producer with 20% of the total EU aquaculture, followed by France (19%), Greece (15%), Spain (12%), and Italy (10%). These five countries are also responsible for more than ¾ of all the EU aquaculture value. Aquaculture production by the 28 European Union Member States (EU28) reached 1.28 million tonnes and 3.51 billion Euros in 2011 according to FAO[2].

In 2012, Scottish marine finfish production (164,380 tonnes) was dominated by farmed Atlantic salmon (162,223 tonnes) with 2,076 tonnes marine rainbow trout, 73 tonnes halibut and 8 tonnes sea trout also produced. Freshwater finfish production included 3,594 tonnes rainbow trout, 36 tonnes brown trout and 0.2 tonnes Arctic charr. In 2012, Scottish shellfish production was dominated by blue mussel (6277 tonnes). 216 tonnes of Pacific oyster (2,706,000 shells), 25 tonnes native oyster (317,000 shells), 0.4 tonnes queen scallop (9,000 shells) and 7 tonnes king scallop (58,000 shells) were also produced[3].

Scotland is well placed to contribute significantly to future aquaculture production of high quality, healthy product and transfer of technology, expertise and best practice. Our coastal marine topography and hydrography provides numerous excellent sites for finfish and shellfish farms. We are also well placed to develop marine aquaculture in more exposed locations which, although technologically challenging, offer great potential. Such locations provide a means of sustainably growing the sector, reducing competition for space in inshore areas, and further minimising actual and perceived environmental impacts. There are exciting opportunities to co-locate aquaculture with marine energy installations, and multi-trophic aquaculture may provide co-operative approaches to mitigating economic and environmental costs and risks.

Scottish higher education and research institutes have a respected international reputation in aquaculture related research and training. This is reflected in the success of these institutions in securing research funding both domestically and at EU level. Graduates and postgraduates from our institutions populate senior positions within industry and regulation across the globe. The Marine Alliance for Science and Technology for Scotland (MASTS) is a research pool that brings together the majority of Scotland's marine research capacity representing approximately 700 researchers and £66 million a year of public investment. MASTS members include one of the largest concentrations of scientific expertise in aquaculture in the world. The Scottish Aquaculture Research Forum (SARF) is an independent charity tasked with prioritising, commissioning and managing applied aquaculture research, based upon the needs of industry and its key regulators and stakeholders. Much of the work commissioned by SARF has had a measurable and practical impact on the way aquaculture is conducted and managed in Scotland.

The Institute of Aquaculture at the University of Stirling is recognised as a leading international centre of excellence in aquaculture. The Scottish Association for Marine Science, Marine Scotland Science and the Universities of Aberdeen and St Andrews have a long and distinguished record of delivering cutting edge aquaculture research and innovation. More recently, Edinburgh Napier, Dundee and Strathclyde and Scotland's newest University – the University of the Highlands and Islands, are developing aquaculture related research capacity. Research interests span the full spectrum of aquaculture from applied production technologies through to cutting edge disease, nutrition and environmental research.

The Scottish Aquaculture Innovation Centre (SAIC), is a virtual hub drawing together the collective expertise and resources found across its 13 research partners and its extensive aquaculture supply chain and will receive core funding through the Scottish Funding Councils (SFC) Innovation Centres programme which is being delivered jointly by the SFC, Scottish Enterprise and Highlands & Islands Enterprise. It will deliver industry-lead aquaculture research and development, consultancy, knowledge exchange, education and training to support the sustainable growth of the aquaculture sector and retain Scotland's international reputation for the provision of premium, high quality, traceable and environmentally sustainable seafood.

Scotland has a world leading aquaculture industry underpinned by a substantive and internationally respected research base. The Government in Scotland supports industry targets to grow a sustainable sector with due regard to the marine environment as set out in the consultation draft of the National Marine Plan which articulates the 2020 aspiration:

Support the industry and other stakeholders to increase sustainable production by 2020 (from a 2011/2012 baseline) of:

- Marine finfish to 210,000 tonnes (159,269 t in 2011)
- Shellfish, especially mussels, to 13,000 tonnes (6525 t in 2012)

Thus, through its various working groups the MGSA will continue to underpin the objectives of delivering the Aquaculture and Fisheries (Scotland) Act, to facilitate the ambition of achieving the 2020 sustainable production targets, to improved co-ordination, innovation and leadership.

METHOD AND APPROACH

The Chair of the Science and Research Working Group (S&R WG) formed a Steering Group, the core of which comprised the Sustainable Aquaculture Research Forum of the Marine Alliance for Science and Technology for Scotland (MASTS) together with additional representation from industry and Marine Scotland. The Steering Group agreed to the following division of subject areas:

- Nutrition
- Stock Improvement

- Health & Welfare
- Food Safety & Hygiene
- Technology & Engineering
- Wild-Farmed Interactions
- Markets, Economics & Social Science
- Capacity
- Blue Biotechnology & Growth

Individuals drawn from the Steering Group with relevant expertise were allocated the role of Task Group Leader and charged with convening a small Task Group of relevant experts to contribute to the process of identifying potential research requirements. The names of the proposed members of each Task Group were circulated to the Steering Group for comment to ensure an appropriate balance of expertise and representation was maintained. A list of Task Group members is provided in Annex 01.

The following process was adopted with the understanding that the strategy would, in the first instance, identify research gaps and any potential contingent deficiencies in research/infrastructure provision which might need to be addressed to contribute to meeting the 2020 sustainable growth targets for Scottish aquaculture production published in Scotland's National Marine Plan Consultation draft on 25 July 2013[4]. In addition, Task Groups were charged with identifying key strategic research requirements which may be applicable in a broader scientific context and over longer timescales than might be applicable to the 2020 targets.

Overall, this process should recognise the complexity of the research funding landscape and the duality of informing and influencing funding whilst responding to opportunities which might favour academic or more applied research in this field.

The process of defining research requirements was similar for each task group and involved the following stages:

- Review of current strategies
- Review of relevant outputs from groups/fora that may be focused on defining research requirements – includes other MGSA Working Groups
- Analysis of an R&D database of projects funded over the last decade

- Consultation with relevant stakeholders – regulators, industry trade bodies and key industry players, NGO's – through established bodies such as SARF (this process was undertaken centrally and the results fed back to the task groups)
- Submit final draft of the S&R Strategy Task Groups to the MGSA for final comment and approval

With respect to their task subject area, each Task Group would:

- Identify and review any relevant 'strategies' that are current and either published or unpublished but available within their respective communities
- Identify and evaluate relevant recent (within last five years) reviews or 'overviews' which may have identified research requirements

In reviewing this information, each Task Group would make a critical assessment of:

- The sources on which the strategy/ overview is based
- Whether the document has been the subject of any form of external review/consultation
- Identify any specific research requirements

Some Task Groups elected to prioritize the research requirements in ranked order and have also indicated the priority as follows:

HIGH – research that is required within the immediate future as it has a direct bearing on the ability of the industry to achieve stated 2020 targets
MEDIUM – research that is required to underpin the long-term sustainability of the industry

HIGH LEVEL OVERVIEW OF UK/EU RESEARCH – OVER THE LAST DECADE

The Aquaculture Research Database generated by the Scottish Aquaculture Research Forum (SARF) and based on original data collated on behalf of Defra, is designed as a tool to assist specialist researchers or groups interested in particular fields of research related to different aspects of aquaculture. Its main purpose is to provide a starting point for such groups, when undertaking their

own analysis of the state of current knowledge in their particular field of interest. The most recent version of the database can be downloaded[5].
(Download Database)

Although the database represents one of the most comprehensive compilations of aquaculture related R&D project information and is likely to account for a significant proportion of publicly funded research in this area within the UK and under recent EU Framework Programmes, users of the database should note that:

- Whilst it is based on a significant amount of review and stakeholder collaboration, it is not a complete record of all the relevant projects that might be currently underway, or that might have been completed in recent years
- It covers research being undertaken in, and funded by, several different countries
- The research covered by the database may not be an accurate reflection of privately sponsored industry led R&D and the overall relevance of the R&D contained within the database to the aquaculture industry must be judged with some care
- The values of different research projects were not always possible to ascertain and whilst the database does provide a good indication of which topics are receiving different amounts of research funding, this aspect should be treated with caution in any analysis
- With the caveats noted above, some analysis of the database and the apparent trends within it are presented

OVERVIEW OF THE DATABASE

The database contains some 841 entries, with projects categorised according to a range of criteria relevant to the sector and subject. In order to provide an overview of recent as well as current research, projects starting as early as 1994 are included in the database.

Figure 1 provides an overview of the number of projects, under the different subject categories used to frame this strategy, within the entire database.

Figure 2 provides an overview of the value of the research in each category – where this is known.

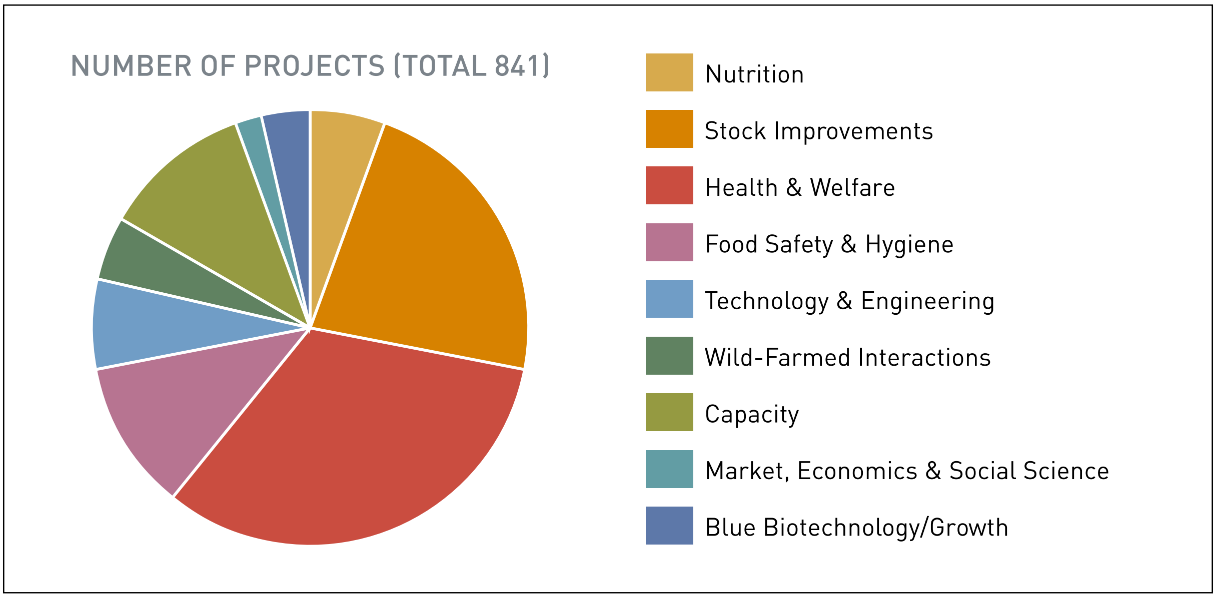

Figure 1 | Analysis of the number of projects within the database, by research category, from the years 1994 to 2013. Total number of projects is 841.

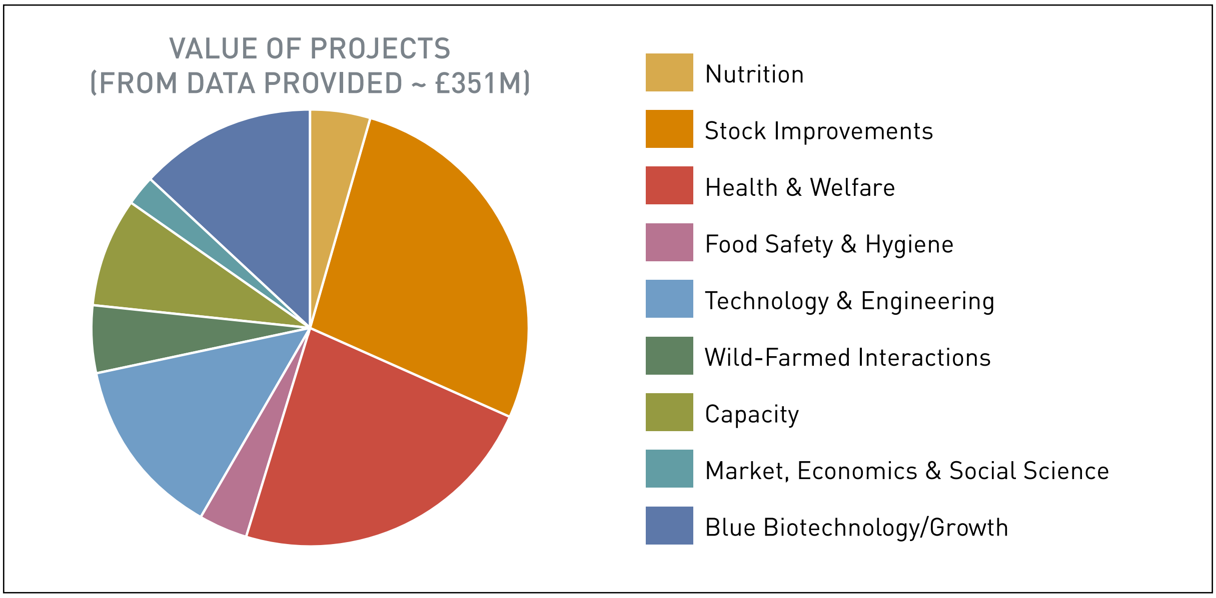

Figure 2 | Analysis of the values of projects within the database, by research category, from the years 1994 to 2013. Total value of projects is £351 million.

TRENDS IN AQUACULTURE RESEARCH

Some categories of aquaculture research remain consistently important over the period 1994 to 2013, but other new ones emerge over the period, as illustrated in **Figure 3** which shows the number of individual projects.

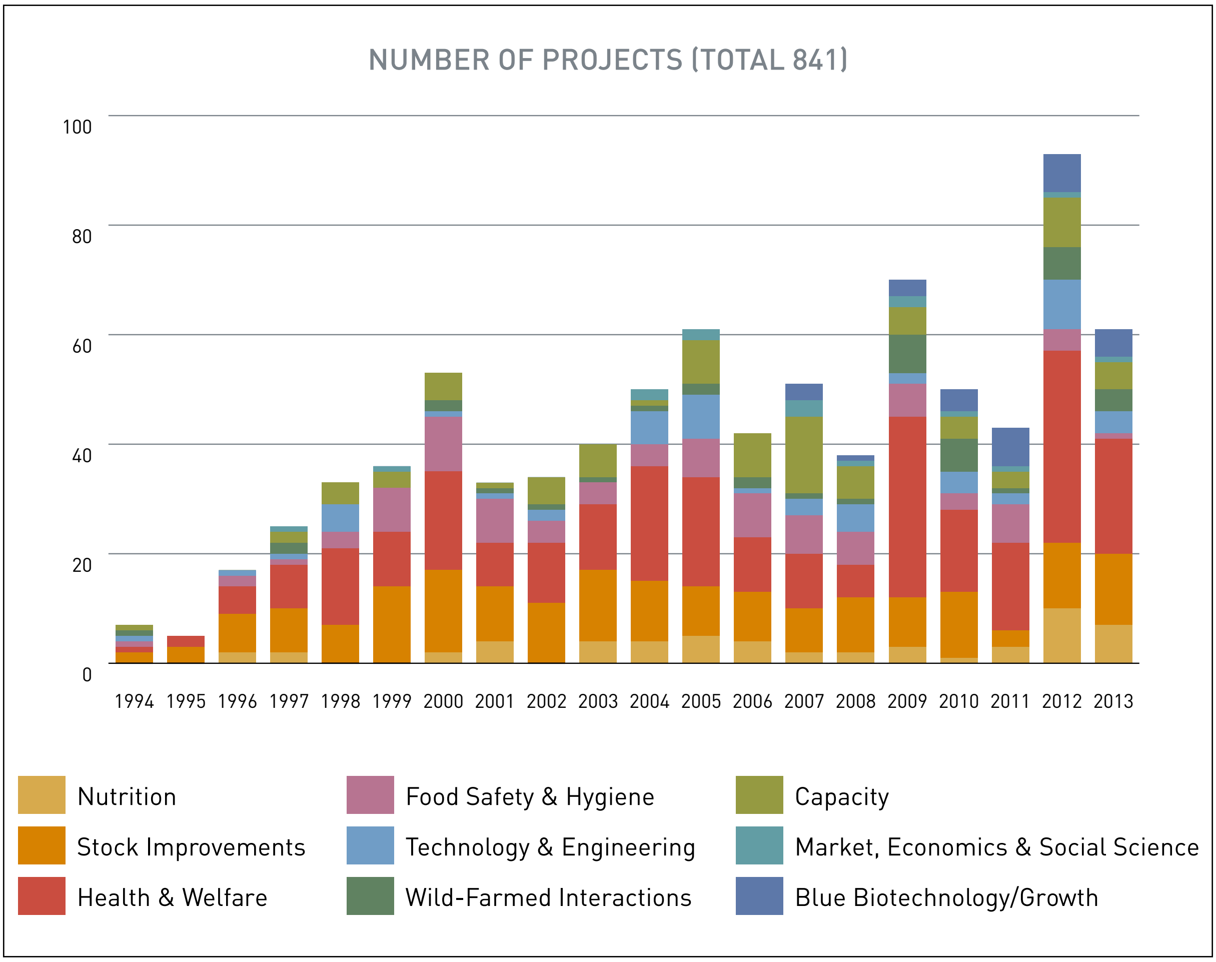

Figure 3 | Number of aquaculture research projects, by category, commissioned between 1994 and 2013. (Note that project durations can be variable: the figure shows the starting year for all projects.)

Preface

Whilst the trend of numbers of projects commissioned each year appears to be slowly increasing over the time period, data prior to 2000 is sparse. Some trends or generalisations can be identified, as far as project numbers are concerned:

- Categories such as Capacity, Health & Welfare, Food Safety & Hygiene and Stock Improvement receive relatively consistent high attention from the research community, over most of the time period – although there is annual variation. This trend is reflective of the main policy, regulatory and commercial drivers for the sector as those categories noted are subject to significant government investment in areas relevant to legal and regulatory requirements. With respect to policy and regulatory related research, the majority of funding has been allocated to Government or Agency laboratories.
- Technology & Engineering, Nutrition and Wild-Farmed Interactions attract rather variable amounts of research interest from year to year. Such variable investment reflects response to specific initiatives – particularly with respect to large EU funded projects.
- The same is true for Markets, Economics & Social Science, but its overall level of research investment is rather low, for a 'new' industry in an era when most business sectors recognise that the market is the main driver of development.

Figure 4 illustrates the trends in apparent expenditure on research categories.

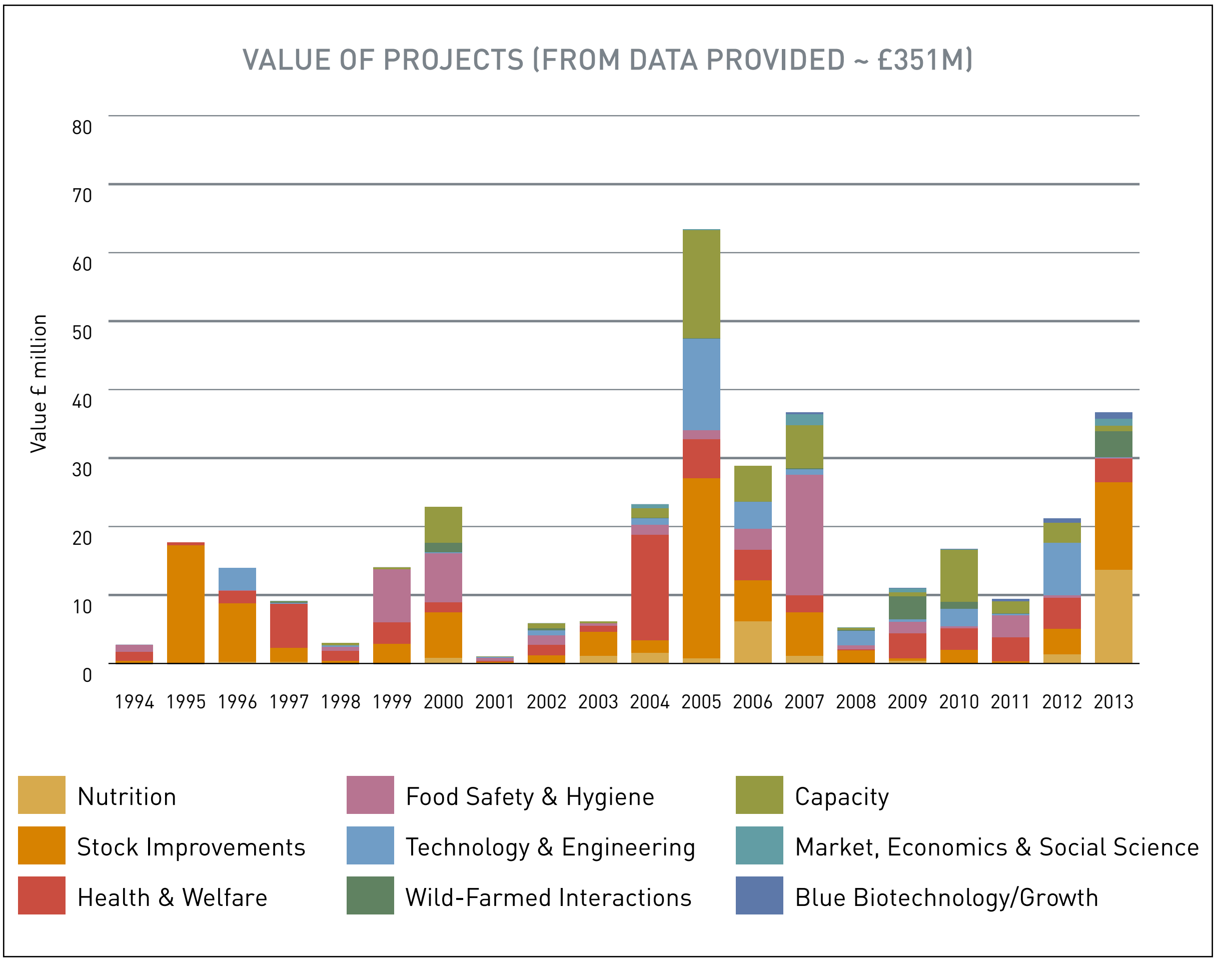

Figure 4 | Value of aquaculture research projects, by category, commissioned between 1994 and 2013. Note that project durations can be variable: the figure shows the starting year for all projects.

The apparent (as ascertained) value of aquaculture-related research appears to have risen relatively sharply since 2008, and it is interesting to note the investment in Blue Biotech – which involves quite diverse projects, ranging from algal cultivation to integrated multi trophic aquaculture (IMTA). Much of this increase is accounted for by significant EU Framework Programme investment in aquaculture related research, together with specific, but quite substantial allocations from the Technology Strategy Board.

RELEVANCE TO SCOTTISH AQUACULTURE

The international nature of the database, both in terms of where research is being undertaken and in terms of its sources of finance, should be carefully considered in the context of the Scottish industry. The relatively sharp increase in aquaculture research funding, illustrated in the database since 2008, may present a somewhat misleading picture.

Of the total research expenditure since 1994 accounted for in the database, approximately £351 million, the largest 72 projects (of value over £1 million) amount to a total of £243 million, i.e. 69% of the overall recorded total. Of these, the projects that appear to relate most closely to the needs of the salmon, trout and shellfish farming sectors in Scotland are limited in number: perhaps 6-8 projects with some degree of immediate industry application, worth around £30-40 million.

What this suggests is that whilst there is clearly increasing interest in funding aquaculture related research, the relevance of much of this work to industry and indeed regulatory and policy requirements remains difficult to quantify. Underpinning research which may not be directly commercially relevant is important, but the driver for much of the publicly funded research portfolio research remains routed in and weighted towards largely academic measures of performance and impact. In addition to focused basic research, aligned with identified areas of research need, there is clearly a requirement for more translational research of direct importance and value to the sustainable development of the industry in Scotland and beyond. In this regard, it should be noted that non-academic research impact is now assuming a growing importance with the university research sector.

STRATEGIC VISION AND RESEARCH REQUIREMENTS

The expansion of the aquaculture sector globally and in Scotland is occurring and will continue as a function of increasing demand. In recognition of this potential, there is renewed and increasing interest in supporting research and innovation in this sector. Much of the funding for these activities is still likely to come from public sources either directly or indirectly through a number of different agents such as the Research Councils, the Technology Strategy Board, the Scottish Funding Council and Scottish Enterprise for example. The EU is also expanding its allocation to aquaculture research under the Horizon 2020 programme.

The proportion of industry investment in research is usually a reflection of the sector and is dominated in the UK and Scotland by salmon interests. Although those involved in the provision of feed and animal health products invest in research which cuts across fish production more generally. The level of industry investment in R&D is difficult to quantify as it is not usually published. Evidence from collaborative research programmes designed to engage with industry suggest that industry cash contributions are usually between 10% and 15% of total budget, but this is highly sector dependent and real in-kind contributions to projects can raise the overall level of investment considerably. The principal recipients of research and innovation funds are research institutes and universities.

From a strategic perspective, it is vital that Scotland and the UK as a whole maximises the potential of available funding to deliver the sustainable expansion of the aquaculture industry. This will require that the relevant funding bodies actively co-ordinate their actions rather than pursuing diverse agenda's in isolation. Government should be predicating the high level allocation of funds to such bodies with this prescription.

The metrics used to assess the performance of the academic research community – who are the main recipients of available research funds, (principally the Research Excellence Framework) are not well aligned with the expressed needs of aquaculture sector, despite the increasing emphasis on 'impact'.

The need to support fundamental research – some of which may ultimately underpin the aquaculture sector remains critical, but there is also a need to support focussed problem solving research – which often requires the translation of basic science, but is directly relevant to the commercial aquaculture sector and clearly responds to the needs of industry, regulation and policy. Whilst industry should be encouraged to take a reasonably broad and strategic view on the research required to underpin the sector there is also a responsibility on those disbursing public funds to support sectorally relevant research. Much of this research does not fit with current definitions of 'research excellence' which favour the pursuit of academic research, though it provides extensive opportunities for achieving impact. If the UK and Scotland is to remain competitive and grow the real economy, the research community and those that fund it will need to reassess notions of excellence and the metrics by which real economic, environmental and social impact is judged.

For some areas of sectorally strategically important research it is necessary to build and maintain research capacity. It is also important that we begin to establish longer term visions and 'road maps' for addressing strategically important issues. Inconsistent, piecemeal and dissipated support for some areas of research activity constrains sustainable development and could jeopardise the capacity of the sector to compete in a global market. Some of these areas are implicitly identified within this document, but a more detailed high level assessment is required to inform investment in the areas of research that attract support in terms of developing capacity and critical mass to meet the anticipated demand.

Resource constraints should dictate that this should be a more directed and co-ordinated activity than has thus far been the case – if Scotland is to maintain its reputation as a leading aquaculture producer, regulator and source of scientific expertise.

Experience over the last 30 years has demonstrated that there are only a few species that are suitable for large scale commercial aquaculture production. Many attempts to cultivate novel aquaculture species have failed because of now well understood biological, market and economic realities which have been ignored. In principle, diversification of the industry could potentially lead to increased economic and environmental sustainability, but evidence thus far, suggests that in the absence of sufficiently profitable markets, new species developments have failed or had limited uptake by industry. Where diversification is justified, a research, development and commercialisation pipeline for new species should be mapped out and the ultimate business model regularly revised. It is crucially important that from a public investment perspective that lessons are learnt from previous attempts to develop new species, and these be applied to any future development at an early stage. The potential impacts of climate change for aquaculture are no longer simply an academic debate. Increasing sea temperature, sea-level rise, and ocean acidification coupled to increased frequency and severity of storms, will have direct and indirect impacts on the sector – some may argue that this is already happening.

Predicted latency in meeting even the most modest of carbon dioxide emission scenarios suggests that the requirement for climate adaptation and the speed with which the aquaculture sector will need to respond is likely to increase over the next few decades and possibly years.

Expansion of commercial and leisure activity in our coastal areas, coupled with the need for defined marine spatial plans, will require careful consideration and the resultant trade-offs are likely to increase pressure for the aquaculture sector to move into more exposed locations and to further explore wholly landbased production where this is economically viable.

Minimising and mitigating potentially negative environmental interactions between wild and farmed species will continue to be a regulatory focus and key to aquaculture maintaining and indeed promoting its social licence. For Scotland, and other salmon producing countries, control of sealice remains paramount, together with the need to prevent escapes and predation. The physical space in which aquaculture is permitted to operate has a current and significant future bearing on the ability of the sector to meet 2020 targets and expand more generally.

The sustainability of the fin fish sector also hinges on the consistent and affordable supply of raw materials for feed. Many of these materials are traded globally and there is an intimate link for this sector between 'feed sustainability' and its ability to contribute to 'food security'.

The following sections provide a focused assessment of research requirements distilled through the methodology set out at the beginning of this document. These sections are not ordered in any priority, but the Task Group authors responsible for each section together with those involved in consultation have, as far as possible, ascribed priority to the research requirements identified within each section. A preamble to each research requirements table designed to provide context for non-specialists and those not directly familiar with the aquaculture sector is provided.

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01 Nutrition

Aquaculture nutrition is a core driver in the sustainable development of the Scottish finfish aquaculture industry, with feed representing approximately 50% of production costs for salmon and trout. Historically the feed sector has been a major user of marine derived fish meal (FM) and fish oil (FO). However, the exploitation of these limited marine raw materials is no longer sustainable. If Scotland is to expand its aquaculture industry to meet the sustainable growth target set for finfish of 210,000 tonnes by the year 2020, there is an urgent need to develop alternative, sustainable, secure and affordable feed materials to increase choice and quality to the aquafeed industry.

Since 1995 the use of marine derived feed materials in aqua feeds has already decreased significantly from approximately 82% to 36% in 2012 in favour of vegetable derived proteins and oils. However there are still further possibilities to help reduce the volatility in cost of feed and supply associated with dependence on FM and FO or reliance on imported vegetable protein materials (**Figure 5**). These potential cost savings would be passed on throughout the supply chain, ensuring the industry is better able to remain competitive with other farmed fish producing countries. The reduced reliance of marine derived protein and oils for locally sourced feed materials that are more sustainable and food-chain secure will also further improve the global market position of Scottish farmed fish as a high quality end product that is both responsible and sustainable.

However, vital research is required to ensure that reduction of marine-sourced dietary ingredients does not compromise long-term fish health and welfare, end-product quality or consumer health benefits derived from eating farmed fish. To maintain economic viability of the industry and safeguard product prices, increased production must be matched by increased sales and expanded markets, highlighting the importance of consumer product preferences such as organoleptic properties and associated health benefits.

In addition, integrated research, education and marketing strategies concerning the benefits of eating farmed fish, shellfish and seaweeds would facilitate expansion of markets for aquaculture produce and serve to improve the nation's health. Developing on-site algal toxin monitoring and early warning systems for harmful algal blooms would greatly improve the efficiency of Scotland's farmed shellfish industry and the safety of its products in the eyes of the public – both crucial if shellfish production and markets are to be expanded to meet the 2020 Scottish production target of 13,000 tonnes of farmed shellfish.

Addressing the issue of nutrition and immune function also has great economic potential. Reduction in inflammatory conditions and the burden of ectoparasites would significantly improve the health and welfare of farmed fish thereby reducing the incidence of clinical disease or mortality, leading to lower production costs for the industry and improving the image of fish farming to the wider public. If the problem of salmon ectoparasites is to be ameliorated using wrasse as a biological control mechanism, research to develop and trial effective wrasse weaning diets is required.

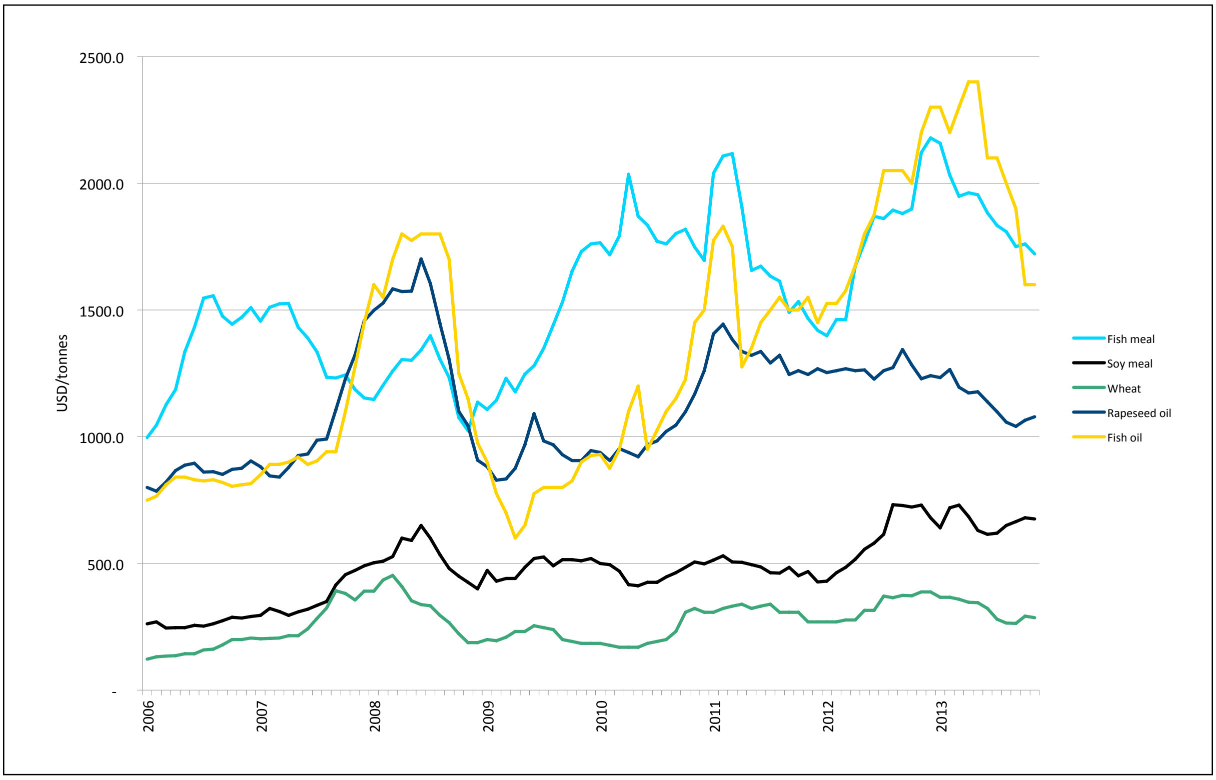

Figure 5 | Price development of selected feed materials in aquafeeds (Holtermann Index).

For environmental, economic and biosecurity reasons, the use of recirculating aquaculture systems (RAS) is likely to increase. This is particularly true of freshwater RAS salmon hatcheries and smolt production units and is highlighted by the fact that Marine Harvest and Grieg Seafood Hjaltland UK Ltd. have already elected to adopt this technology. These systems require specialised diets to be developed which not only optimize the performance of the fish, but also that of the RAS mechanical and bio-filters. RAS diets need to be better refined in terms of nitrogen and phosphorous loading, with higher protein digestibility and lower oil levels. Careful selection and trialling of dietary ingredients in replicated RAS feeding trials will be necessary.

A significant limitation for the Scottish aquaculture industry is the very poor availability of feeding trial facilities in Scotland. As a result, the majority of industry research and development is carried out overseas and therefore investment and commercial benefits are drawn away from Scotland. In addition to tank-based facilities plus a 12-replicate cage-site at the NAFC Marine Centre in Shetland, the main options currently available are the Marine Harvest Ardnish FTU cage site at Lochailort and the University of Stirling tank-based facilities at Machrihanish, which are heavily utilised or at capacity under contracted commercial use. Whilst all these facilities would benefit from upgrading, in order to achieve the prescribed expansion of aquaculture in Scotland, significant improvement of available feeding trial facilities is essential – specifically: construction of both sea cage and tank-based facilities is urgently required.

01 Table Nutrition

General Topic Priority Ranking (1-10)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
1) Replacement of marine resources within aquaculture diets & improved utilization of fish by-products as fishmeal[1-16].	Developing suitable and sustainable alternative sources of lipid & n-3 long chain polyunsaturated fatty acids (n-3 LC PUFA) e.g. oils & PUFA from cultured microalgae[1-6, 15,16]. In the medium to long-term, and in view of recent developments in Canada and USA, the UK salmon industry may well need to re-assess its position concerning de novo production of n-3 LC PUFA from GM oilseed crops. Finding suitable & sustainable alternative sources of protein for fish feed and better fish by-product utilization[7-16]. The salmon industry already uses or is developing a range of protein alternatives. Fish	Developing alternative sources of lipids, n-3 LC PUFA and proteins is a pre-requisite to providing the increased volume of sustainable finfish feed needed to meet 2020 targets. Necessary to improve production efficiency and feed conversion ratios of alternative feeds; supply satisfactory levels of essential nutrients to maintain the long-term health of cultured fish;	Few options for undertaking large-scale, replicated feeding trials. There's a clear and urgent need to provide one/more pen-based marine ongrowing facilities similar to the existing trials site at Ardnish. Without this, the industry will struggle to test raw materials or develop new diets. **HIGH PRIORITY** Currently reasonable choice of traditional and new raw materials to provide protein,

General Topic Priority Ranking (1-10)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	meals have 60-70% protein content but plant-based alternatives range from 8.5-64% protein for corn & soybean concentrate, respectively. Many of these products are already used in aquafeeds but novel concentrates are required that blend different plant-based products & significantly increase protein levels to 50-60%. A number of such products are available, though most are not produced inside the UK. The EU's recent reauthorization of non-ruminant processed animal protein (PAPs) within fish feeds is also pertinent here, as is the option of using GM soya as a protein source. Optimizing minerals, micronutrients & essential amino acid bioavailability in alternative diets and reducing plant-origin anti-nutritional effects[1]. Using fish meal/oil in salmon diets helped provide balanced amino acid & fatty acid profiles & contributed to dietary vitamin & mineral content, so their replacement with	maintain protein and phosphorus retention and reduce faecal waste. Need to increase farmed salmon sales and attract more consumers, so it is vital that salmon fed with plant or alternative-origin ingredients retain their appealing organoleptic properties and human health promoting characteristics, especially in terms of n-3 LC PUFA content. Will help find satisfactory balance between health benefits to consumers, health & welfare of farmed fish, environmental impact, growth performance, efficiency and economic cost.	energy and oil requirements for salmon culture but there are concerns about maintaining & increasing future supplies, particularly of fish oils and n-3 LC PUFA, and availability of locally-produced plant protein concentrates. **MEDIUM-HIGH PRIORITY** Need more species-specific information regarding losses, logistics & economics of utilizing by-products in different locations[14]. **MEDIUM-PRIORITY**

General Topic Priority Ranking (1-10)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	vegetable-origin ingredients requires more exact knowledge of nutrient requirements. We must re-assess mineral requirements focussing on retention, growth & health of farmed fish and consumer expectations of quality. Trace element nutrition must be re-examined especially for selenium and zinc as well as other minerals. Investigating effects of alternative diets on long-term fish health, ideally by monitoring over whole life-cycle (rather than usual 3-6 month trials) or by developing alternative evaluation methods. Ensuring organoleptic appeal and consumer health benefits are maintained in salmon fed diets with plant/alternative-origin ingredients.		
2) Human health benefits of eating farmed fish, shellfish and marine	Integrated strategy of research/education/ marketing concerning the health benefits of eating farmed fish (especially	Increasing capacity of the Scottish aquaculture industry by expanding	Generally poor 'outreach' facilities for schools & public. Recent SEAFOOD

01

Nutrition

General Topic Priority Ranking (1-10)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
vegetables. (cross-reference to remits of the Marketing Task Group and the Fish & Shellfish Hygiene Task Group).	salmonids), shellfish and macroalgae and should encompass less well-known benefits such as selenium and zinc intake. **MEDIUM-HIGH PRIORITY** Developing on-site, real-time monitoring of algal toxin levels[18]. to support statutory shellfish bioassays would reduce risks and adverse publicity from HAB-affected shellfish consumption and costs to farmer of recalling/destroying affected sales. Providing routine shellfish samples for centralised bioassays is very costly and sampling logistics restricts weekly numbers of shellfish harvested – if real-time monitored risks could dictate the obligatory sample number per site, sampling costs at low-risk sites could reduce. **MEDIUM PRIORITY** Early-warning forecasts for harmful algal blooms (HAB)[19,20]. **MEDIUM PRIORITY**	markets (especially the domestic market) while improving the nation's health. Increasing capacity of the Scottish aquaculture industry by expanding markets and improving public perception, safety and acceptance of its products.	IN SCHOOLS[17]. initiative valuable but short-term – needs to be extended and allocated more resources. Requires a lot of foundation work and tests to be undertaken, and therefore this is currently a long-term goal. Long-term funding of ASIMUTH[19,20] HAB early forecast system to be trialled this year.

General Topic Priority Ranking (1-10)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
3) Specialized feeds for recirculation aquaculture systems (RAS)[21,22].	Develop feeds with low faecal-waste, suitable for use within RAS, which optimize the performance of the cultured species and also that of the mechanical and bio-filters in order to generate optimal physical and chemical water parameters. Investigate feeds with higher protein digestibility, lower oil levels and careful ingredient selection. **MEDIUM PRIORITY**	Increasing trend towards RAS which can provide biosecurity; reduced environmental impact and water abstraction/ discharge plus improved energy efficiency when culturing species from warmer/colder waters than ambient for Scotland.	It is important to understand the effects of scaling-up. Trial RAS diets need to be tested in an industrial or at least semi-industrial scale RAS, but there are relatively few large scale recirculation systems for running replicated trials.
4) Exploration of the metabolic interactions of dietary amino acids, soluble carbohydrates, fatty acids and lipids[1].	Determine absolute and relative amino acid and fatty acid and vitamin and mineral requirements with respect to life-stage, health, growth rate and feed efficiency. **MEDIUM PRIORITY**	Improved nutrition and, ultimately, output.	Few options for undertaking large-scale, replicated feed trials.
5) Wrasse weaning diets[23].	Reduce wrasse weaning period and associated mortalities. Develop diets that provide complete nutrition, optimal particle properties and attractants to encourage swift transition from live prey to formulated pellets.	Simplify and economise wrasse production for the purpose of biological control of parasites which adversely affect salmon production and welfare.	Relatively low economic incentive for feed companies to undertake this research since only low volumes of feed required at present.

General Topic Priority Ranking (1-10)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	MEDIUM PRIORITY. Small sector, but efficient diets are vital if wrasse is to be widely used by industry for the biological control of sea-lice.		
6) Immunological effects of dietary ingredients[1].	Explore capacity of dietary ingredients to positively affect the immune systems of farmed fish. Investigate fish gut integrity; gut-mediated immunity and dietary effects on gut microflora and fauna. **MEDIUM PRIORITY**	Supports biosecurity and stocking measures to improve health, disease resistance and output. Improve public perception and economics by reducing use of chemical therapeutants.	Few options for undertaking large-scale, replicated feeding trials, coupled with limited disease-challenge research facilities available to the industry.
7) Nutrigenomics[1]: studying interactions between gene function and nutrition	For example: identifying the gene(s) responsible for freshwater parr's superior ability to synthesise long chain PUFAs compared to post-smolt and adult salmon and investigating if the parr gene function could be reactivated in later salmon life stage. Present importance: **LOW PRIORITY** Future importance: **POTENTIALLY HIGH PRIORITY**	Making better use of nutrients – for example: reducing dietary requirements for long-chain PUFAs in marine stages of salmon. Knowledge of gene/nutrition interactions is also beneficial for selective breeding programmes.	This topic will increase in importance in coming years. At present, still a lot of foundation work is required, so it remains a relatively long-term goal.

General Topic Priority Ranking (1-10)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
8) Improved organic aquaculture feeds[24,25,26].	Explore new organic sources of specific ingredients, such as antioxidants to maintain ingredient quality and increase the performance of organic feeds. **LOW-MEDIUM PRIORTY** since small organic sector, but vital to the organic industry.	Increase efficiency and capacity of the organic aquaculture industry and improve nutritional quality of organic feeds.	Relatively low commercial/ economic incentive to undertake this work because of current small size of organic aquaculture sector.
9) Understanding and improving dietary pigment uptake and deposition in salmon flesh.	Increase biological uptake and deposition of pigments and investigate how raw materials interact. Importance: low impact in terms of meeting 2020 targets, but more important scientifically.	Increase the efficiency of pigment utilisation to help reduce dietary costs.	Few options for undertaking large-scale, replicated feed trials.
10) Live-prey substitution and delivery of water-soluble nutrients in larval feeds[1].	Reduce/eliminate the need to culture live-prey diets such as Artemia and rotifers for marine larvae without creating water-fouling and digestibility issues. **LOW PRIORITY** since small sector, but may increase if marine sector grows.	Simplify and economise larval nutrition in marine species such as wrasse, cod, and halibut. Improved nutrition, survival and production with reduced waste and fouling of culture water.	Research trials are often small scale. It is more difficult to maintain good tank hygiene in large, well-stocked tanks so replicated trials should be at least semi-industrial scale.

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Research Requirements

02 Stock Improvement

The long-term future of the Scottish aquaculture will rely on the timely supply of high quality seed (eggs, fry, smolts, spat) with the traits/characteristics that match the changing requirements of the production, processing and retail sectors. In terrestrial livestock there have been enormous improvements in the performance of chickens, pigs and dairy cattle by the application of pedigree breeding (i.e. breeding using family information and statistical prediction of performance). This allows efficient breeding for improved performance and the application of new genomic methods. In the major aquaculture species in Scotland pedigree breeding is only used for Atlantic salmon. In the other species of interest in Scotland (cod, halibut, rainbow trout and shellfish), pedigree breeding is not used or is at a very early stage of development and probably not targeted specifically at traits of importance to Scottish industry/conditions. The quality of seed for the industry can also be improved through one-off manipulations in the hatcheries that enable improved strains to achieve their full potential. Environmental manipulation of light, temperature and water chemistry ensures the correct development and timing of the life-cycle of the farmed fish to match the production requirements. The production of single-sex or sterile animals may result in improvements in productivity and could reduce issues related to escapes and welfare. There are however, issues of quality which may need to be addressed. For Scotland to become a global centre for aquaculture the industry will need access to strains that are selected for yield and quality traits and that perform well under Scottish conditions.

Selective improvement has been practiced for millennia by farmers but it is only in the last 30 years, with our increased understanding of genetics, that scientifically based breeding programmes in terrestrial livestock have shown enormous improvements in production (growth performance in broiler chickens >300%). Aquatic species still lag well behind in their potential performance because of the short period of domestication associated with this important animal production system. However, selective improvement in aquatic organisms can be rapid because of the higher selective pressure possible, the greater genetic diversity and the larger family sizes. Increases in growth rate of 100% or more have been seen in in several fish species, including salmon, within 5-6 generations of selection. Atlantic salmon is still the only farmed fish species globally for which virtually all production is based on fish originating from breeding programs, although these will have been running for no more than 10 generations.

The lag in applying selective breeding to other fish species was mainly a result of them having more complicated breeding and early life-cycles that did not lend themselves to the approach used in salmon. However, in the last ten years the rapid development of new and ever more powerful and cost-effective genetic fingerprinting and DNA sequencing techniques has enabled pedigree assignment in many new marine species with complicated larval development, when combined with individual fish (RFID) tagging systems, has enabled bespoke broodstock management and genetic improvement to be adopted in a wide range of other new and less tractable fish and shellfish species. The rate of technological change in genetics and genomics means that we can now look at many individuals in great detail and identify those with the greatest possible breeding value for a number of commercially important traits. At this stage in the development of the industry growth performance and disease resistance are high priorities but in the future traits related to yield, flesh quality and improved food conversion and retention of nutrients will become important. These are much more difficult and expensive traits to identify and select for because many require the animal to be killed before they can be assessed.

However, developments in functional genomics over the last decade enables us to describe how sequence information can be used to define the heritability and the functioning of genes associated with commercial traits. We now have access to draft genomes for Atlantic salmon and rainbow trout (became available during 2011), which has directly led to improved tools for identifying the genetic basis for performance differences between individuals in production traits.

When genomics is undertaken in collaboration with pedigree breeding programmes accurate estimates of the performance differences between different genotypes for the genes that control an individual trait can be assessed. In subsequent generations selection can be based on the presence or absence of a given marker for the trait rather than having to kill or challenge fish to assess the trait as done at present. This has enabled a Marker Assisted Selection (MAS) approach to be used for some traits (IPN resistance, muscle yield), so speeding up the rate of improvement in these species. We still do not have full genome sequence or good high definition genetic maps for most farmed Scottish species, sequencing and mapping should be a priority activity as new Next Generation Sequencing technologies now makes this quick and cost effective so we can apply these methodologies across all species. New sequencing technologies have been the cornerstone to many of the new methods, but with such as vast amount of information being generated there is also a need to ensure maximal information can be retrieved. It is essential to develop the bioinformatics capacity – the computational analysis of sequence data and integrating this with phenotypic data – in parallel with the genetic improvement and genomics. We also need to develop new scanning technologies for non-destructive analysis of phenotypic parameters (e.g. CT scanning for fillet and conformation) to speed up trait identification and selection.

Genomics does not only address breeding potential, but also how the genes are expressed and translated into proteins. Transcriptomics, which examines the expression of tens of thousands of genes in parallel, can reveal how individual fish respond to factors such as disease, nutrition, sexual maturation and environmental changes. It is now recognised that the environment under which an organism develops can have a long-term impact on individual's and its offspring subsequent performance. With a better understanding of these epigenetic effects it should be possible, by manipulating the environment, to programme the fish to maximize their performance under a range of different production environments.

The genetic potential of the fish is of little significance if it cannot be produced when and in the quantities and with the qualities the industry requires. Stock management strategies must be developed to first ensure timely and predictable production of optimal quality eggs and second control sexual maturation of farmed stocks. This involves the development and implementation of environmental regimes to manipulate broodstock spawning and hormonal therapies when required in species either not spawning spontaneously or to meet requirements for a selection program (e.g. milt volume). While protocols exist in species already established and domesticated to some degree for aquaculture (e.g. salmon, trout, tilapia), broodstock spawning remains one of the main bottlenecks in most emerging or new candidate species. There is therefore a need to develop such protocols based on basic understanding of reproductive physiology and environmental perception.

Strategies to control sexual reproduction of farmed stock include photoperiodic manipulation as routinely done in salmon ongrowing, sterilisation through triploidy as commercially done in rainbow trout and oyster (under experimentation in salmon), mono-sexing as done in trout, tilapia and recently halibut, and selection although the latter is longer term in species where no selective breeding program has been established yet. Importantly, the control of sex and reproduction is relevant to all aquaculture species. The reproductive containment of fish stock can increase productivity through enhanced growth (energy put towards somatic growth rather than gonad) and flesh quality, reduce downgrading at processing, protect wild stock from potential interbreeding and overall improve fish welfare. All of the above requires fundamental research to better understand light perception and biological efficiency, sex determination systems and ploidy impact on quantitative genetics and gene expression. New means of sterility should also be studied (e.g. vaccination, PGCs and GnRH inactivation, gene silencing technologies).

This brief outline suggests how the stock used in Scottish aquaculture will need to be managed if the industry is to compete on quality and performance in the global marketplace.

02 Table Stock Improvement

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
1) Selective breeding	Increase the resistance of salmon to parasite infections from sealice and Amoebic Gill Disease (AGD). Use selective breeding enhanced with the application of the latest genomic tools to increase the resistance of farmed salmon strains. Research indicates there is a genetic basis for sealice resistance in Atlantic salmon. Lice challenges, both controlled and natural of pedigreed salmon strains will identify individuals with greater resistance as future breeding candidates and strains with greater resistance. Use selective breeding enhanced with	Sealice are an immediate and major concern for the Scottish and global salmon farming industry. Salmon strains with increased resistance to lice will reduce the frequency of treatments and add to a multifaceted approach to controlling this parasite. AGD is an emerging problem that requires frequent costly, time-consuming and stressful treatment. The cost of managing and	Resources for the production of lice for experimental work are presently inadequate either for producing lice for challenges or different strains of lice e.g. naïve and resistant to different therapeutics. The development of experimental lice breeding facility should have a **HIGH PRIORITY**. Experimental facilities that enable large numbers of fish from pedigreed or newly selected strains to be

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	genomic tools to estimate levels of innate resistance to this new parasite in salmon strains.	treating this parasite is restricting the growth and the long-term sustainability of the salmon sector in Scotland.	assessed under commercial conditions are not available. Such facilities would also benefit research into nutrition and fish health. The genetic improvement research should be done in collaboration with these other priority areas. **HIGH PRIORITY**
2) Production of more robust disease resistant salmon	To increase resistance to viral and bacterial diseases. Breeding programs have increased the robustness of salmon strains to a number of viral (IPNV, ISA, PD, HSMI) and bacterial diseases (Furunculosis). New and emerging diseases needed. Increased disease resistance particularly benefits early development stages prior to any possible vaccination. Cumulative effect of increasing resistance will result in more robust farmed strains.	There are new/emerging viral and bacterial diseases appearing on a regular basis. New genomic technologies can result in the rapid identification of markers or genes associated with resistance that can speed up the rate of selection. Emerging viral pathogens often have chronic subclinical but result in	The new genomic tools to sequence, assemble and analyse the function and structure of fish genomes and potentially also those of shellfish and crustacean are still not available or are at an early stage of development compared to terrestrial farmed animals. Next Generation Sequencing (NGS) technologies now

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
		major losses in production.	mean that whole genome assembly of the main farmed species can be achieved rapidly and cost effectively and should be undertaken as a priority. This will speed up the rate of genetic improvement. This work will also have major benefits for those involved in fish nutrition and fish health This research should be done collaboratively with these groups. **HIGH PRIORITY**
3) Production of fish and shellfish with traits for higher production value.	To identify the genes underpinning important production and value traits e.g. growth, foodstuff utilisation, body conformation, flesh quality and fillet yield.; in the context of the industry using new more sustainable feed ingredients (new sources of fats and protein).	Classical selection of fish stock is critical to the long-term sustainability of any farmed species. Today most breeding programs utilize genomic technologies to define the traits and speed up the rate of selection.	The transcriptomes of farmed species have still to be studied in detail under a range of normal and different challenge conditions. NGS technologies offer a rapid methodology to better

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
		Simple growth performance is no longer a priority: priorities will be traits that improve the survival and quality and value of the farmed stock and that can make optimal use of new feeds or which are better at retaining polyunsaturated fatty acids (PUFAs) in their muscle tissue and have improved efficiency of protein deposition. Particularly if these can be assessed directly and non-destructively in breeding candidates, as this will speed up the rate of genetic improvement.	understand the functional genomics of farmed fish. Functional genomic studies of fish reared under various feeding regimes need to be undertaken. This research and development should be closely linked to the Nutrition Research. **HIGH PRIORITY** There is a need to develop new non-destructive methods to assess post harvest quality traits in aquatic organisms application of new technologies such as CT scanning and Near Infra Red need to be assessed. **MEDIUM PRIORITY**

02

Stock Improvement

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
4) Genetic management and improvement of new fish and shellfish species.	To improve the genetic management, particularly in the early stages of the domestication process to avoid the genetic degradation that can occur if the broodstock replacement process is not closely monitored. New fish species include various wrasse species and lumpsucker as biological controls of sealice. New shellfish hatchery for Scottish production of disease-free oyster, sea urchin and mussel spat.	New species need appropriate broodstock management and replacement strategies at an early stage in the domestication process to avoid genetic degradation of the newly acquired wild or farmed animals. That will hinder the future management and improvement of these stocks.	Development of pedigree assignment and broodstock replacement strategies. Molecular markers need to be developed for the above. **MEDIUM PRIORITY**
5) Stock management strategies to help productivity	Many production traits can be manipulated without changing the genetics of the organism.	Single sex stocks increase the productivity of existing strains of farmed fish. Sexual maturation reduces performance and increases the risk of disease and mortality in most species.	Our understanding of sex-determination and its manipulation in most species of fish and shellfish is still at an early stage. NGS/genomics techniques are starting to change this and offer the potential for rapid progress in this area. **MEDIUM PRIORITY**

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
6) Gender control and sterility	To develop single sex or sterile production fish and shellfish to reduce the impact of sexual maturation on the performance and quality of fish and shellfish in the grow-out phase in farmed Scottish species,e.g.: Single sex female trout and halibut Sterile Salmon, trout, oysters	Sterile fish also reduce the risk of interaction between farmed and wild strains and can reduce the costs of environmental manipulation to avoid maturation in normal stocks. Single sex/sterile production systems enable year round production of high quality fish and shellfish.	Single sex/sterile fish will become the norm for farmed and recreational fish species. Response to pathogens will be impacted by both state of maturation and ploidy needs to be addressed in relation to health and welfare. **MEDIUM PRIORITY**
7) Epigenetic and maternal programming	To understand the environmental factors that can cause heritable but non-genetic effects on the phenotypes of young animals that can have either long-term positive or negative effects on the performance of these animals and their offspring.	It is already known that the environmental conditions under which fish are reared can impact on their subsequent performance and that of their offspring. Optimising rearing environments and husbandry will ensure higher quality offspring, manipulating	We need to develop an epigenomic toolbox including novel sequencing technologies and bioinformatics. Due to rapid changes in molecular tools these techniques will allow for large scale screening of epigenetic changes in gametes and embryos. So we better understand

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
		these environments may result in fish that are better adapted to rearing conditions resulting in better performance.	the regulation of genome expression under different environments.
8) Environmental manipulation	To develop appropriate reproductive controls technologies. There is a need to increase our basic understanding of reproductive physiology and environmental perception in existing and new farmed species. Ontogeny during embryogenesis key for sensor organs smolts.	Light manipulation is critical in the timely and consistent production of gametes. Control of smoltification, puberty and therefore productivity as well as ensuring better welfare through more even dispersion of fish in rearing pens. Ontogenetic development is better synchronized and is critical to the development of sensory receptors in young fish and their subsequent development and performance.	This work requires the availability of experimental facilities with precise control of lighting and water. Research is needed to develop biomarkers that accurately define seed quality traits in farmed fish and shellfish.

02

Stock Improvement

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Research Requirements

03 Health & Welfare

Aquatic animal health and welfare (AAHW) improvements have continually tracked the expansion of the industry which has enabled the avoidance, prevention, and mitigation of pathogenic and parasitic diseases, and when required, eradication. Disease management can be costly, for example the industry in Scotland spends an estimated >£30M per year implementing an integrated approach to sea lice *(Lepeophtheirus salmonis)* management, highlighting that disease can have implications for production costs as well as environmental constraints that affect access to new locations for industry expansion. Although there are methods in place for reducing the impact of long-understood pathogens and parasites, there is a constant need for greater understanding of these agents and how they are adapting under selection pressures such as changes in climate, ecological communities and farm production methods. In addition, alternate methods of health and welfare management require continual development due to both changes in legislation relating to control procedures (such as the changes impacting on the management of Saprolegnia) and also to provide a greater suite of applications to avoid the development of disease agent resistance. Similarly there is a constant need for developing research to understand emerging issues such as those posed by Amoebic Gill Disease (AGD), which has been suggested as one of the possible contributors to the predicted reduction in salmon production in 2013.

The importance of AAHW is highlighted by its inclusion in a range of strategies and frameworks both nationally and internationally such as:
'A Fresh Start: The renewed Strategic Framework for Scottish Aquaculture', the 'Scottish Marine Science Strategy 2010-2015'. AAHW is a critical component underlying the principles in the 'Code of Good Practice for Scottish Finfish Aquaculture', in addition the European Aquaculture Technology and Innovation Platform incorporates AAHW for improved production as part of its vision statement and is a priority for the Federation of European Aquaculture Producers. Proposals for work to be addressed under the recently approved Scottish Aquaculture Innovation Centre includes substantial applied innovative research and development relating to health and welfare. Whilst a recent workshop between Marine Scotland and representatives of the salmon aquaculture industry highlighted that pioneering, explorative science is required to establish an understanding of the fundamental biology of the agent for AGD such as establishing life-cycles, physiology and aspects of pathogenicity as well as developing accurate diagnostic methods. AAHW research is crucial to industry and regulators and scientific researchers who are drawn together to participate in the regular international workshops organised by the Gill Health Initiative, Sea Lice Multination and Pancreas Disease (PD) Trination.

The recognition for AAHW as part of sustainable food security is highlighted by specific call for tenders under previous Framework Programme and upcoming Horizon 2020 programmes.

The key AAHW research developments for supporting the progression of a sustainable aquaculture industry concern predominantly sea lice, PD, Saprolegnia and AGD, however it must be noted that general topic areas are proposed to allow flexibility to accommodate changing priorities. Research needs include evaluating the benefits from employing modern approaches to problems for which original studies may not have worked. An important example being non-therapeutant treatments for sea lice.

03 Table Health & Welfare

General Topic Priority Ranking (1-10)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
1) Between farm transmission mechanisms	Investigations of the modes of transport between farm sites through environmental transmission and production activities.	Enable the establishment of appropriate aquaculture production zones such as farm management areas or catchments to aid disease management.	**HIGH PRIORITY**
2) Within site farm management practices	Explore differential approaches to managing disease on farms between pens/ units to minimise within farm pathogen transmission. Develop alternate methods of remote surveillance (e.g. imagery to detect change in behaviour, optical methods for counting lice).	Minimise agent transmission, to limit farm level infection. Allow for the development of greater automation and more effective detection to allow earlier targeted intervention.	Limited involvement of engineers for developing technological solutions. Physical oceanographer input required to identify within farm pathways. **HIGH PRIORITY**

General Topic Priority Ranking (1-10)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
3) Pathogen Genetics	Identify mechanism of virulence and disease emergence (e.g. ISA HPR0, VHS, OHV, Vibrio) to establish suitable risk assessments for disease introductions in to Scottish Aquaculture systems. Including disease emergence in diversifying fin and shellfish culture. Categorise mechanisms of resistance to chemical treatments and medicines in order to optimise rotation of treatments. Establish methods such as refugia, for promoting genetic diversity within parasite/pathogen populations to retain susceptible strains within the population allowing extant treatments to remain effective. Rapid diagnosis.	Inform the development of disease prevention, control, mitigation and eradication procedures to minimise production losses of farmed animals as a result of pathogenic disease.	Suitable assays for strain discrimination. **HIGH PRIORITY**
4) Alternate therapeutants	Develop alternate treatments to enable greater rotation and replacement of out-phased treatments, especially for Saprolegnia in freshwater phase.	Due to planned removal of formalin for use during freshwater phase of salmon and trout, the industry is	Substantial time from concept to market. **MEDIUM-HIGH PRIORITY**

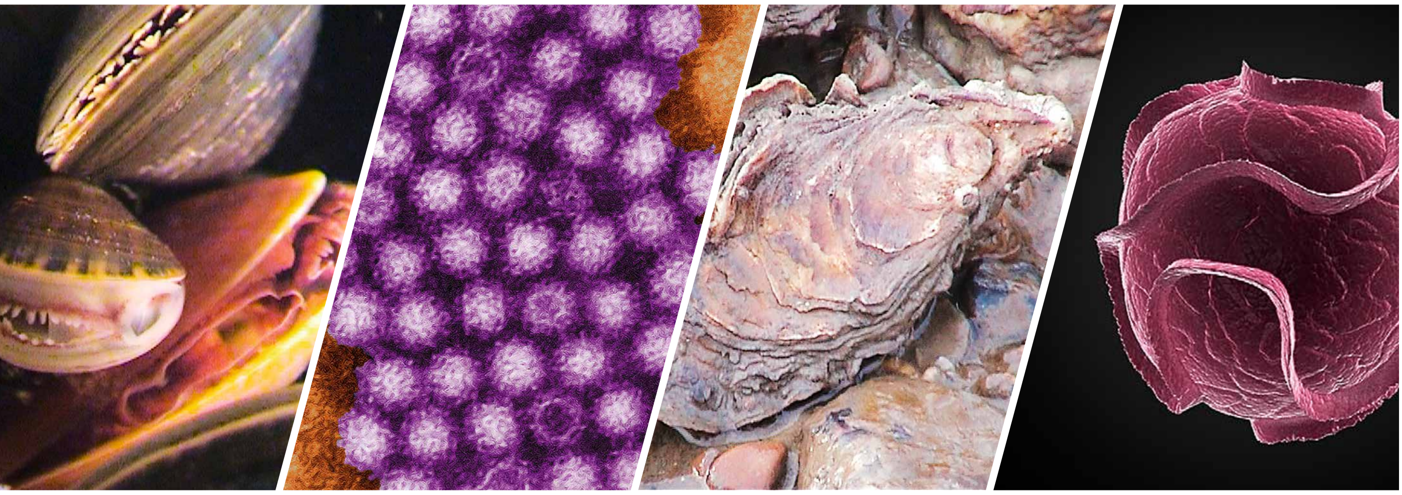
General Topic Priority Ranking (1-10)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
		vulnerable to a Saprolegnia epidemic which would cause contraction of production of fin fish.	
5) Diseases in trout	Establish best practises of using triploid fish in order to reduce abnormalities. Identify causes and develop mitigation for emerging disease syndromes such as 'puffy skin' and existing diseases such as Red Mark Syndrome.	Enable the diversification of fin fish production.	Currently small market share (although important for game fishing sector), so more focus currently targeted at salmon diseases. **MEDIUM-HIGH PRIORITY**
6) Emerging diseases. Changes in disease due to climate induced sea and freshwater change	Assessment of the potential disease risks of emerging (e.g Oyster Herpes Virus uvar) and predicted issues (e.g. AGD), and consequences for current known transmissible diseases (e.g. warmer seas enabling potential introduction of agents; temperature mediated sea lice maturation leading to change in management requirements).	Enable mitigation of losses from alternate sources to current issues.	Prediction of future conditions. **MEDIUM-HIGH PRIORITY**

General Topic Priority Ranking (1-10)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
7) Health and welfare of cleaner fish	Address emerging issues arising with the use of cleaner fish as biological controls for sea lice. Require categorisation of potential including behaviour, interactions with stocked salmon, biosecurity and escapes, emerging diseases, management and optimisation of use, selective breeding, husbandry practices, avoidance of feeding on pellets.	Reduce the dependency on chemical treatment, and issues concerning possible resistance. Diversification of fin fish culture (Produce a new sector). Limit need for capture stocking of cleaner fish ecological and biosecurity implications.	Infancy of breeding programmes. Identifying microorganisms which may pose risk to cohabiting stock. Development of assays for cleaner fish pathogens. **MEDIUM-HIGH PRIORITY**
8) Welfare	Identifying practical and measurable welfare outcomes.	High fish welfare is a characteristic of the Scottish industry. Measuring this for will become more important in the future for assurance.	The best fish indicators require to be identified, in terms of telling us about the welfare state of the fish. **MEDIUM-HIGH PRIORITY**
9) Genetics and breeding	Test the application of disease resistant animals to establish whether phenotypes are expressed to provide benefits under farm conditions. Ensure that breeding for resistance does not result in undesired	Reduce the need for medicines and therapeutants thereby establishing less diseased fish and reducing environment chemical input.	Breeding undertaken by limited number of organisations without wider dissemination of procedures. Lacking suitable test facility.

General Topic Priority Ranking (1-10)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	attributes such as suboptimal growth or a diminishing product.		Perception & regulation of GMO's. **MEDIUM-HIGH PRIORITY**
10) Immunology and Vaccines	Investigate the consequences of individual animal vaccination to herd/population immunity at the various production unit level.	Allow an assessment of the level of intervention required to limit the susceptibility of disease mediated production losses.	**MEDIUM PRIORITY**

Research Requirements

04 Food Safety & Hygiene



Ensuring product quality, food safety and human health are fundamental to the long term sustainability of the aquaculture industry. At European level, food safety and public perception of risk with regards to shellfish toxin/viruses and fish feed ingredients were highlighted as a major risk to the industry[1].

From a strategic perspective, key areas to be addressed are to[1]:

- Identify, manage and eliminate existing and potential physical, chemical and biological new hazards and emerging risks; including virus, bacteria, toxins, persistent organic pollutants (POPs) and other toxic substances
- Make available to producers of aquaculture products user-friendly methods to monitor and control the safety of the production, targeting known and emerging hazards
- Ensure the manufacture of authentic aquaculture products, regarding the species, quality, processing, use of additives, production method and geographic origin
- Better understand the mechanisms and synergies underlying the health risks of undesirable compounds potentially present in aquaculture products for risk management purposes

A number of strategic reviews of aquaculture refer to the need for research related to shellfish hygiene in particular together with generic requirements for traceabilty and provenance[2].

Considerable public funding has been committed to research related to the early detection of Harmful Algal Blooms (HABs), but the ability to predict the occurrence of HABs and their toxicity remains elusive. The need for rapid and cost effective test methods for detecting marine biotoxins in shellfish is a priority. Water borne viral contamination of shellfish requires better test methods.

The following research topics have been highlighted through the Shellfish Forum/ Ministerial Working Group. All of these issues are of generic concern to the UK and European shellfish industry:

- Development of rapid testing methods for detection and quantification of the marine biotoxin in shellfish
- Modelling of overflow incidents and their impacts on shellfish waters and the development of a rapid alert system
- Development of tools to detect Azaspiracid
- Development of a shellfish toxin management system
- Development of smart packaging to improve the traceability of aquaculture products
- Determine threshold levels for human consumption of Norovirus in shellfish
- Develop better Norovirus testing for end product testing differentiating between viable/non-viable viruses
- The dynamics of Norovirus in shellfish waters
- The use of indicator species for shellfish testing

In the Scottish Aquaculture Research Forum (SARF) database of research projects approximately 90 projects fall under the remit of Hygiene and Food Safety. These projects over the last decade had a total value of £11.9M. Of these projects 76% were concerned with shellfish (90% by research cost) and 24% were concerned with fin-fish (10% by cost) – these figures reflect that the overarching concern with respect to the real or perceived risk to public health is shellfish. Historically the majority of the funding for these research projects has come from The Food Standards Agency (FSA) or The Food Standards Agency Scotland (FSAS), which between them have funded 72% of the research effort. Public or non-departmental public bodies such as The Crown Estate, Scottish Government DEFRA and HIE have funded 13%, and the remaining 15% has been funded equally between RCUK, European Commission, and SARF. In 2015, Food Standards Agency Scotland will become a separate body to Food Standards Agency (UK) irrespective of the outcome of the Scottish referendum in September 2014. Although still heavily influenced by EU Directive requirements, this change in status may lead to differences in the way that the shellfish industry is and could be regulated in Scotland. This could offer opportunities for more streamlined risk based regulation which intern may shift the cost benefit equation in favour of increased investment in shellfish aquaculture. However, anthropogenic and climate change pressures will need to be carefully considered as these could impact on shellfish hygiene through increased incidence of viral and bacterial contamination together with increased exposure to HABs.

It would seem unlikely that the burden of supporting the necessary research to underpin this sector can continue to be met largely by the regulator. The shellfish sector remains relatively small and market failure with respect to the ability to support R&D required for its development applies. As such, those research councils with responsibilities for both the environment and food security should seek to increased investment in delivering the research and innovation needed.

Whilst there has been a long term aspiration to develop and expand the shellfish sector in Scotland (Ref: Scotts report from Stirling) and indeed the UK as a whole, this has a occurred to a limited extent only and (in Scotland) largely as a result mussel *(Mytilus edulis)* production. Whilst the industry is keen to expand, this is tempered by the realities of the market which would suggest that unless the domestic market for shellfish expands significantly, growth will only occur through exports. Historically, the industry in Scotland has failed to attract the investment needed to secure economies of scale – a scale needed to develop hatcheries and, potentially, selective breeding programme which could dramatically change the economics for this sector in the future. Investment is a function of confidence in economic return and having the capacity to produce fish and, in particular, shellfish that are safe and healthy to eat (and can continue to be produced economically subject to these caveats) remains fundamental to securing the desired expansion in production by 2020.

04 Table Food Safety & Hygiene

General Topic Priority Ranking (1-5)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
1) Detection, quantification and management of algal biotoxins in shellfish production	Development of on farm or at processing site of rapid testing methods and equipment for detection and quantification of the marine biotoxin in shellfish. Development of tools to rapidly detect and quantify Azaspiracid (AZA). Development of a shellfish toxin management/OC system.	Creating a consumer confidence in the products of aquaculture is key to expanding domestic market and to drive demand for the expansion of the industry. Biotoxins are the principle concern for regulators and producers alike. For example areas in Scotland are subject to AZA closures but no rapid kits/methods for shellfish testing exist for use by harvesters. Currently they 'take their chances' and may have to recall product.	The lack of a Scottish Shellfish Bio-toxin testing facility has the potential to reduce the speed at which these new tests can be developed and certified. **HIGH PRIORITY**

General Topic Priority Ranking (1-5)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
2) Norovirus detection and management	Determine threshold levels for human consumption of Norovirus in shellfish. Develop better Norovirus testing for end product testing differentiating between viable/non-viable viruses. The dynamics of Norovirus in shellfish producing waters.	The presence of Norovirus genetic material in shellfish has received a lot of publicity, and this has the potential to reduce consumer confidence and reduce demand. There is a UK wide research effort in this area, however identification of 'safe' limits for norovirus would be a massive step forward.	The lack of a Scottish Shellfish facility to test for Norovirus. **HIGH PRIORITY**
3) Environmental quality of shellfish growing waters	Modelling of overflow incidents and their impacts on shellfish waters and the development of a rapid alert system. Evaluation of how best to use phytoplankton monitoring as a tool in algal toxin warning systems. Evaluation of current management tools of area classification.	Increasing production will be reliant increasing the capacity and provision of shellfish growing waters. Understand how environmental influences impact on aquaculture food safety and hygiene is crucial to further developing the capacity of the industry.	This would require and integrated approach drawing on hydrodynamic modelling, microbiology, phytoplankton ecology and a study of current and prospective governance structures. **MEDIUM PRIORITY**

General Topic Priority Ranking (1-5)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
4) Ecophysiology of Harmful Algal Species and microorganisms	Improved models of transport of biological organism e.g. harmful algae and better physiological understanding and hence biological models of key organisms. Improved understanding of environmental factors that govern algal toxicity. The response of Vibrio bacterial in Scottish shellfish waters to climate change.		These are fundamental research questions that underpin more applied solutions as such would be suitable for funding under more traditional basic research channels. **MEDIUM PRIORITY**
5) Product traceability	Development of smart packaging to improve the traceability of aquaculture products.	Promoting consumer confidence and to creating a secure supply chain would again increase industry resilience and increase consumption and reduce waste.	**MEDIUM PRIORITY**

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Research Requirements

05 Technology & Engineering

Much of the engineering and technology used in the aquaculture sector has been developed by the industry as a result of innovation, largely within SME's. Although some novel aquaculture centric/ driven innovation has occurred, the industry has drawn heavily upon the transfer of technologies and materials developed in other sectors. This is likely to continue, but as the scale of the industry increases together with the expectation that it should operate in more challenging environments and potentially in more contained systems at sea or land-based demand for more bespoke and innovative technological solutions will be required (Ref: SARF-Telford report + Offshore aq report).

The UK has a world leading offshore sector built around oil and gas exploitation and more recently marine renewables development. There may be opportunities to adapt and transfer technologies and the underpinning expertise from these sectors. The challenges of working in more exposed and remote locations will require the ability to continue to operate within the biological scope of the species cultivated as well as meeting the physical engineering challenges. The capacity to monitor, manage and conduct operations and husbandry remotely will increase. Multidisciplinary research will be needed to ensure that such innovations lead to environmentally, operationally and commercially sustainable solutions.

Minimising potentially negative environmental interactions whether that be; escapes, disease transfer, predation or pollution, will remain a focus. The development and use of novel and adapted technologies will play an increasing role in this process. The use of robotic systems is likely to increase across all areas of industry over the next few years, coupled to remote sensing and the use of 'intelligent' materials and structures. Whilst the aquaculture sector is not of a scale to drive these developments, it is part of the future market for such innovation and may secure advantage by ensuring that the needs of the sector are considered and understood by those working at the vanguard of this area of science and innovation.

Although at an early stage in its development, the marine renewables sector could occupy large areas of our coastal waters. It is inevitable that opportunities to co-locate other commercially and operationally compatible activities in these areas will need to be investigated. Early attempts to co-locate aquaculture activities have had mixed success and none are currently considered viable. However, both food and energy security coupled to climate change drivers and major macro-economic shifts suggest that we should continue to explore opportunities and do so on meaningful scales. Aquaculture is largely synonymous with food production, but in the future it may also be responsible for the production of other products and environmental/ecosystem services that may be required to actively manage anthropogenically impacted marine ecosystems.

Recirculating Aquaculture Systems (RAS) are an integral part of some aquaculture production systems. Refinement of their commercial operation coupled to capital and operational cost reductions suggests that use of RAS technology will increase in some areas. Whilst much work has already been done, the expanded use of such systems will demand further innovation, with respect to engineering and technology as well as optimising the biological inputs and processes including, nutrition, fish health and stock improvement.

Scotland has recently established legally binding engineering standards for marine cage fish farming Research Council and EU investment in aquaculture related technology and engineering development has been quite limited over the last decade. In the UK there are no centres of expertise that would be recognised as being a focal point for this activity. The growth of the aquaculture sector globally, the aspiration to grow the industry in Europe and the continued expansion of the sector in Scotland suggests that there will be a need to cultivate the relevant technology and engineering expertise within the research community. Close international collaboration (particularly with Norway) on technological innovations offers exciting opportunities for mutual progress.

Scotland in particular is well placed to take a lead in technology and engineering developments, through multidisciplinary research pools, such as the Marine Alliance for Science and Technology for Scotland and the National Telford Institute, together with recently funded Innovations Centres focusing on aquaculture and sensors.

05 Table Technology & Engineering

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
1) Non-chemical treatment of sea lice	(1) To investigate non-intrusive methods of counting (see Topic 3 also) and removing sea lice on affected finfish. Optical delousing has been investigated in Norway[1,2], using short burst lasers but the practicality of this technique for full scale conditions has not been demonstrated. This technique should be investigated further, as should the use of light (and/ or colour, motion and chemicals) as an attractant to trap sea lice (presently being investigated in Canada[3]). (2) To investigate through feasibility studies and consultation the use of acoustic and electric field methods to delouse finfish.	Significant reduction in losses of fish to sea lice infestation and resultant increases in fish health, without recourse to expensive or ineffective chemical treatments, is essential if the industry is (i) to achieve the 2020 targets in increased finfish production and (ii) to do so in a sustainable manner without damage to the marine environment.	Many non-chemical methods of removing lice from fish or preventing the attachment of lice to the fish are already being pursued within the industry or at a pilot laboratory scale, albeit at an early stage. There is scepticism within the industry over the practicability of some of the innovations proposed or being investigated and some of the suggested techniques (e.g. acoustic and electric

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	Such methods have advanced considerably in recent years (particularly in the field of imaging) and they offer, in principle, advantages of being non-intrusive and durable. (3) To investigate improvements in methods of mechanical removal of lice (including the use of thermal methods[4]) that minimise stress and overcome deficiencies in filtering of stripped lice due to requirement of large volumes of water and insufficiently fine filters to retain egg strings and lice. (4) To investigate design innovations to nets and cages to prevent ingress of sealice, including those presently under investigation in Norway[5,6] using plankton nets, lice skirts, underwater feeding, snorkels, electric fields.		fields techniques) have not been tried yet or the results of early tests are not clear or unavailable. A great opportunity exists to collaborate with Norwegian researchers in this area. Much of the key innovative work on non-chemical removal and treatment of sea lice is underway in Norway[4,5,6,7], even at an early stage. Agreement has been reached to enhance joint working and information sharing under the Scotland-Norway MoU on aquaculture that helps bring both countries up-to-date with current industry developments and enables the further sustainable growth of Scottish salmon

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
			farming to achieve 2020 targets[8]. Of relevance to this Task Force is the agreement to collaborate on (i) tackling sea lice and (ii) improving containment to reduce escapes. **HIGH PRIORITY**
2) Anchors & Moorings	(1) Define hydrodynamic loading regime on pen/mooring line systems for future exposed offshore locations and the resulting mudline loads that the anchors must support[9,10]. This should include study of increases in these loads due to subsequent fouling[9]. (2) Reduce seabed footprint of moorings[10]. Use of taut line rather than catenary moorings allows potential for vertical mooring lines (tension leg arrangement). This would include potential for anchor sharing to improve efficiencies while	Subject to other biological, environmental and regulatory considerations, anchoring and mooring is a key technical hurdle to allowing expansion into offshore/exposed locations to significantly increase production (see Topic 6). Use of such locations also opens possibilities for co-locating with other offshore facilities (renewables/oil & gas).	(1) Little/no field or tank test data on mooring line forces or mudline (anchor) loads for aquaculture-specific problems; Potential for use of existing modelling infrastructure used for offshore renewables (wave tanks etc.). **HIGH PRIORITY** (2-4) Transfer potential of technology from offshore oil & gas industry[11,15] is high, but has hugely different design

05

Technology & Engineering

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	avoiding progressive failure. This will maximise density of production for a given site and reduce damage to seabed environment from chain scour. (3) Develop new, more efficient anchoring systems[10]. Design of taut leg moorings from Obj. 2 is controlled by anchor capacity[11]. Anchor efficiency defined in terms of: static holding capacity per unit dry anchor weight, resistance to cyclic loading, cheaper/quicker/more efficient installation[9], no requirement for specialist vessels. Such anchors will need to perform closer to their limiting states (i.e. at lower factors of safety), requiring more accurate loading information from Obj. 1. Moorings and anchors to be considered as a combined system, e.g. use of elastic dampers[12,13] in the lines could be used to reduce line tensions and therefore allow smaller anchors due to reduced mudline loads.	Reduction in footprint & use of efficient anchors additionally allows greater density of production in inshore/existing sites. Improvements in moorings and anchors[14] will contribute to improvements in containment, with resulting increases in production.	requirements (fewer, larger over-designed anchors). Fundamental development and validation of new design methodologies required for more efficient use in aquaculture. **MEDIUM-HIGH PRIORITY**

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	(4) Development of aquaculture specific engineering standards[10]. Required to support design of moorings/anchors (and cages) in exposed locations (offshore). To incorporate guidance based on Obj. 1 and be applicable to systems developed in Obj. 2 & 3.		
3) Sensors, automatic monitoring and intelligent systems	(1) Undertake survey of manually intensive work in aquaculture work-tasks (e.g. cleaning, feeding, sampling of stock) to determine those which show opportunities for automation. Many of the sensors required are already in commercial production. Others are at various stages of TRL (technology readiness level). Many sensors are physically large (esp. chemical sensors) and could be miniaturised to good effect. (2) Develop a vision of an aquaculture facility that uses a range of sensors for monitoring various parameters, under computer control. Parameters could	Incorporation of sensors into aquaculture operations has been recognised by industry[14] as offering opportunities to monitor fish health more efficiently than at present, contributing to the increased production required by 2020 targets. Satisfying such 2020 targets depends on improving containment; deployment of sensors to monitor automatically the nets,	In the general sensor market, over the last 5-10 years there has been an explosion in the number of devices. Market growth is driven by lower cost and lower power (of sensors themselves and the associated microelectronics), chip-level integration (e.g. lab on a chip technology) and increasing availability of wireless connectivity. With fish farms growing in

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	include water quality (dissolved oxygen, pH, conductivity, ORP (oxidation/reduction potential), TDS (total dissolved solids), turbidity, salinity, temperature, prescribed chemicals), meteorological/marine properties (currents, waves), mooring behaviour/performance, net tension and net deformation. (EU Project WARMER[16] demonstrated progress with chemical sensors, networking, satellite/in-situ data integration for estuaries, inland water bodies). Intelligent mooring sensor systems could sense changing weather and sea conditions and control moorings automatically. Data sent by wireless communications to the base station, where software measures, correlates and interprets trends in the data. Robotic machines could be used for various manually- intensive tasks. (3) Develop sensors for monitoring of fish feeding and behaviour (fish weight, quality, condition, mortality, net condition, optical/	cages, fish and water conditions, together with the development of associated control systems, provides an important contribution to prevent escapes, particularly when aquaculture installations are unattended.	size and number and with their imminent move further offshore, there is a growing need to automate much aquaculture. There is a need for water quality monitoring in real time to feed into estimates of carrying capacity of coastal waters. Comparisons should be made with 'The field of the future', in which the Oil & Gas industry is forward looking (5-10 years) to plan for extensive automation, remote working, and communications (largely wireless). The aquaculture industry could do likewise – 'The farm of the future'. **HIGH PRIORITY**

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	thermal imaging, fish health monitoring and miniaturised devices attached to fish[17] (measure temperature, pressure, physiological parameters, speed). (4) Investigate sensor networks and communications. Wireless Sensor Networking is developing rapidly; many aspects of the technology could be adapted for underwater networks. So there could be an array of sensors, networked together wirelessly. The array gives fault tolerance and resilience, dynamic re-configurability and the ability to make correlated sets of measurements. Low power consumption is achieved through: low-power hardware, software (controlling processor sleep modes), optimised communication protocols. Energy scavenging (e.g. light, vibration). Wireless communications offered by (i) mobile phones, 2.9GHz standards, various serial telemetry options, SatCom, etc. and (ii) WSN		

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	technologies, IEEE 802.15.4, above water, under water, RF, acoustic. (5) Investigate standards: There is a need to make sensors plug and play, with standard interfaces. Hardware interface standards: IEEE1451, I2C, 1-Wire. Software standards: Open Geospatial Consortium Sensor Web Enablement. Permits sensors to be part of the Internet of Things. OGC SWE includes SensorML (MarkupLanguage), TransducerML, Sensor Observation Service, Sensor Planning Service, etc.. (6) Exploitation of computer vision has been applied experimentally to a range of monitoring tasks, and in some cases has resulted in commercially available devices. Opportunities are (i) counting (eggs, larvae, fry, fish), Dimensions and shape of fish (sometimes using stereo camera pair), hence mass, (ii) gender identification, (iii) quality assessment –		

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	mainly with dead fish, but there have been a few trials with live fish (mainly colour, gender and sizing), (iv) species & stock identification, (v) monitoring fish behaviour and (vi) monitoring fish welfare. Little has been done so far on sea lice detection and counting by computer vision; difficulties arise due to the relatively small size: <1mm (juvenile), up to 5 (male) or 10 mm (female) adults. Could CV be used for automated monitoring of fouling?		
4) Anti-predator developments	(1) Development of 'burglar alarm'-type intelligent systems that initiate sound when fish panic detected[18]. (2) Investigate use of other anti-predator (seal) techniques (non-acoustic?), including (i) electric field deterrents[19,20], (ii) robotic deterrent devices operating outside nets. 3) Investigate structural analysis of net design[21,23,24] and automated net tension	Predator behaviour (in particular seal attacks) remains an important threat to containment and thereby is a significant consideration in assessing the industry's capability to attain 2020 increases in finfish production.	Though the effective deterrence and control of seals remains an important concern, there is evidence from within the industry that the number of seals being shot has decreased significantly and that bigger, tenser nets help (as does removal of dead fish) in this regard. Intelligent 'burglar

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	devices to determine optimal tension to prevent seal exerting pressure on slack net to obtain fish. Include investigations of smart designs of nets to detect holes and activate self-sealing measures[10]. (4) Investigate the benefits and disadvantages of using predator nets[25], including considerations of hydrodynamic drag.		alarm'-type systems[18] for seal scaring are on the market but there are opportunities for further research in this. Deterrence and control of predators by non-acoustic methods are attractive, not least because of the need to overcome seal familiarity and adjusted behaviour with present scarer systems. **MEDIUM PRIORITY**
5) Location to open water sites	(1) To intensify reviews of all engineering and technological aspects of location to 'more exposed'/'less sheltered', 'open water' sites[10,26]. There is a view within the industry that such location will present sets of problems that need to be tackled primarily by engineering solutions. The types of engineering problems of	Strategic considerations of moving aquaculture production to open sea sites are associated with the horizon beyond 2020 though there are implications for 2020 targets.	Work is already underway (SARF Project SARFSP009 – Technology for the Development of Aquaculture in More Exposed Locations in Scotland) within the industry to look comprehensively at strategic issues associated

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	relevance here are associated primarily with the hostile wave climates[27] in which the open water farms are to be situated and the upscaling in spatial extent of the farms. These factors have consequences for the design of (i) innovative moorings and anchors matching the local ground conditions and achieving reduced plan area, (ii) large, accessible feeding structures (and perhaps accommodation structures) and (iii) submerged cages. (2) To re-visit and improve the hydrodynamic dispersion models[28] (particle tracking) and AUTODEPOMOD regulatory software packages[29,30] presently in use in UK industry for predicting the fate of waste from cages. Such models and software packages are currently suited to sheltered sites. Improved models are required in order to obtain predictive estimates of the fate of waste materials and the environmental impact of large installations in water conditions dominated by wave forcing.	Open water aquaculture developments are inevitably linked to issues of co-location (Topic 6) and to the improvements needed for moorings and anchors (Topic 2).	with expansion of the industry to open water locations. This industry-led project will provide (in late 2014) important guidance on technology, engineering and management research requirements associated with open water aquaculture. In addition, experience from existing and planned aquaculture installations in UK waters[31] will inform strategic plans involving engineering and technology innovation development. **HIGH-MEDIUM PRIORITY**

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
6) Co-location with and multi-use of existing and new marine structures	(1) Identify matches between requirements of energy converters and species. Promising initial results have been achieved through use of shallow water blue mussels within a shallow water wind farm at North Hoyle[32]. However, even in these shallow conditions, the currents were challenging for the mussels. As the Scottish marine environment is more extreme, the limits of endurance of proposed species should be evaluated in order to provide better focus for proposed pairings. This should be extended beyond shellfish. General approaches using criteria scoring matrices have been adopted for similar studies elsewhere[33,34], and whilst this may be helpful to begin with, it would be anticipated that these need supporting scientific evidence to ensure confidence. (2) Commercial scale field trials. The conclusions of the North Hoyle work, and the subsequent report to the Shellfish	The crowding of the marine environment is a key theme for future planning[33,36,37,38] and by investing over 10M euros in multiple research projects, the EU have clearly prioritised this too. The 2020 target is to increase shellfish production (especially mussels) significantly. Co-location offers opportunities to contribute to this increase in production. For Offshore Renewable installations (ORIs), the co-location of aquaculture activity offers opportunities (i) to use aquaculture production to offset the loss of commercial fishing within the exclusion zone around the ORI and (ii) to	(1) There are probably sufficient data available for high-level consideration of species suitability. Some further exploration may be necessary for more detailed consideration of the most promising activities. **HIGH PRIORITY** (2) Few options for undertaking large-scale co-location trials in suitable

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	Association of Great Britain[32], identified a tentative success with the need to adopt a larger scale field trial. (3) Scottish environment, shallow water: Partnership strategy for integrating aquaculture into offshore energy farms. The output of Obj. 1 is to identify species that may be suitably cultivated in the environments into which renewable energy farms are located. Whilst the EU projects[34] are focussing on new structure design, many of the energy installations around Scotland are already sufficiently advanced in the planning that a redesign to accommodate aquaculture is unlikely. Therefore, this project must identify how the species identified in Obj. 1 may be suitably integrated into the existing fields. This requires consideration of the aquaculture science, the legal and logistic framework for ownership and operation, and the structural integrity under these new, non-designed loading.	provide a zone within which commercial fish and shellfish can recover from overfishing. This contributes to the sustainability objectives within the 2020 targets. Co-location will demonstrate good custodianship of the zone and provide nutrients to restore indigenous shellfish populations and increase productivity (scallops). Co-location is relevant also to Scotland's first National Marine Plan[39] which will provide a single framework to manage all activity in Scottish waters and guide development of a sustainable and successful offshore renewable energy industry.	conditions. **MEDIUM PRIORITY** (3) An appropriate selection of species on which to concentrate is required (Obj. 1) as well as an initiation of debate between stakeholders to identify barriers to success in Scottish waters. **MEDIUM-HIGH PRIORITY**

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	(4) A modular platform suitable for use in the Scottish environment: deep water. The shallow water/near shore cultivation of shellfish is promising, but with offshore energy being increasingly driven into deeper waters and into open ocean, there exists significant scope for a different combination of activities. These deeper water solutions would require significant improvement in current engineering knowledge of the structural and foundation design, and as such projects are not at an engineering planning stage then a novel platform design may be considered. This would require a significant amount of interaction between engineers (electrical and civil), marine scientists and potential stakeholders in order to achieve a priority-balanced design and accompanying usage guidelines.		(4) There are many uncertainties in all areas of deeper water offshore energy even without considering the additional shared-use element. As such, this remains a long-term goal, although one for which debate should be initiated now. **LOW-MEDIUM PRIORITY**
7) Seaweed and algae cultivation	The key engineering challenges of seaweed (macroalgae) aquaculture in coastal and/or open-sea areas relate	The developed knowledge will underpin both optimal seaweed farming as a	Currently available engineering solutions in seaweed aquaculture world-

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	to cultivation of seaweeds at special 'farms', seaweed harvesting, and transportation[40,41]. Among them, the knowledge base, underpinning the design of optimal cultivation devices/structures, is the weakest point of seaweed aquaculture engineering and technology. To develop optimal seaweed growth structures that maximise the rate of biomass production and minimise adverse deployment effects (e.g. instability/destruction at high waves/ flow velocities) at given hydrodynamic conditions, nutrient supply, and sea-bed composition, the following research objectives are to be achieved: (1) To identify key mechanisms and develop process-based models of seaweed growth and interactions between seaweed farms and combined wave-current environments at all relevant scales (from blade to patch (unit) to the whole farm), including effects of drag forces, mass-transfer processes, and light attenuation.	stand-alone operation and integration of seaweed aquaculture into larger-scale operations involving multiple users of marine resources. This later aspect highlights direct potential contribution to achieving the Scottish Government targets in relation to finfish and shellfish production. Indeed, seaweed operations, as part of the Integrated Multitrophic Aquaculture (IMTA), may significantly enhance sustainability of fish and shellfish farming and minimise their environmental impacts[40].	wide are largely empirical[42,43] and thus with high level of uncertainties in relation to the structure stability, biomass growth rate, and environmental impacts. The specialised modelling tools are practically absent making any optimal design and operational predictions for particular environmental conditions unrealistic. **MEDIUM-HIGH PRIORITY**

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	(2) To develop optimal mooring/anchoring structures, specific to seaweed farms, for a range of typical sea-bed conditions (also as a part of the Anchors, Moorings, Foundations topic above). (3) To identify key mechanisms and develop modelling capabilities for assessing the multi-scale effects of seaweed farms on the marine environment, particularly associated with effects on wave climate, water currents, sea surface roughness, nutrient depletion, and sea-bed (also as a part of the topic Improved Hydrodynamic Modelling above). (4) To perform multi-scale pilot deployments to provide data for testing research findings and inform Strategic Environmental Assessment and the development of appropriate Environmental Impact Assessment methods and thresholds.		

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	The research priorities related to biological and biochemical aspects of seaweed farming are outlined in the section Marine/ Blue Technology.		
8) Closed containment	Application of closed containment technology in the form of either land-based Recirculating Aquaculture Systems (RAS) or Floating Closed Containment (FCC) systems represents a potential route for expanding Scottish salmon growout production. Recent international developments have seen increasing interest in completing the production growout cycle to harvest weight or rearing Atlantic salmon to an interim weight, 600 to 1,000 grams, before transfer into seawater pens. (Current Scottish RAS expertise is directed towards early-age culture, smoltification and holding broodstock). Key challenges in adoption of closed containment technology by the industry are	If the research indicates that adoption could be sustainably viable then adoption would provide the potential for shortening the seawater production phase in Scotland, enable the industry to increase its overall production in existing coastal locations and thereby contribute to the industry's strategic growth plan, and in addition would provide the prospect for reducing interactions with populations of wild migratory salmonids.	Work is already underway modelling of the potential for shortening the pen-based phase of the salmon ongrowing Cycle, (SARF Project SP008). However there is scepticism within the industry over the potential adoption of closed containment technology, particularly on-land RAS, to complete the growout cycle and deliver commercially viable Atlantic salmon. A great opportunity currently exists to collaborate with Norwegian, and North American researchers in

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	both biological and engineering, together with the comparatively high level of initial capital investment required for an on-land RAS system and building confidence through increasing operational predictability/ repeatability and standardising solutions. Research objectives: (1) To undertake an economic assessment and evaluation of the development of potential revenue generation streams from RAS waste. Options should include aquaponics, algae biomass production and anaerobic digesters. **HIGH PRIORITY** (2) To determine the optimal rearing conditions (temperature/salinity/stocking density) re welfare & growth rate when cultured at high densities in RAS systems for Scottish strains of Atlantic salmon. **HIGH PRIORITY**		this area and economically efficient high value research. **MEDIUM-HIGH PRIORITY**

General Topic Priority Ranking (1-8)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	(3) To evaluate technological solutions for capturing and thickening waste, e.g. polymer technology, de-salting marine sludge. **MEDIUM PRIORITY** (4) To research technologies to deliver energy efficiencies including: low energy/ low head gas control systems; application of constant flow technology pump; and combining processes/units, e.g. pumping and oxygenation. **MEDIUM PRIORITY** (5) To investigate emerging technology solutions to achieving enhanced water quality including: improving removal of organic matter before it enters the biofilters; use of denitrification reactors and use of use of Anammox systems. **MEDIUM PRIORITY**		

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Research Requirements

06 Wild-Farmed Interactions

There are many potential interactions between aquaculture activities and the environment in which it operates. However the most important farm-wild interactions with respect to the long term sustainability of the salmon aquaculture sector are sea lice and escapes.

The potential exists for sea lice emanating from fish farm cages to impact on wild salmonids and vice versa. However, detailed scientific evidence to assess and quantify the extent of any impact in Scotland is limited and it is important that key knowledge gaps are filled through experimental and other studies.

Introduction of non-native salmon into the environment may occur through accidental escapes from aquaculture facilities or historically through deliberate introductions of stocked fish. Several studies outwith Scotland over the last decade report that when hybridization between indigenous and non-indigenous fish occurs a fitness cost may be incurred to wild populations, causing increasing awareness and concern about both conserving native fish gene pools and to the continuing health and viability of the wild populations. However, in Scotland there has been a general decline in reported escapes, which is partly due to activities of initiatives such as the Improved Containment Working Group including moves towards a Scottish Technical Standard for Containment.

There is also a lack of information on the potential for transfer of disease between farmed and wild fish. Wild fish are the ultimate source from which pathogens emerge in farmed fish and he exact role of farmed and wild fish in pathogen outbreaks will be determined by their respective densities in a given area.

06 Table Wild-Farmed Interactions

General Topic Priority Ranking (1-5)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
1) The dispersal patterns of sea trout and salmon and subsequent distribution in relation to the Scottish Coast	Salmon smolts depart rapidly from home rivers but little is known about their subsequent distribution in relation to the Scottish coast. It is believed that, in general, sea trout remain near shore for their first two months at sea and then disperse more widely, although some may move further afield soon after entering the sea. Little is known about the scale of dispersal or whether it is uniform in direction relative to the home river. Sea lice affect both wild and farmed salmonids. In the life cycle of both	Work on the dispersal of wild salmon and sea trout would help inform management aimed at growing the aquaculture industry in a sustainable manner in accordance with 2020 growth targets.	A multi-year research programme would be required. There is significant opportunity to tie in such research with existing and ongoing research relating to marine renewables. **HIGH PRIORITY**

General Topic Priority Ranking (1-5)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	salmon and sea trout it is the smolt stage that is most at risk from physiologically significant impacts of sea lice. From a wild fish perspective, it is important to have a better understanding of the migration pathways for salmon and key marine habitats for sea trout, in order that the potential impact of any interaction between wild and farmed fish can be better understood. From an aquaculture perspective, it is important to understand the migration pathways of both juvenile and adult fish (which will carry sea lice with the potential to infect fish within cages) in order to better understand and minimise the risks that arise from the presence of parasites and pathogens on wild fish. A number of the techniques used to chart fish movements are well-established. An opportunity exists to deal with gaps in understanding, by supplementing existing ongoing work in Scottish waters.		

General Topic Priority Ranking (1-5)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
2) The effects of sea lice at a population level on wild salmonids	It is the smolt stage of salmon and sea trout which is most at risk from physiologically significant impacts of sea lice infestation. The scale of any effect of sea lice on wild sea trout at the population level cannot be determined from existing published information. Knowledge gaps in the Scottish context are: • The scale of any association between levels of lice on salmon farms and on wild salmon. • The effect of sea lice on salmon at the individual level. • The effect of sea lice on salmon at the population level.	Information on the potential for sea lice present on farmed fish to impact on wild salmonids is incomplete and the issue remains controversial in relation to 2020 growth targets. Filling the knowledge gaps highlighted above is fundamental to meeting the 2020 target.	A multi-year research programme would be required. Work to answer these research questions would focus on the release of fish treated prophylactically with systemic sea lice medicines vs. untreated controls. Treatment will protect the fish, particularly in the first 6-8 weeks of their marine migration, and allow survival to the natal river to be assessed. Other than in a very small number of rivers, infrastructure to allow the recapture of treated and untreated fish is not in place in Scotland and having such infrastructure in a number of representative locations is important in achieving a statistically significant sample size for returning fish. **HIGH PRIORITY**

General Topic Priority Ranking (1-5)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
3) Improving understanding of sea lice dynamics	Interactions between sea lice, wild and farmed fish in open water are complex and specific to local geography, hydrodynamics, weather conditions, the number of fish farms and the number of fish within any given area. • Sea lice dispersal modelling is at a relatively advanced stage, but gaps in knowledge remain. Sea lice dispersal models should be developed to the stage that predictions relevant to the risk management requirements for new and modified developments are possible. • A greater understanding of the effects of farming stategies employed to manage and minimise lice numbers on sea lice dispersal is required. • Potential cumulative effects of multiple farms and/or increased fish numbers within sea lochs on the presence of sea lice in the environment need to be better understood.	Fulfilling the objectives would help inform management aimed at growing the aquaculture industry in a sustainable manner in accordance with 2020 growth targets.	MSS and others have developed/are developing sea lice dispersal models in a number of areas of Scotland, but significant parts of Scotland are not currently covered and it is recognised that some knowledge gaps still remain. **HIGH PRIORITY**

General Topic Priority Ranking (1-5)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
4) Investigations of routes of emergence from subclinical infection of wild fish to disease in farmed fish	All diseases of farmed fish have emerged from existing infections occurring in wild fish[1]. However, many of these infections have been sub-clinical with little impact on their wild hosts. Identification of aquaculture practices that facilitate such emergence can be used to develop methods that reduce the probability of new diseases arising. A variety of techniques are available to assess these routes. Case histories of emerging diseases[2] can be used to identify conditions and practices that have led to emergence of existing diseases. Network analysis of contact structure can be used to assess conditions under which an emergent pathogen might spread[3]. Epidemiological modelling can assess practices that allow pathogens to emerge[4]. Risk analysis of production practices can be used to identify key stages that increase risk of emergence. There are key questions /research	Avoiding emergence of new diseases is an important part of the Scottish Government's role in supporting sustainable development of aquaculture while protecting the environment. This will be of particular importance should new species be brought into aquaculture on a larger scale. This work would help inform management aimed at growing the aquaculture industry in a sustainable manner. Specifically, it would lead to tools for early identification of potential problems, leading to more cost effective surveillance for potential emerging diseases and hence tools to mitigate impacts. The project would benefit strongly	The project will require a review of existing analyses and sources of data relevant to emergence of new diseases. Such a project would take around three years to complete. This research would help inform the ongoing development of the Industry Code of Good Practice; and surveillance and regulatory measures to reduce the risk of disease outbreaks. **HIGH PRIORITY**

General Topic Priority Ranking (1-5)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	objectives that remain to be answered in order to allow the processes of emergence to be evaluated: • What are the environmental conditions affecting wild or feral populations that promote/retard risk of pathogen transfer to farmed fish? • How powerful is the surveillance for emerging diseases and how rapidly can sufficient information be collected to enable an objective assessment of control strategies to be made? • What is the economic trade-off between controlling production activities, including anthropogenic movements between farm sites, and reducing disease risk? • In what circumstances do such diseases significantly spill back into wild populations?	from close collaboration between different interest groups, farmed and wild fish interests, academics and government and lead to the development of networks that could promote sustainable aquaculture.	

General Topic Priority Ranking (1-5)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
5) Escapes of farmed fish	Introduction of non-native salmon into the environment may occur through accidental escapes from aquaculture facilities or historically through deliberate introductions of stocked fish. Non-indigenous fish (both from outwith Scotland, and from rivers systems across Scotland and the UK) will show varying degrees of genetic differences to indigenous stocks and may, in some way, be less well adapted to their new environment. Several studies outside of Scotland over the last decade report that hybridization and introgression by escaped farmed fish may incur a fitness cost to wild populations. In Scotland there has been a general and significant decline in reported escapes, due largely to farming industry initiatives to improve awarenesss, training and equiment standards. More recent initiatives, such as the Improved	The importance of avoiding genetic introgression in wild stocks is a priority for the Scottish Government to support sustainable development of aquaculture while protecting the environment[7]. Relatively little is known about the extent of any genetic interactions between indigenous and non-indigenous salmon.	The importance of this area has been acknowledged by the ICES Working Group on the Application of Genetics in Fisheries and Mariculture. At this point it would seem sensible to engage with this review, which is scheduled for 2014, rather than set up a separate piece of work[8]. Once standard tools have been agreed upon they could then be applied, although at present it is difficult to predict the time or cost that this would involve. **MEDIUM-HIGH PRIORITY**

General Topic Priority Ranking (1-5)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	Containment Working Group[5] including moves towards a Scottish Technical Standard for Containment[6]. However there are key questions/research objectives that remain to be answered in order to allow the incidence, impacts and mitigation of introgression to be evaluated: • What are the incidences of introgression in the wild in Scotland, and where have the non-indigenous fish originated from? • What are the impacts of non-indigenous fish on populations of wild salmon in Scottish river systems?		

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Research Requirements

07 Capacity

Scotland produced over 162,000 tonnes of farmed Atlantic salmon in 2012 worth an estimated £600 million to the Scottish economy. Scottish shellfish farms produced approximately 6500 tonnes of mussels, oysters and scallops in 2012 (see **Figures 6** and **7** below). The majority of this production comes from the inshore regions of the west coast, western and Northern Isles where farms are located in most of the suitable sheltered sea lochs and embayments. Achieving Scottish 2020 production targets will require a substantial increase in the size and/ or number of fish and shellfish farms already present in these regions of Scotland and it is currently unclear what capacity limits for the inshore areas should be and where the areas of greatest expansion potential are. It is generally accepted that while there may be some additional capacity in the inshore, greatest expansion potential is in the more exposed offshore waters where there is better potential for waste assimilation, greater space availability and reduced conflicts with other sectors. However the increased production costs associated with more robust equipment, increased travelling time and more challenging Scotland produced over 162,000 tonnes of farmed Atlantic salmon in

2012 worth an estimated £600 million to the Scottish economy. Scottish shellfish farms produced approximately 6500 tonnes of mussels, oysters and scallops in 2012 (see **Figures 6** and **7** below). The majority of this production comes from the inshore regions of the west coast, western and Northern Isles where farms are located in most of the suitable sheltered sea lochs and embayments. Achieving Scottish 2020 production targets will require a substantial increase in the size and/or number of fish and shellfish farms already present in these regions of Scotland and it is currently unclear what capacity limits for the inshore areas should be and where the areas of greatest expansion potential are. It is generally accepted that while there may be some additional capacity in the inshore, greatest expansion potential is in the more exposed offshore waters where there is better potential for waste assimilation, greater space availability and reduced conflicts with other sectors. However the increased production costs associated with more robust equipment, increased travelling time and more challenging environmental conditions for both stock and staff have so far prevented a change towards offshore production.

Capacity potential is limited by a number of factors. Environmental, economic and social. Economic factors relevant to capacity (market factors etc.) are dealt with in another section of this document (08 Markets, Economics & Social Science). Environmental limits on capacity stem from the receiving environment's ability to provide oxygen and assimilate wastes (nutrients and organic matter from fish feed, medicines and chemicals for finfish) and provide planktonic food from primary and secondary production (shellfish). Significant environmental impacts to water and sediment quality as well as marine life can result from unsustainable production levels causing breaches of environmental quality standards and the total standing biomass of aquaculture stock able to be supported without causing such adverse effects is generally referred to as the carrying capacity (assimilative or biological). Social factors influencing capacity include local community acceptance of aquaculture and the influence of local democracy on the planning regime. Local public objection to aquaculture developments plays a significant part in the restriction of aquaculture capacity and needs better understanding. Landscape and visual impacts play an important role here and the concept of landscape capacity (to impact from visible infrastructure) is well known but poorly quantified for much of Scotland's coastline. Nationally adopted science-based regulatory approaches also play a part in restricting capacity. Changes in our understanding of acceptable thresholds of environmental impact or improvements in the accuracy of regulatory tools and models could also result in changes to carrying capacity for aquaculture in specific areas.

Expanding both sectors within sustainable limits to achieve the 2020 targets will require new development consent and new discharge consent capacity (for finfish). Aquaculture planning is undertaken by Local Authorities and in the future will be conducted in accordance also with policies identified in the National Marine Plan and spatial direction that may arise in Regional Marine Plans created by Marine Planning Partnerships. Such bodies have yet to be established but will need to develop spatial guidance to identify optimum use of space for aquaculture where environmental constraints are lowest and an equitable sharing of space can be achieved with other marine uses.

There are unknowns surrounding all these areas of capacity limitation, many of which could be better addressed with improved science and research. Key gaps in understanding are identified below.

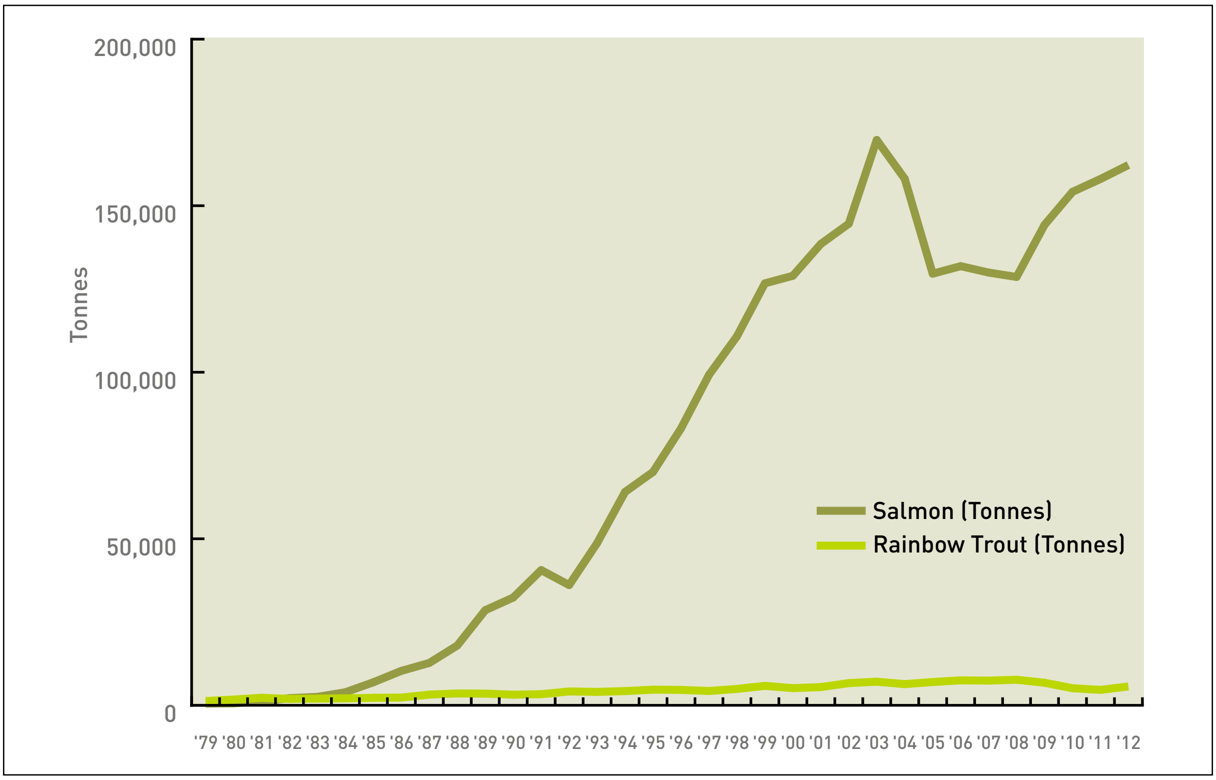

Figure 6 | Scottish farmed marine finfish production 1979-2012.

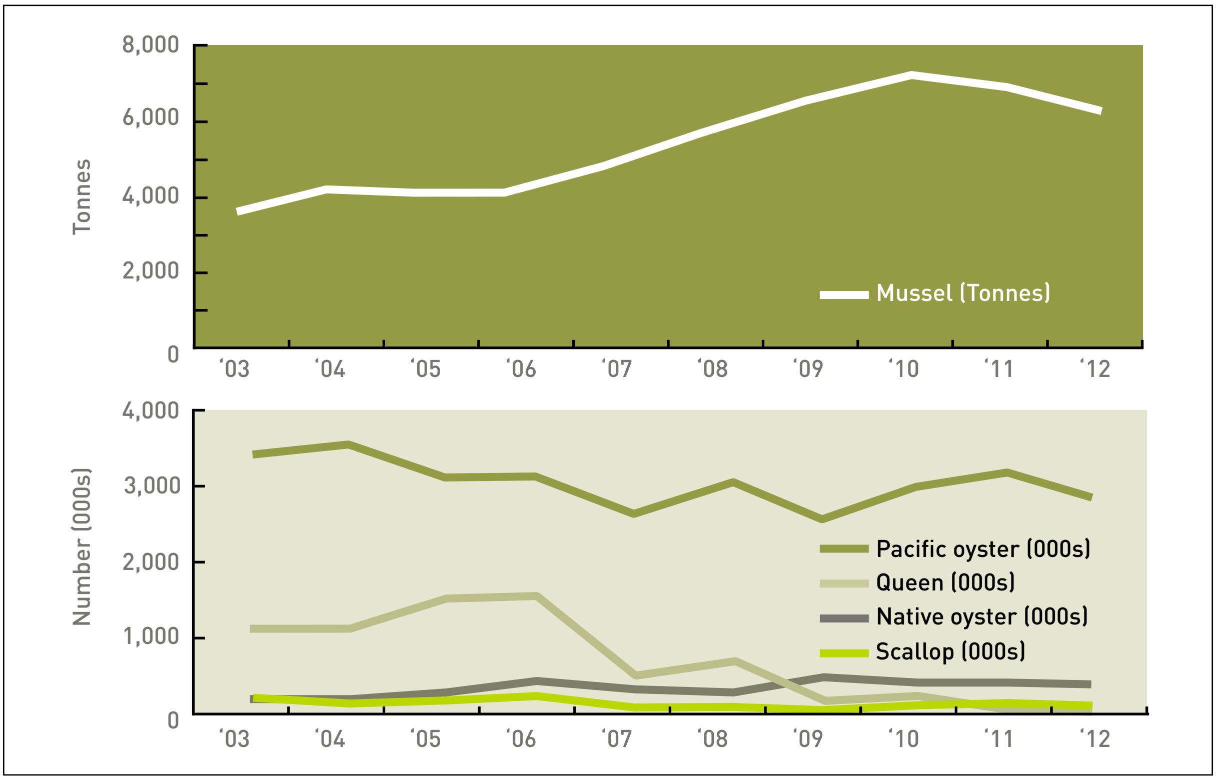

Figure 7 | Scottish farmed shellfish production 2003-2012.

07 Table Capacity

General Topic Priority Ranking (1-4)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
1) Improved inshore capacity estimates would allow greater certainty as to the appropriate sustainable capacity for new development	(1) Improve understanding the spatial distribution of the environmental, economic and social factors that constrain aquaculture development and identify areas that should be avoided. (2) Application of Multi-Criteria Evaluation GIS to identify areas of expansion potential based on (1) above. (3) Understanding and mapping of social acceptance of aquaculture across local communities. (4) Improved spatial guidance on landscape sensitivity.	Aquaculture will need to be integrated into Regional Marine Plans. Without some improved aspects of spatial guidance this will be difficult to do in a consistent way. The inshore marine space is already crowded and intelligent techniques for planning and site selection will be required to both find locations with spare capacity and take account of competing claims from other marine sectors.	Marine Planning Partnerships that would use the outputs have yet to be formed.

General Topic Priority Ranking (1-4)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
2) Improved estimates of assimilative and biological carrying capacity for fish and shellfish farms in inshore and offshore marine ecosystems	(1) Improve forcing data availability and ground truthing of available sea loch scale capacity models and improve usability of models (GUI). (2) Development of offshore capacity estimates at varying spatial scales through modelling approaches. (3) Improve sea loch scale capacity models to account for mixing from non-tidal sources (coastal currents and wind-driven events). (4) Apply wide scale hydrodynamic models to predict cumulative impacts from multiple farms.	Current inshore capacity estimates are restricting development potential in many areas and could be made less precautionary in some cases with improved capacity models used for planning and licensing. Combining hydrodynamic, eutrophication and particle tracking models to address cumulative impacts at a seaboard scale has not yet been attempted but is entirely tractable with the advent of efficient models and cheap computing.	Data availability for these models is poor. Model ground truthing is resource intensive. Relevant modelling expertise in this area is good. (4) Dependant on the output of Scottish coastal shelf model under development.
3) Optimisation of site selection for disease management (cf Section 06 Wild-Farmed Interactions)	(1) Application of large scale hydrodynamic models to predict spatial distribution of infective pathogen and parasite transfer. (2) Optimisation of management areas and	Salmon are farmed in management areas to allow strategic control of sea lice and diseases such as amoebic gill disease. These	Requires output of e.g. Scottish coastal shelf model.

07 Capacity

General Topic Priority Ranking (1-4)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	site selection to minimise risk of infection and maximise production potential from chemotherapeutant limits.	management areas may be sub-optimal. Use of the new shelf-wide spatially varying grid hydrodynamic models to simulate the transport of disease and parasites between farms offers massive potential benefits to disease management. The platforms are nearly ready but resource is needed to run multiple simulations of a wide range of scenarios and forcing.	
4) Improved management of shellfish aquaculture to account for changing environmental conditions	(1) Improved ability to predict spatial and temporal variability of spat-fall and on-growing success of mussels from environmental parameters. (2) Early warning and characterising the spatial/temporal dimensions to risk from harmful planktonic events (algal toxins, jellyfish, high biomass blooms).	Research is needed to better understand (i) how climate change will influence factors such as mussel larvae density/timing/quality, planktonic food abundance/quality, harvesting site hydrography and (ii) how increasing inorganic and	

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Capacity

General Topic Priority Ranking (1-4)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	(3) Understanding the impacts of climate change on shellfish aquaculture.	organic nutrient runoff from land based agriculture will impact shellfish aquaculture (potential to increase phytoplankton food for shellfish, but also the balance of benign/harmful organisms).	

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Capacity

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Capacity

BIBLIOGRAPHY CAPACITY

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Research Requirements

08 Markets, Economics & Social Science

Aquaculture is a significant contributor to economic activity in Scotland and provides particular benefits in fragile economic areas, both in remote coastal locations but also, through processing and other support activities, in the Central Belt and elsewhere. In addition, the aquaculture sector generates substantial human and social capital in the communities within which it operates.

Newly completed research for Marine Scotland and Highlands and Islands Enterprise shows that[11] the aquaculture industry contributes:

- A direct production income of £550m, with a GVA of £165.8m, and over 2,800 jobs, though it’s wealth generation goes far beyond this value
- It provides over 4,800 jobs in total, £800m in revenue and £293m across the supply chain in Scotland alone
- In total, a minimum of £1.5bn in turnover across the UK, including Grimsby processing and national retailing

Although aquaculture provides sustainable employment and income generation in remote areas that may otherwise lack alternative economic options, it also has a substantial impact on jobs in other parts of Scotland such as the Central Belt and this ‘other half’ remains largely unrecognised.

In terms of the benefits of aquaculture to Scottish communities, human capital in terms of participation in employment, as well as the skills and experience which provide ‘employment security’ was found to be most important, with financial benefit in terms of income to local ancillary businesses (particularly transport and tourism) the second most important. Negative opinions were generally low and most often related to environmental impact.

The sector growth targets must be achieved in a way that is profitable for the sector and sustainable for affected communities. This is possible and there is a broad consensus that growth of the aquaculture sector can bring benefits to the businesses involved, to communities and to Scotland as a whole. It is estimated that should the industry achieve the 2020 targets the industry could directly be worth over £1.2 billion and provide 7,000 jobs for Scotland.

Particular areas of research identified within the social sciences to support sustainable growth include:

- Skills – availability of skilled work force, provision of training and future skills needs
- Competitiveness – opportunities to add value and, in particular, reduce costs
- Markets – understanding consumer preferences; balancing domestic and export markets
- Governance – maintaining and enhancing community engagement to support appropriate development
- Technologies – cost effectiveness assessment of new technologies e.g. in offshore production
- Finance – drivers and barriers of investment, particularly for small firms

08 Table Markets, Economics & Social Science

General Topic Priority Ranking (1-7)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
1) Human Capital	Recruitment – assessment of recruitment to the industry, exploring barriers and drivers to attracting and retaining talent, identify requirements and possible bottlenecks as sector develops, challenges of recruitment and retention in rural areas. Skills – a stocktake or gap analysis to establish the current level of skills provision and the likely need in the future; availability of training and skills development in training institutes and within the industry itself; identification of best practice within Scotland and elsewhere.	Develop supply-side capacity to enable expansion and productivity improvements and uptake of new technologies.	Requires industry cooperation and involvement.

General Topic Priority Ranking (1-7)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
2) Consumers and new markets	Multidisciplinary/interdisciplinary research to explore opportunities for new products and species (e.g. seaweeds for non-food uses) – understanding of production, processing, marketing, consumer preferences etc.. Explore opportunities for creation/development of local/UK markets; Explore linkages with other sectors e.g. tourism; explore, for example through future scenario workshops, opportunities to develop products and to engage creatively with consumers (e.g. Catch a Piece of Maine); Examine risks and opportunities from demographic change and its associated impact on preferences and demand. Develop a better understanding of how consumer preferences develop and opportunities for industry to be proactive influencing perceptions and preferences; how sensitive are preferences to positive	Development of new and existing markets to ensure continued and growing profitability of sector.	Likely to require cooperation and participation of players within the downstream value chain.

General Topic Priority Ranking (1-7)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	messages (e.g. celebrity chefs, health benefits) and negative messages (e.g. environmental concerns) to enable effective and proportionate responses. This links to some of the research proposed by the Nutrition Task Group e.g. concerning human health benefits. Make use of existing research on markets and demand including from other comparator sectors; review existing literature, research and analysis to develop its real-world application. Review of export opportunities – exploration of current and potential export markets available to Scottish and competitor firms to identify high-value markets with growth opportunities; identification of best-value marketing and product differentiation strategies to secure growth opportunities in high-value export markets; identify barriers and constraints for example in distribution networks.		

General Topic Priority Ranking (1-7)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
3) Impact Assessment and Appraisal	Improve our ability to appraise and balance economic, social and environmental impacts. In particular to develop approaches to better understand non-market impacts e.g. on ecosystem services – either by improved monetary valuation of e.g. environmental and social impacts or through use of alternative decision-making tools such as multi-criteria analysis, Bayesian Belief Networks etc. – this will enable more credible and consistent decisions concerning marine planning, choice of production technologies and can also contribute to e.g. positive marketing, community engagement etc.; ensure policies consider potential impacts of management measures on aquaculture from a vertical (local, national, regional and international) and horizontal (between sectors e.g. aquaculture and fisheries) perspective. Life cycle analysis of aquaculture production – to inform marine planning, choice of production technologies and can	Better decisions around planning, policy and aquaculture development will facilitate community acceptance of aquaculture growth and ensure best use of marine environment.	Well-recognised difficulties in developing monetary values for ecosystem services and in accounting for social and cultural values within standard assessment frameworks.

General Topic Priority Ranking (1-7)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	also contribute to e.g. positive marketing, community engagement etc..		
4) Governance	Identify the factors within rural/coastal communities that can contribute to the success or failure of aquaculture developments e.g. demographics, governance arrangements, skills, training – links to research proposed by Capacity Task Group. Identify processes for community engagement to ensure developments appropriate and supported – links to research proposed by Capacity Task Group.	Ensure community support for and benefits from growth of aquaculture sector.	No obvious constraints.
5) Sector Competitiveness	Identify the key drivers of and barriers, throughout the product chain, to the competitiveness of the aquaculture sector in particular in relation to equivalent products in international markets, but also relative to alternative protein sources	Successful and sustained development of the sector relies on its ability to compete at a national and international level while maintaining profitability and	Requires industry cooperation and involvement.

General Topic Priority Ranking (1-7)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	within the UK; production costs, feed costs, regulatory costs, supply chains, marketing.	environmental and social integrity.	
6) Finance and Investment	Identify the key incentives for and barriers to investment in Scottish aquaculture and identify actions for government and industry; including competitiveness, skills, planning and governance, community engagement. Investigate demand and opportunities for innovative financing of aquaculture investments for example through community/private sector partnerships.	Access to finance is a key issue for growth of small scale aquaculture developments, in particular in shellfish and non-salmon finfish production.	Requires industry cooperation and involvement.
7) Production Techniques and Technologies	Impact assessment (e.g. cost effectiveness/ value for money assessment) of innovative production technologies – specifics will depend on activities elsewhere but could include measures to manage the ecological footprint of aquaculture, development of offshore technologies etc..	Need to demonstrate that development of aquaculture production and development of new products and technologies meet basic requirements for sustainability.	Relies on technical assessment of technological developments to feed into financial analysis. Requires industry cooperation and involvement.

General Topic Priority Ranking (1-7)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	Much of the research proposed by the Technology and Engineering Task Group could usefully include a cost effectiveness/ value for money component.		

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Research Requirements

09 Blue Biotechnology & Growth

According to the latest Horizon 2020[1] documents approximately 15% of the European economic activity centres on the marine environment and they are predicting that blue biotechnology will have an expected yearly growth of between 5 to 10% with approximately 7 million people employed in this field by 2020. The immense biodiversity of the marine environment is largely unexploited and the potential applications within the pharmaceutical, animal health, cosmetic and biotechnology industries unrealised. But it has been recognised that 'Blue Growth' within Horizons 2020 under Societal Challenge 2 is an important area for the future EU bioeconomy, and the European Science Foundation Position Paper 15[2] (2010) highlighted many of the research challenges that this sector faces. Scotland has yet to define a value for its marine biotechnology sector but there are some Scottish based researchers active in this field and it has been recognised within the recently funded Scottish Funding Council IBioIC[3], an innovation centre for industrial biotechnology (IB). IB uses enzymes and microorganisms and various forms of biomass to generate base materials for a wide variety of products including agrochemicals, food and feed, detergents, paper and pulp and textiles. **Figure 8** highlights the main processing pathways the IBioIC will be implementing which does include blue biotechnology. It is an emerging sector that can transform traditional manufacturing. Some applications are already 'live' and green technology[4,5,6] is becoming core to the function of many businesses. This field of science not only has potential benefits for industry but also for aquaculture. Marine or blue biotechnology is an extension of this and is the exploitation of marine bioresources for the production of products and services. This can also include the development of services for use in the marine environment in the form of basic research, bioremediation and marine environmental monitoring through to biodiscovery for food and pharma. Within Europe and at an international level the focus on 'Blue Growth' will support the Atlantic Ocean Cooperation Research Alliance launched in May 2013 as part of the Galway Statement[7].

Commentators suggest that the current value of IB is globally valued at \$53-\$80 billion and is expected to grow to \$225-540 billion by 2025[1,4]. Currently the largest value segments are:

- Derivation of chemicals
- Production of biofuels (where the market could reach a value of \$100 billion by 2018)
- Production of food and feed ingredients

For marine biotechnology the world market is projected to reach \$4.6 billion by 2017. Growth will be driven by the demand for environmentally safe, bio-derived feedstocks and Scotland has an unexplored and underexploited marine resource.

A number of underpinning technologies are required for IB including: plant and microbe biology, systems biology, synthetic biology and genetic engineering, marker assisted breeding, and other platform techniques that can be used to produce new species for the supply of sustainable feedstocks, and process engineering and fermentation. All of these underpinning technologies are available in Scotland through HEIs and are broadly applicable to marine biotechnology. A small number of Scottish institutes have some experience within marine biotechnology including SAMS, Strathclyde, Stirling, Heriot Watt and Aberdeen.

Scotland has strengths in the underpinning platforms including:

- Marine and algal biotechnology
- Microbiology and fermentation
- Enzymology
- Synthetic biology
- Bioinformatics, genomics and proteomics
- Downstream Processing (DSP)

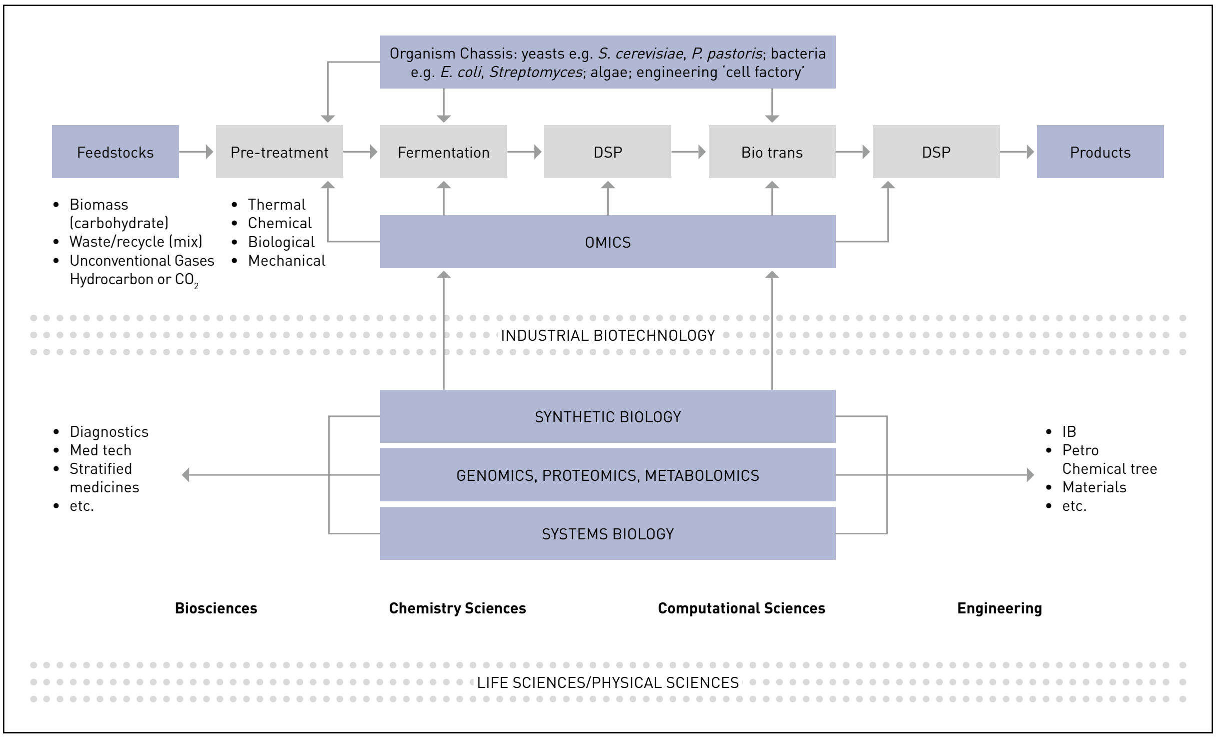

Figure 8 | An illustration of IBioIC converage of the entire integrated bioprocessing span (from the IBioIC Non-Confidential Executive Summaryc).

09 Table Blue Biotechnology & Growth

General Topic Priority Ranking (1-5)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
1) Marine Biotechnology exploitation	The environmental pressures marine organisms experience has lead to unique metabolic adaptations and they are considered to have an enormous potential for unique biotechnological applications[8,9]. These unique properties have resulted in several novel applications of enzymes in industrial processes. Similarly, the novel biochemistry of marine organisms is predicted to generate novel chemicals that are distinct in structure from those from more conventional organisms. However, only a minor fraction of them have been exploited. And there is a need	At a very basic level biotechnology is seen as the application of biological knowledge and cutting edge techniques to develop products and other benefits for humans. Within Europe Marine biotechnology has been highlighted as a priority research area. Approximately only 5% of the European economic activity centres on the marine environment this is expected to rise to 10%. The biodiversity of	Only a minor fraction of extremophile organisms have been cultivated and exploited. Sustainable harvesting of macro-organisms from their natural environment is rarely possible and has environmental implications. Current methods often fail to replicate the conditions needed to yield the target high-value compounds. There is a need to develop enabling technologies for culture and isolation of

General Topic Priority Ranking (1-5)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	to develop and standardise bio-prospecting procedures for screening and identifying novel biomolecules produced by these marine organisms.	the marine environment is largely unexploited and the potential applications within the pharmaceutical, animal health, cosmetic and biotechnology industries unrealised. This field of science sits between both aquaculture and industrial biotechnology.	uncultivated microorganisms and culture methods adapted to vertebrate or invertebrate cell lines for production of active compounds. **HIGH PRIORITY** Skills and training – there is a major need to train the next generation of marine biotechnologists. This should focus on an interdisciplinary approach and include aspects of sustainability. There are courses that have being developed at or are being developed at the postgraduate level but the potential of marine biotechnology should be introduced at the undergraduate level

General Topic Priority Ranking (1-5)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
			and not only to marine undergraduates. **HIGH PRIORITY** The area of bio-engineering of marine microorganisms is largely untouched, for example there is a need to optimise microalgal cultivation systems with respect to energy supply, productivity and cost and to promote research on the biorefinery approach based on microalgae production to develop a long-term alternative to petrochemistry. **HIGH PRIORITY** Identify and prioritise new marine model organisms, which are needed to fill critical knowledge gaps.

General Topic Priority Ranking (1-5)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
			Investigate identified marine model organism cultivation and perform genomic and chemical analyses. **HIGH PRIORITY**
2) Health	Development of novel drugs, treatments and health and personal care products. Understanding of genomics and metabolomics of interesting microorganisms linked to the compounds they produce.	Again this priority fits clearly within the European 'Blue Growth' agenda.	Increase the focus on the basic research (taxonomy, systematics, physiology, molecular genetics and (chemical ecology) on marine species and organisms from unusual and extreme environments to increase the potential for success in finding novel bioactives; – Improve the technical aspects of the biodiscovery pipeline, including the separation of bioactives, bio-assays that can accommodate diverse material from marine

General Topic Priority Ranking (1-5)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
			sources, dereplication strategies and structure determination methods and software; – Overcome the supply problem to provide a sustainable source of novel pharmaceutical and healthcare products through scientific advances in the fields of aquaculture, microbial and tissue culture, chemical synthesis and biosynthetic engineering.
3) Environment	Biotechnological approaches, mechanisms and applications to address key environmental issues. Metagenomic approach to identify microorganisms and their variability in the original environment including the systematic sampling of different microorganisms (viruses, bacteria, archaea, pico- and microplankton), algae and invertebrate	Aid in the protection of Scotlands marine biodiversity. Increasing Scotland's aquaculture capacity and aid the developing marine renewables industry in terms of biofouling.	Automated high-resolution biosensing technologies for in situ marine environmental monitoring to address coastal water quality, including prediction and detection of HABs and human health hazards.

General Topic Priority Ranking (1-5)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
	taxa. Implement metagenomic studies of aquatic microbiomes and macrobiomes.		Cost-effective and non-toxic antifouling technologies combining novel antifouling compounds and surface engineering for both aquaculture and renewable energy structures. DNA-based technologies for organism and population identification and support the development of commercial tools and platforms for routine analysis.
4) Food	Food products and ingredients with a marine origin (algae, invertebrates, fish) with optimal nutritional properties for human and animal health.	As the world population continues to grow there will be a major need within Scotland and Europe for alternative food supplies to ensure 'food security.'	Innovative methods based on -omics and systems biology for selective breeding of aquaculture species are beginning to be developed. **MEDIUM PRIORITY**

General Topic Priority Ranking (1-5)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
			The sustainability of aquaculture through biotechnological applications including alternative preventive and therapeutic measures to enhance environmental welfare and sustainable production technologies for feed supply. This should be coupled to integration of low environmental impact feed ingredients to improve quality of products and human health benefits.
5) Energy	Development and demonstration of viable renewable energy products and processes, notably through the use of marine algae this should include both microalgae and macroalgae.	Bioenergy within Europe is still a major focus. There has been a conceptual shift and for algae bioenergy a biorefinery approach should be taken with energy production as the last step	Improve knowledge of basic biological functions, tools for steering the metabolism, and cultivation methods of both marine macroalgae and microalgae to improve optimum characteristics

General Topic Priority Ranking (1-5)	Objectives	Relevance to 2020 target	Potential deficiencies in Infrastructure/Resource Requirements
		in the manufacturing chain. There is also potential in growing algae for waste remediation.	for mass cultivation (mixed & mono cultures), biofuel production and biorefinery. This has the potential to feed into health and feed, as sources of compounds for pharmaceutical, animal health, cosmetic and biotechnology industries. **MEDIUM-HIGH PRIORITY**

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Names of individuals and affiliations of those involved in compiling the strategy

Annex 01

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Sandy Murray	Marine Scotland Science, Aberdeen
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Capacity

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Karen Alexander	Marine Social Scientist, Scottish Association for Marine Science
Corrine Baulcomb	Environmental Economist, Scottish RUC

Blue Biotechnology & Growth

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Brian McNeil	University of Strathclyde

List of consultees invited to comment on the strategy

Annex 02

The following consultees were invited to comment upon the draft MGSA Science and Research Strategy document. Not all consultees provided responses and whilst the authors of the document may have amended some sections in response to consultees comments, the content of the final version of the document should not necessarily be considered as being endorsed by these individuals.

1st ROUND OF CONSULTEES
MGSA CHAIRS AND POLICY LEADS

Steve Bracken (Marine Harvest)
Iain Sutherland (HIE)
Charlotte Wright (HIE)
Randolf Richards (University of Stirling)
Jimmy Turnbull (University of Stirling)
Lauren Ferrari (Scottish Government)
Jeff Gibbons (Scottish Government)
Stephen Cameron (Scottish Shellfish Marketing Group)

2nd ROUND CONSULTEES
CONTAINMENT WG

Steve Bracken (Marine Harvest Scotland)
David Bassett (BTA)
Iain Macintyre (The Scottish Salmon Co)
Iain Sime (SNH)
Ishbel Crawford (LANTRA)
Jamie Smith (SSPO)
Douglas Sinclair (SEPA)
John Offord (Gaelforce)
Jamie Young (Gaelforce)
Peter Davies (Telford Institute, Dundee)
Reay White (Scottish Sea Farms)
Ron Smith (Marine Scotland – FHI)
Steven Divers (Fusion Marine)
Rhuaridh Edwards (Fusion Marine)
Roger Dehany (Knox Nets)
Tom Macrae (Sunderland Marine)
Dawn Purchase (MCS) representing Scottish Environment Link
Alan Wells (ASFB) representing wildfish interests
Douglas Sinclair (SEPA)
Ian Walker (Marine Scotland)
Stuart Middlemas (Marine Scotland – Science)
Ron Smith (Marine Scotland – Science)
Jeff Gibbons (Marine Scotland)
Paul Haddon (Marine Scotland)

WELLBOATS WG

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Catriona Graham (Marine Scotland)
Charles Allan (Marine Scotland)

Mike Bland (Marine Scotland)
John Webster (SSPO)
Tony Boyd (Marine Harvest)
Mark Woods (Loch Duart)
Willie McCosh (Scottish Salmon Company)
John Rae (Scottish Sea Farms)
Grant Cummings (Hjaltland)
Hugh Murray (Migdale Transport)
Roger Halsbakk (Solvtrans, Norway)
Jan Leikanger (Solvtrans, Norway)
Petter Gunnarstein (Fosnavaag Shipping, Norway)
Svein Martin Saele (Aquastar, Norway)
Gibby Clark (North Isles Marine)
David Leask (Island Innovations)
Dave Cockerill (Marine Harvest)
John Barrington (Scottish Sea Farms)
Ian Armstrong (Nevis Marine)
Colin Blair (Meridian)
Alan Dykes (Scottish salmon Company – left company since first meeting)

INTERACTIONS WG

New Chair – TBC
Alex Adrian (The Crown Estate)
Scott Landsburgh (SSPO)
Phil Thomas (SSPO)
David Bassett (BTA)
Alan Wells (ASFB)
Chris Horrill (RAFTS)
Jim Gallagher (Scottish Sea Farms)
Nick Lake (ASSG CEO)
Carole Barker-Munro (Marine Scotland)
Alastair Mitchell (Marine Scotland)
Jeff Gibbons (Secretariat – Marine Scotland)

FARMED FISH HEALTH & WELFARE WG

Randolph Richards (University of Stirling)
Kate Smith (Marine Scotland – Head of Aquaculture Health and Welfare)
Lauren Ferrari (Marine Scotland)
Rob Raynard (Marine Scotland)
Charles Allan (Marine Scotland)
Sandy Murray (Marine Scotland)
Andrew Voas (Animal Health and Welfare)
Colin Macaldowie (DCVO Animal Health and Welfare)
John Webster (SSPO)
Tom Turnbull (Scottish Sea Farms)
David Sandison (Shetland Aquaculture)
Dave Cockerill (Marine Harvest)
Chris Matthews (Fish Vet Group)
David Bassett (BTA)
Douglas Sinclair (SEPA)

SHELLFISH WG

TBC Chair
Lauren Ferrari (Marine Scotland)
Stephen Cameron (SSMG)
David Attwood (Loch Fyne)
Alex Adrian (Crown Estate)
Michael Tait (SSMG)
Craig Burton (Seafood Scotland)
David Donnan (SNH)
David Fell (SI Seafarms)
Douglas Sinclair (SEPA)
Hazel McLeod (SEPA)
Iain MacKinnon (Argyll and Bute Council)
Iain Sutherland (HiE)
Mark Steward (Argyll and Bute Planning)
Jennifer Howie (Food Standards Agency Scotland)
Iveta Matejusova (Marine Scotland)
Andy Mayes (Marine Scotland)
David Fraser (Marine Scotland)
Joyce Carr (water Environment)
Ruth Henderson (Seafood Shetland)
Adam Hughes (SAMS)
Fiona Garner (Scottish Water)

CAPACITY WG

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Matt Gubbins (Marine Scotland Science)
Alan Balfour (Loch Duart)
Alex Adrian (Crown Estate)
Cameron Sutherland (SDI)
David Sandison (Shetland Aquaculture)
Dougie Hunter (Marine Harvest)
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Rebecca Dean (Scottish Salmon Company)
Scott Landsburgh (SSPO)
Sheena Warnock (Scottish Sea Farms)
David Attwood (Loch Fyne Oysters)
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Stephen Cameron (Scottish Shellfish Marketing Group)
Suzanne Henderson (SNH)
Michael Tait (Shetland rep)

Organisations connected in relation to the SARF Aquaculture Database

Annex 03

ORGANISATION	2013 RETURN	2013 NIL RETURN
Swansea University	Yes	
Association of Scottish Shellfish Growers	Yes	
BBSRC		
British Trout Association	Yes	
DARD NI		
DEFRA		
CEFAS	Yes	
Environment Agency		
Food Standards Agency	Yes	
HIE		Yes
Marine Scotland Science	Yes	
Marine Scotland Analytical Unit	Yes	
UHI	Yes	
Ornamental Aquatic Trade Association		Yes
Shellfish Association of Great Britain		
SEPA		
Seafish	Yes	
SNH	Yes	
Scottish Salmon Producers Organisations		
Shetland Aquaculture		
The Crown Estate		
Highland Council		Yes
Welsh Assembly Government		Yes
Marine Management Organisation		
Stirling University		
Scottish Association for Marine Science	Yes	

ORGANISATION	2013 RETURN	2013 NIL RETURN
The National Telford Institute		
Marine Conservation Society)		Yes
WWF UK		Yes
Skretting		Yes
Biomar		
Ewos		
IFFO		Yes
Bangor University		
European Aquaculture Society		Yes

NOTES

- A return indicates the organisation provided information about research projects.
- A nil return indicated the organisation responded, but had no information of any relevance.
- A blank entry indicates no response.

In addition to these specific requests to other organisations, the SARF Secretariat conducted an extensive search and analysis of two online data sources:

1. The European CORDIS site: http://cordis.europa.eu/fetch?CALLER=FP7_PROJ_EN&QZ_WEBSRCH=aquaculture&QM_PJA=&USR_SORT=EN_QVD+CHAR+DESC
2. The Norwegian Research Council site: http://www.forskningsradet.no/en/Project_database/1184150364215?site=ForskningsradetEngelsk

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