An update on the 2014 report: “Review of Recirculation Aquaculture System Technologies and their Commercial Application”

Final Report for Highlands and Islands Enterprise RAS Lot 1 002

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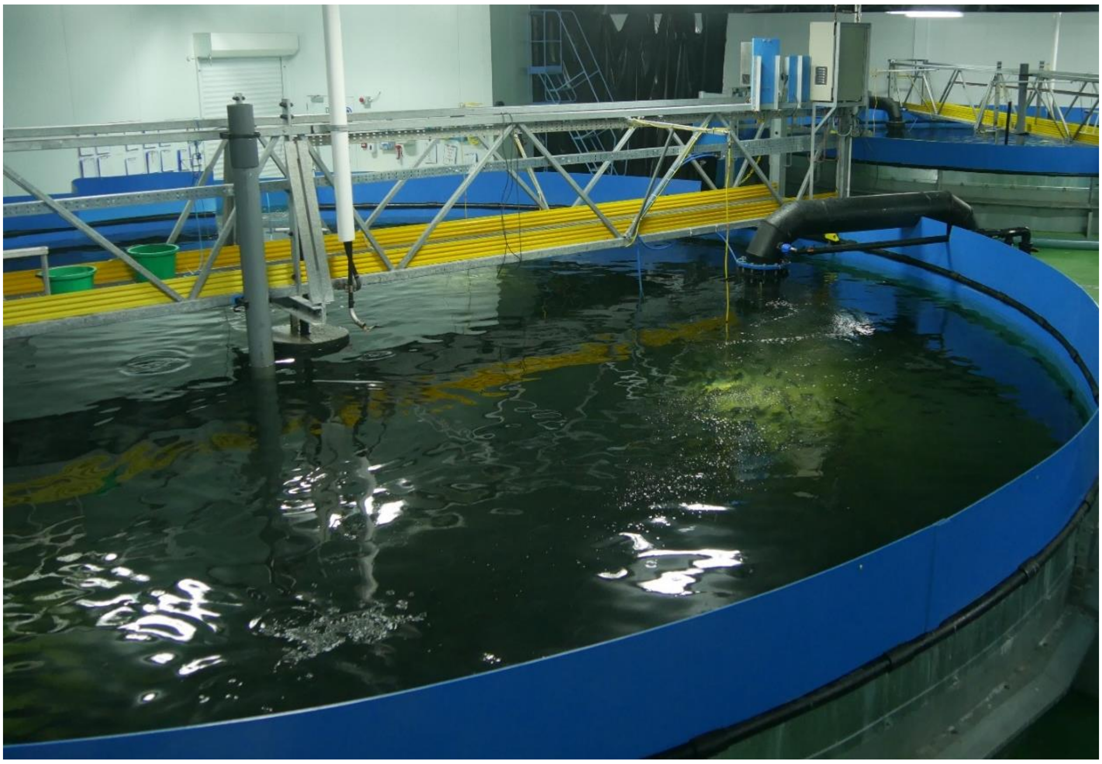
EKOS Limited, St. George’s Studios, 93-97 St. George’s Road, Glasgow, G3 6JA
Reg SC145099

Telephone: 0141 353 1994
Web: www.ekos-consultants.co.uk



Direct enquiries regarding this report should be submitted to:
John Bostock, Institute of Aquaculture, University of Stirling
Co-authors are: David Fletcher, Maddi Badiola, Francis Murray
Email: j.c.bostock@stir.ac.uk
Tel: 01786 466575

Preface

This report is intended as an update supplement to the 2014 report "Review of Recirculation Aquaculture System Technologies and their Commercial Application" (Murray et al 2014) which is available from http://www.hie.co.uk/common/handlers/download-document.ashx?id=236008c4-f52a-48d9-9084-54e89e965573. The focus is therefore on events and information that has become available after 2014, although evidence is drawn from other less recent work where appropriate for context and comparison. As the aim is to review the most recent developments, extensive use is made of news media reports as sources of information. For this reason, the report emphasises current utility when developing analyses and drawing tentative conclusions.

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Executive Summary

This report has been commissioned by Highlands and Islands Enterprise to provide an update on the earlier report "Review of Recirculation Aquaculture System Technologies and their Commercial Application" from the same authors and published in 2014.

The leading salmon aquaculture companies are all making strategic investments in RAS, mainly for juvenile production. This has been a trend over the past 20 years and has contributed substantially to technology development. The established industry has therefore demonstrated a willingness to adopt RAS technologies where they perceive a strong business case, such as enabling more consistent year-round supplies of juveniles.

Parallel to the strategic adoption of RAS by existing salmon producers has been a series of RAS-based grow-out projects based on a mix of optimistic technology promises and ethically driven enthusiasm for land-based farming drawing in investment from equity investors as well as government and other non-government organisations. Most of these have experienced a range of technical, financial and market problems and have either failed completely or are operating at a loss. Nevertheless, there is substantial momentum and lessons are being learned and technology is developing at a faster rate than when previously assessed in 2014. The lack of investment in grow-out RAS by established producers, notably salmon companies already culturing smolts in RAS, may reflect their greater understanding of market and economic fundamentals and/or reluctance to invest in disruptive technology given their heavy investments in cage grow-out production. More encouragingly, entry into the RAS sector by major water and sanitation companies such as Veolia, capable of more standardised technology development suggests previous barriers will be overcome.

The immediate interest of the Scottish salmon industry is in strategies to reduce the impact of sea lice and other disease problems. One element of this is to reduce the time the fish are in sea cages through the stocking of post-smolts of between 250g and 1 kg in weight. It appears likely that land-based RAS could provide an economic means of achieving this, although sea-based closed containment systems are also being investigated as a potential alternative. Land-based RAS are also being used for cleaner fish production as another part of the sea lice control strategy.

RAS offers opportunities for new species development in Scotland, with examples including sturgeon (caviar), yellow tail, sole, tropical shrimp, and spiny lobster. However, these are generally high value products for which domestic markets may be more limited

If already planned investments in salmon grow-out RAS go ahead in the USA, China and other important export markets for Scotland, long-term market opportunities are likely to be affected. A more substantial risk to the Scottish industry in the short to medium term could be a further decline in social license necessary to achieve ambitious growth-targets due to perceived conflicts with environmental and conservation targets. For this reason, combined with steadily maturing technology and new species opportunities, it is anticipated that aquaculture production using recirculated aquaculture systems will gradually expand in the coming years.

1. Introduction

1.1 Background and Purpose of Report

This report has been commissioned by Highlands and Islands Enterprise to provide an update on the earlier report “Review of Recirculation Aquaculture System Technologies and their Commercial Application” from the same authors and published in 2014.

Recirculation aquaculture systems (RAS) are fish or shellfish farms where the water used to culture the aquatic animals is continuously recycled through various filters and water treatment systems to maintain good water quality conditions for the stock. There are many variations on this basic idea with differing degrees of water retention and re-use (as discussed in the previous report). The main drivers for their development have generally been one or more of (1) increase production from a limited water supply; (2) achieve greater control over water quality parameters, especially temperature; (3) improve biosecurity by restricting contact with the surrounding environment; (4) increasing production cycle flexibility e.g. for out-of-season salmon smolt production and (5) enable species to be cultured in locations where natural conditions would be unsuitable. More recently the potential for closed-production in RAS to mitigate a range of environmental impacts has been seized on by a variety of civil society and other interest groups and they are also gaining attention as a technology solution to climate change challenges such as drought and rising sea temperatures.

RAS have been widely implemented throughout the aquaculture industry, but predominantly for the more specialised stages of hatchery/nursery production yielding outputs of high-unit value. Various degrees of water reuse have been more widely implemented, and a somewhat different approach using biofloc is becoming more common in shrimp farming (primarily for its biosecurity attributes). The use of RAS for grow-out has been limited to niche high value species; or to lower value warm-water species that can be cultured at very high densities over short grow-out cycles (e.g. Clarias catfish and Tilapia). However, expectations that such species can be profitably farmed in simpler lower cost RAS so called ‘brown-water’ systems due to their relative tolerance of poorer water quality have proved short-sighted (Murray et al 2014). To achievable optimal biological performance, Israeli company Aquamaof for example engineer their latest tilapia production systems using most of the elements common to smolt RAS including ozonation. Consequently, there have been many commercial ventures into grow-out using RAS, many of which (particularly in the UK) have failed due to a combination of design, management, economic and marketing factors (see previous 2014 report).

The key questions for this update are therefore: Is RAS technology becoming more reliable, and are RAS systems becoming more economically viable? Achieving this clearly depends on a wider range of factors, particularly ongoing investment and research and technological development. The context and drivers for this are therefore important, particularly with respect to Scotland.

1.2 Drivers for RAS Development

At the outset it is important to realise that globally, most of the fish and shrimp produced from aquaculture is from pond systems and a smaller proportion from cages in fresh or seawater. Analysis presented in Bostock et al (2016) indicated that RAS contributed less than 3% of EU finfish production in 2012. However, within the wider European Economic Area, finfish production is dominated by marine cage-based aquaculture, particularly the farming of Atlantic salmon (Norway, Scotland, Faroes), although seabass and seabream are significant in the Mediterranean region. This industry started in the 1970s and after a period of rapid growth has gradually consolidated, especially in Scotland.

The leading salmon aquaculture companies are all making strategic investments in RAS, mainly for juvenile production. This has been a trend over the past 20 years and has contributed substantially to technology development. The established industry has therefore demonstrated a willingness to adopt RAS technologies where they perceive a strong business case, such as enabling more consistent year-round supplies of juveniles.

In addition to internal industry drivers for RAS development, there are several external drivers. Foremost is probably a relatively small, but highly persistent group of lobbyists against cage-based fish farming. The most organised has probably been the Coastal Alliance for Aquaculture Reform in Canada, involving the David Suzuki Foundation, the Georgia Strait Alliance, Living Oceans Society and T. Buck Suzuki Foundation[1]. Moreover, the state of Washington (US) is enacting legislation to ban marine cage-based farming after current leases expire in 2022, directly affecting producers such as Cooke Aquaculture (Mayer 2018).

1 http://www.farmedanddangerous.org

In Scotland, opposition to aquaculture has come from veteran campaigner Don Staniford[2] and recreational fishing interests such as Salmon & Trout Conservation Scotland, the Sustainable Inshore Fisheries Trust and a range of other bodies involved with salmon and trout management and conservation as well as other environmental campaign groups. These groups have long argued that salmon farming is damaging wild salmon fisheries as well as the wider environment and that the only solution is to rear salmon in "closed containment systems" which mean land-based RAS or types of floating tanks where exchanges with the environment are more closely controlled.

The impact of this negative campaigning is difficult to assess. A simple Internet search on salmon farming shows that negative messages from these campaign groups have been propagated through mainstream media and many other websites. However, organisations such as the Global Salmon Initiative[3] as well as national producer organisations and other industry bodies do counter some of the negative media coverage through information on their websites. Despite adverse publicity, market demand for salmon remains resilient and is globally increasing. For example, a well-funded (& subsequently discredited) study reporting elevated organochlorine contaminant loads in European Salmon (Hites et al 2004) was associated with marginally depressed demand in the UK for only 5-6 weeks after the initial media-storm.

Froehlich et al (2017) carried out an international study of newspaper headlines and used the analysis as a proxy for public sentiment. They found that coverage of aquaculture in general is increasing, and that most was positive or neutral. Overall sentiment appears more positive in developing than developed countries and negative sentiment is most strongly linked with "marine" and "offshore" aquaculture. This suggests society is becoming more aware of aquaculture and general supportive of its aims, but with significant concerns, most strongly influenced by sustained campaigns against coastal salmon farming. The importance of public consent for commercial activity has become a focus for development studies and is often framed as an industry's social licence to operate (RIAS Inc., 2014). This can be seen as an important factor influencing policy makers and choice editors (e.g. supermarkets).

Amplification by lobbyists of the environmental issues associated with cage-based aquaculture does threaten the cage-based aquaculture industry's social licence to operate. Given the premium on shareholder value associated with strategic growth planning, this is perhaps most critical with respect to site-licensing requirements. An indication of this challenge and the divergence in attitudes across the public sector can be found in the ambitious government backed plan to double the value of Scottish salmon production from £1.8 billion in 2016 to £3.6 billion by 2030 (Food & Drink Scotland, 2016); contrasted with the

2 http://salmonfarmingkills.com
3 https://globalsalmoninitiative.org

approach of the Scottish Parliament Environment, Climate Change and Land Reform Committee (Scottish Parliament, 2018). Their recommendations include: “The Committee is supportive of aquaculture, but further development and expansion must be on the basis of a precautionary approach and must be based on resolving the environmental problems. The status quo is not an option” and “The current consenting and regulatory framework, including the approach to sanctions and enforcement, is inadequate to address the environmental issues. The Committee is not convinced the sector is being regulated sufficiently, or regulated sufficiently effectively. This needs to be addressed urgently because further expansion must be on an environmentally sustainable basis”.

Some entrepreneurs and technology developers anticipate a long-term decline rather than improvement in the social licence for coastal cage-based fish farming operations and are investing in alternative production systems in anticipation that the industry will switch and there will be a substantial business opportunity for new system supply or exploitation. In this context, closed containment systems including land-based RAS, have been promoted as a more sustainable solution and the way ahead for the future. RAS projects initiated by investors outside the aquaculture industry appear to be particularly driven by this analysis, and the expectation that RAS will enjoy higher levels of social acceptance and therefore become the preferred system by policy influencers, consumers and regulators. These assumptions and attempts being taken by the industry to use RAS to champion social licence (Section 3.6.1) are examined more closely in this report.

2. Recent commercial developments

2.1 Global Context

The number of RAS farms around the world is steadily increasing (Martins et al. 2010; Badiola et al. 2012). Norway, Canada and Chile represent important RAS industry countries, mainly for salmon production (Dalsgaard et al 2013), whilst China the world's largest aquaculture producer is constructing new, large indoor RAS facilities (Murray et al 2014). Research for this study suggests the trend is continuing with 36 RAS grow-out projects identified from recent media reports and many more used in hatcheries and juvenile production. Globally there are probably over 100 RAS salmon hatcheries and smolt units (mostly in Norway and Chile). In the context of global aquaculture however, the use of RAS for grow-out production is negligible. Total finfish production in 2014 was almost 50 million tonnes (FAO, 2016). Production of food fish from RAS is thought at most be in the tens of thousands of tonnes. If it reached 100,000 tonnes that would still only be 0.2% of total production. However, there are several examples of major new developments which demonstrate innovation and investment in this area variously targeting niche-market, or up-scaled cost-leadership strategies for grow-out options. For instance:

- The biggest salmon farm to date is being built in Miami (Florida, US) by Atlantic Sapphire Inc. using the European technology supplier Billund Aqua. This utilises technology tested in the Danish farm Langsand Laks. The long term aim of the company is to supply around 80% of the total US market. The Miami farm is designed to produce around 10,000 metric tons of salmon, by the time the phase-one build-out is complete, expected by late 2019 or early 2020.

- Superior fresh, based in Northfield (Wisconsin, US), is a leading aquaponics facility specializing in combining Atlantic salmon and rainbow trout production with a variety of leafy green vegetables. It claims to be the largest of its kind in the world with zero-discharge of production water.

- Emirates Aquatech claims to be the largest caviar farm in the world, located in Abu Dhabi, UAE. It is a RAS design with a capacity for 700 t of sturgeon and 35 t of caviar per year.

- The salmon industry continues to invest heavily in RAS for smolt production, recent examples in Norway being the Leroy Sjotroll Kjaerelva farm costing US$ 83.5 million; Marine Harvest facility at Skervoy costing US$ 83.5 million and SalMar investing US$77 million in a RAS unit at Jovika4.

2.2 Salmon

Salmon are of greatest interest in the context of this report both because salmon production is of major economic importance in Scotland, but also because through its pioneering of smolt-production and high unit market value it has become the focus of attention for proving the viability of commercial RAS technology. Many other species are cultured in RAS, but the most ambitious up-scaling efforts are currently targeted at this species.

2.2.1 Smolt and Super-smolt Production

There is now a clear trend for investment in RAS for salmon smolt production in all the key producing countries including Norway, Chile, Scotland, Canada and Faroes. The move to RAS is perhaps mostly driven by freshwater resource constraints to further expansion (or associated environmental impact controls), although improved fish growth rates and biosecurity have enabled RAS to be economically competitive with flow-through and cage-based systems.

In Norway, in 2016, there were 117 juvenile production companies and 187 licenses (source: Directorate of Fisheries). There were 23 RAS smolt farms in 2013 (Norwegian Veterinary Institute, 2016) increasing to 34 in 2015 (Krogh, 2016) with continued development to date. The top five smolt producers in Norway by revenue in 2015 were Salmar Settefisk AS, Smolten AS, Sundsfjord Smolt AS, AS Saevareid Fiskeanlegg and Fjon Bruk AS (Ernst & Young, 2016). These are all investing in RAS and a similar pattern of expansion has been seen in Chile, Canada, Faroes and Scotland.

Larger smolts are routinely produced in RAS (e.g. 120 to 150g compared with 70g in cage-based systems) which can help reduce the length of time required for grow-out at sea. The increasing size of smolts is illustrated in Figure 1 (data from Marine Harvest ASA) which projects mean smolt size to be 200g by 2021.

[4] http://salmonbusiness.com/here-are-norways-10-largest-smolt-sites/

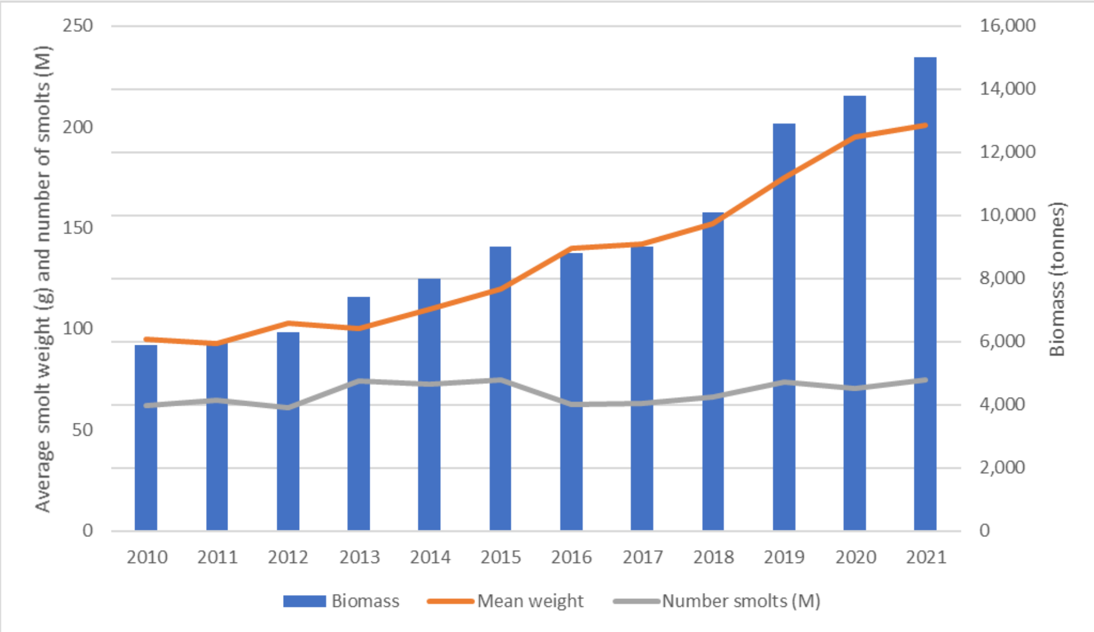

Figure 1: Actual and projected production and mean weight of salmon smolts for Marine Harvest Norway. Redrawn from Joensen (2016)

However, there are now substantive moves to further increase smolt size, possibly to 1 kg with specific projects in Faroes, Norway and Chile. For instance, Marine Harvest are producing 2.8 million smolts at an average 650g at a RAS unit in the Faroes and have built a new post-smolt RAS in Nordheim in Norway which is scheduled to produce 7.5 million smolts per year at a mean weight of 350 g (Anon, 2017). However, there are also competing sea-based solutions for intermediate grow-out (sea based closed containment systems) (e.g. Rosten, 2017), which makes this development less certain over the longer term.

2.2.2 Grow-out of Salmon in RAS

We have identified over 25 RAS grow-out farms for salmonids (Atlantic or Pacific salmon or trout) around the world established over the last 15 years. Some of these are currently operating, others recently closed or of uncertain status, and several more in the construction phase or simply announced. Currently operating farms have capacities up to 3,000 tonnes. Announced plans run to 33,000 t or even 50,000 tonnes.

Table 1: Companies (operating and announced) using RAS for grow-out of a salmonid species (Excluding UK)

Country	Company	Notes
Canada	**Kuterra (Namgis First Nation)**	**Seeking new investors 250-300 T**
Canada	West Creek Aquaculture	
Canada	**Sustainable Blue**	**Restarted after previous failure due to power failure**
Canada	Golden Eagle Aquaculture	
Canada	**Little Cedar Falls**	**100 t**
Canada	Swift Aquaculture	1,000 t planned, also Aquaponics
China	**Shandong Oriental Ocean Sci-Tech Co.**	**1,000 t Still operating? Not mentioned on website, last news 2015**
China	Urumuqi	1,000 t
China	**Seafood Dragon**	**6,000 t planned**
Denmark	Danish Salmon	2,000 t
Denmark	**Langsand Laks**	**1,000 t**
Estonia	Osel Harvest	
France	**BDV SAS**	**100 t**
Norway	Fredrikstad Seafoods	6,000 t
Norway	**Salmo Terra**	**2,400 t**
Poland	Jurassic Salmon	Certified by ASC
Poland	**AquaMaof**	**Pilot**
Russia	F Trout	500 t
Switzerland	**Swiss Alpine Fish AG**	
US	Superior fresh	70 t- with aquaponics
US	**Hudson Valley fish farms**	**3,000 t ? Also testing shrimp**
US	AquaBounty	1,200 t Purchased Bell Aqua site - GM salmon
US	**Nordic Aquafarms Inc**	**33,000 t (announced - $450 million)**
US	Atlantic Sapphire	10,000 t (in development with further plans up to 90,000 t)
US	**Whole Oceans**	**50,000 t (announced) $250 Million**

The largest announced projects are Whole Oceans[5], Nordic Aquafarms[6] and Atlantic Sapphire[7]. Each of these is developing off the back of increasing transatlantic cooperation on RAS technology development. This is a result of collaboration between the US Conservation Fund Freshwater Institute which has led on development of RAS in the United States, and the Norwegian research organisation Nofima which has a substantial research RAS at Sunndalsøra. The Freshwater Institute is a partner in a major Norwegian project on closed containment aquaculture (CtrlAqua) which has a budget of US$25 million over 8 years[8].

Atlantic Sapphire is collaborating with the Danish RAS technology company Billund Aqua. Nordic Aquafarms are Norway based with Danish collaboration and seeking to develop in the US as Freedom Salmon. Whole Oceans are working with the Freshwater Institute. As discussed later (Section 3.2), there is little evidence to date that farming salmonids in RAS will be competitive with cage-based production. However, Investment in this area is moving from tens to hundreds of millions of dollars.

2.3 Cleaner Fish

With an annual Gross Value Added (GVA) of £540m, Atlantic salmon is the UK's largest single food exported, directly employing 1,555 FTE and with a total employment impact of 10,340 FTE mostly located in rural communities in Scotland (Westbrook & Imani Development, 2017). Scottish salmon is exported to 60 countries and has built a reputation for quality, sustainability and welfare, with Protected Geographical Indication status and 70% of fish being accredited under RSPCA Freedom Food Standards. However, plans for growth are being hampered by the challenge from sea lice, which is estimated to cost the economy in excess of £30m annually[9]. Failure to control sea lice invites criticism from NGOs and regulatory bodies and represents a threat to the good reputation of the industry and the premium prices obtained in the salmon market. Losses due to sea lice are limiting the capacity of the salmon industry to achieve sustainability, as sea lice have become increasingly resistant to a range of medication. This issue is common to Scotland, Norway and other salmon producing countries.

5 https://wholeoceans.com
6 http://www.nordicaquafarms.com
7 http://www.atlanticsapphire.com/
8 https://www.conservationfund.org/projects/ctrlaqua-research-center-and-the-freshwater-institute
9 http://www.gov.scot/Publications/2014/07/4459/12

The use of cleaner fish for biological control of sea lice has evolved in recent years, mostly involving the ballan wrasse (*Labrus bergylta*), which is also cultured in small numbers for this purpose. However, wrasse do not grow well at low temperatures and so lumpish (*Cyclopterus lumpus*) is also farmed to work in association with wrasse species. Using an estimated load ratio of 5% of cleaner fish to salmon, several million lumpfish are required by the salmon industry in the UK each year. Lumpfish have been shown to greatly reduce reliance on medicines for sea lice control. Availability of farmed lumpfish will allow this strategy to become part of integrated lice management, reducing cost and volumes of medicines discharged into the environment and diminishing the risk of sea lice resistance.

However, evidence from other food production sectors suggests longer-term dependency on bio-controls is likely to pose significant challenges. Cage-production of any aquatic species represents one the most intensive forms aquaculture production (prior to RAS adoption) and a shift from polyculture to monoculture is a key attribute of the intensification process. Thus, any co-culture system can impose significant additional management interdependencies and risks e.g. of cross-species disease transmission. Furthermore, the very low recovery levels of biocontrol species currently being achieved also point to the risk of a potential animal welfare concerns.

Nearer-term technical challenges include dependency on wild lumpsucker broodstock to meet egg demand for UK hatcheries while suitably sized wrasse species are still mostly taken from the wild which has been shown to impact wild populations (Halvorsen et al., 2017). Equally, a significant proportion of lumpsucker eggs are imported from Norway to the UK with subsequent juveniles being released in Scotland. Combined deployment of wrasse and lumpfish, which is more tolerant of low temperatures and faster growing (reaching deployable size by 6 months post hatch), provides a more efficient control of sea lice than can be achieved by a single species alone. Ballan wrasse are relatively slow-growing taking 18 months from hatch to reach a size at which they can be deployed to cages. This longer production cycle puts constraints on hatchery/nursery space and reduces the number of wrasse available for deployment each year without significant capital investment in larger hatcheries. It remains that there is a need to completely close the cycle of both species as there is insufficient data on the status of wild populations and continued harvesting of wild stock exposes the salmon industry to new pathogens.

2.4 Other Species

Numerous freshwater and marine species are now claimed to be farmed in RAS. However, there are a wide range of designs that are termed "Recirculating Aquaculture Systems" with substantially different levels of water reuse and control over water quality. The lack of clear standards and definitions together with limited information from operators can make it difficult to identify those farms where the operator has full control over water quality including a capability to eliminate pathogen access via raw farm water supplies. Without this capability a farm remains vulnerable to pathogens and disease organisms entering the farm and infecting the stock. Similarly, does the RAS technology enable full control over water quality? As discussed in Section 4.5, systems which do not have the capability to properly control solids and dissolved organics accumulation within the culture system can lead to problems such as chronic gill irritation, exposure to toxic substances such as hydrogen sulphide and heavy metals or flesh tainting substances[10]. The range of species that can be considered to have been cultured in properly designed and managed RAS may therefore be substantially less than the number suggested by use of the label "RAS".

There really is no limit to the species that might be farmed using RAS technology. The challenge is to identify projects that can deliver a quality product, generate a profit while maintaining high animal welfare standards. Currently, marine food fish species being commercially cultured in RAS include sea bass, meagre, yellowtail, sole and several species of grouper. Also cultured in marine RAS are numerous coral reef species for the aquarium trade including invertebrates. Commercial fresh and brackish water species farmed in RAS include barramundi, tilapia, catfish, zander, perch, jade perch, eel and sturgeon. Success is highly dependent on local economics and the competence of the management as well as fundamental technology.

[10] For instance, some "RAS" farms constructed for market size salmon production require separate depuration systems (e.g. purging by holding in clean or water for a period of time) to clear the fish flesh of off-flavour taints prior to marketing

3. Challenges for RAS

3.1 Operational Reliability and Health Management

In principle, RAS should provide a more secure environment for the stock without the risks of environmental stressors including storms, predators, algal or jellyfish blooms etc. They should also provide substantially better biosecurity, resulting in lower mortality levels or welfare issues associated with disease. In practice, as the earlier report discussed, many problems have occurred. Due to commercial sensitivities there has been relatively little documentation of disease problems in RAS or losses caused due to equipment failures. It is likely that almost every new RAS has experienced a problem resulting in complete or almost complete loss of a production cycle as demonstrated by the following recent events.

Table 2: Examples of documented losses at RAS farms

Farm/Location	Issue	Source
Canada, Nova Scotia	**600,000 salmon smolts slaughtered after outbreak of ISA at two RAS farms**	**Woodbury (2018)**
Marine Harvest, Nordheim, Norway	140,000 salmon smolts slaughtered due to unidentified health problem	Olsen (2017)
Marine Harvest, Steinsvik Farm.	**734,499 smolts died due to "water quality problems, water poisoning, or acute gill inflammation triggered or caused by the aforementioned"**	**FIS (2017)**
Langsand Laks (Atlantic Sapphire), Denmark	250 tonnes salmon lost due to hydrogen sulphide poisoning	Undercurrent News 2017
Niri, Scotland	**All fish slaughtered (26,000 salmon smolts stocked) after water contamination issue**	**Hjul, 2017**
Norway	Cases of Yersiniosis (Yersinia ruckeri) in RAS	Norwegian Veterinary Institute 2015
Norway	**Cases of ISA (Infectious Salmon Anaemia) in RAS (Notifiable disease requiring destruction of stock)**	**Norwegian Veterinary Institute 2015**
Denmark	Cases of furunculosis (Aeromonas salmonicida) in RAS resulting in serious losses	Norwegian Veterinary Institute 2015

Many of above loss situations indicate an on-going need for greater diligence in managing treatment of raw supply waters to RAS farms to reduce pathogen risk. One approach in instances of RAS adoption by less experienced operators may be for suppliers to offer a longer-term programme of cooperation to assist with biosecurity training and system operation over and above a common commissioning approach which often lasts just a few months.

Third-party support in this respect may also avoid conflicts of interest between RAS engineering suppliers and clients that have been a recurrent problem in the past.

Equally, investors in land-based aquafarming, using RAS technology, need to be aware that the technology remains under development. Effective monitoring and economic management of a range of harmful substances that can accumulate in RAS are still in the development phase. It also needs to be appreciated that expertise in freshwater RAS is no guarantee of success with marine RAS which is widely recognised as more complex.

That said, it also worth noting that with their growing practical experience of smolt production, larger salmon companies such as Marine Harvest are taking greater control of the entire project management process, including civil engineering. This has also been accompanied by growing staff specialisation in management, engineering and husbandry fields.

3.2 Financial Competitiveness

3.2.1 Financial Analysis

In the earlier (2014) report, RAS were shown to be more capital intensive compared with cage-based farms, with overall higher cost of production. On this simple analysis RAS appeared uncompetitive. A small number of studies incorporating further cost-benefit analysis have been published over the past three years.

Warrer-Hansen (2015) reviewed the potential for land-based salmon grow-out in RAS in Ireland. This involved estimation of capital and operating costs for a 5000 tonne per annum production of Atlantic salmon in a RAS. This suggested basic variable operating costs are comparable with cage farms, but capital costs for an equivalent production capacity are around 2.5 times higher. Once the cost of financing is taken into account, financial viability appeared very marginal, with annualised unit cost of production of €3.62 per kilogram of whole fish or €4.84 per kilogram for delivered head-on gutted salmon. This was equivalent to the average wholesale price in 2014, suggesting a venture would just break even, and take 8-9 years to repay the initial investment.

King et al (2016) modelled several scenarios using Australian and US data. They compared finances for 6000 tonne production units based on (1) conventional inshore cages; (2) offshore cages; (3) onshore freshwater RAS; and (4) Post-smolt production in seawater RAS followed by shorter grow-out in offshore cages. As with previous analysis, the grow-out RAS had the higher capital cost, but other scenarios assumed better biological performance and lower disease treatment costs resulting in the best performance from the offshore cage production, but with freshwater RAS more profitable than inshore cages.

Table 3: Summary financial analysis from King et al (2016)

Production scenario	Inshore Sea-Pens	High-Energy / Remote Site Sea-Pens	Freshwater RAS	Post-smolt RAS & High Energy Remote Site Sea-Pens
Initial Capital (US$ Million)	19.9	14.7	40.6	25.9
NPV (US$ Million)	65.8	135.1	116.8	125.1
IRR (%)	32.6	61.9	43.6	52.8
COP (US$/kg HOG)	5.5	4.41	4.96	4.72
3rd Year Net Income (US$ Million)	11.4	18.3	14.6	16.3
Payback Period (Years)	4.5	3	4.3	3.3

Jeffery et al (2015) also considered the role of onshore RAS (freshwater or marine) to produce up to 1 kg post-smolts for stocking into sea cages. They calculated the cost of production to this stage to be £3.34 per kg (UK costs). A full economic model was not presented, but the authors did provide a tool for companies to enter their own production cost data for comparison. They considered that the reduction of the final grow-out in cages to less than 12 months, and hence greater overall productivity from investment in sea cages, would substantially compensate for higher costs at the post-smolt stage, especially if there was also a saving in disease treatment and improvement in survival rates. However, extension of this logic may be restricted in practice, as limits on biomass or feed inputs linked to site licensing become the limiting production factor.

Liu et al (2016) compared the economics of 3000 t production units for Atlantic salmon using open net pen (ONP) and land-based freshwater closed containment systems (LBCC-RAS). Once again, they found very similar variable operating costs, but significantly different capital costs. These were estimated to be approximately 80% with the open pen system costing approximately US$30 million, and the freshwater RAS unit $54 million. Financial analysis shown below suggests that grow out in RAS would not be profitable unless a 30% price premium can be obtained.

Table 4: Financial analysis from Liu et al (2016)

Economic indicator	ONP system	LBCC-RAS system	LBCC-RAS system premium price
Operating (gross) margin	**38.39%**	**17.75%**	**40.64%**
Profit margin	23.62%	(-)	18.18%
NPV (million US$)	**3.54**	**-120.2**	**-20.34**
IRR before EBIT	15.96%	(-)	13.28%
IRR before EBIT	**7.94%**	**(-)**	**2.67%**
ROI	17.77%	(-)	9.01%
Break-even production (MT)	**1251**	**3307**	**2387**
Pay-back period (year)	5.63	(-)	11.1
Break-even price (US$)	**5.33**	**(-)**	**6.44**

Bjørndal & Tusvik (2017) studied the economics of full grow-out RAS, compared with conventional cage aquaculture, or shortened cage-based grow-out through the use of post-smolts from RAS in Norway. This again showed traditional cage-based production to be most competitive under Norwegian conditions.

Table 5: Financial analysis from Bjørndal & Tusvik (2017)

	Land based NOK/kg	Traditional farming (2015), 100g smolts	410g post-smolt
Feed	**16.1**	**13.18**	**13.18**
Roe/smolt	0.3	2.72	7.19
Labour	**2.3**	**2.07**	**1.68**
Other variable cost	12.5	6.44	4.44
Sum variable costs	**31.2**	**24.41**	**26.49**
Interest and depreciation on investments	6.6	3.97	3.22
Other fixed costs	**0.9**	**0.16**	**0.17**
Sum fixed costs	7.5	4.13	3.39
Total production cost	**38.7**	**28.54**	**29.88**

Note: It was assumed that the land-based RAS could be operated at any desired salinity

3.2.2 Operating Costs

The studies cited above generally show that on direct operating costs, onshore RAS is competitive with cage farming.

Table 6: Major direct variable operating costs as percentage for different Atlantic salmon systems

Item	Warrer-Hansen 2015 - RAS	Liu et al 2016 - RAS	Bjørndal & Tusvik 2017 - RAS	*Bjørndal & Tusvik 2017 - Cages*
Feed	**59.4**	**46.7**	**51.6**	***54.0***
Smolts / Ova	10.3	2.9	0.96	*11.1*
Power	**9.2**	**8.1**		
Salaries	5.0	12.8	7.3	*8.4*
Oxygen	**3.3**	**3.7**		
Chemicals	3.9			
Other	**8.9**	**25.8**	**40.0**	***26.4***
Total	100	100	100	*100*

Note: Above figures calculated from cited papers

The most important direct operating cost for all intensive grow-out operations is feed, comprising up to 60% of direct variable production costs. There is relatively little published data, but assuming normal operations RAS should provide superior feed conversion rates (FCR) based on lower mortality rates and lower direct feed loss. Liu et al (2016) assumed an economic FCR of 1.09 for growout in RAS compared with 1.27 in coastal cages. Marine Harvest (2017) cite an average economic FCR of 1.2 for cage-based farming. Growth of RAS output should stimulate further development and availability of specialised RAS grow-out diets with potential for further FCR reduction.

The energy requirements for RAS are frequently discussed as a constraint, but generally constitute less than 10% of direct operating costs and are generally decreasing with scale (whilst feed increases as a proportion of total operating costs). This can be more than direct labour costs so is clearly significant, but not a critical brake on development, especially once the full value chain is considered. Robinson (2017) found an average energy efficiency of 5 kWh/kg for salmon grow-out in RAS. However, energy requirements become much more significant if heating or cooling are required, especially if this cannot be achieved through simple heat exchange with warmer or cooler water supplies. Potential technologies and strategies for reducing this are discussed in Section 4.3.

3.2.3 Capital Costs

It is with respect to capital cost where RAS is currently uncompetitive compared with cage-based growout being approximately two to three times higher per tonne of production capacity. One of the best publicised grow-out salmon RAS projects is Kuterra owned by Namgis First Nation in British Columbia. This had substantial government and non-government organisation support and after significant teething problems is reportedly operating successfully with a production of between 200 and 300 tonnes per year. However, in 2017 Namgis First Nation announced plans to sell the farm. Don Svanvik of Namgis is quoted as saying "It just needs scale up to become profitable. If the farm is even twice the size it is now, we'd be making money. But Namgis can't afford to keep subsidizing the operation and are looking to divest or otherwise attract new investors" (Bennett, 2017). The same article gives the total capital investment in the farm as CAD 10 million (£5.64 million) – approximately £18,800 per tonne of production capacity. Larger projects generally project lower costs per tonne, so as might be expected, there is some economy of scale evident in the available data.

Table 7: Recent published data and estimates of capital cost per tonne of production capacity per year

Source	Production scale	Estimated capital cost per tonne of production capacity – Landbased RAS	Estimated capital cost per tonne of production capacity – Coastal cages
Warrer-Hansen 2015	**5000 t (LWE) / 4,00 t (HOG)**	**€6600 / 7,500**	
Liu et al 2016	3300 t (HOG)	US$16,242	US$9,000
King et al 2016	**6000 t (HOG)**	**US$6,767**	**US$3,317**
Robinson 2017	3000 t (HOG)	CA$ 20,000	
Bjørndal & Tusvik 2017	**1000 t (LWE)**	**NOK 149,800**	
Bjørndal & Tusvik 2017	2000 t (LWE)	NOK 137,900	
Bjørndal & Tusvik 2017	**3000 t (LWE)**	**NOK 118,500**	
Bjørndal & Tusvik 2017	4000 t (LWE)	NOK 116,400	
Bjørndal & Tusvik 2017	**5000 t (LWE)**	**NOK 115,600**	
Gjendemsjø, 2015	5000 t (LWE)	NOK 60,000 – 90,000	NOK 65,000 – 80,000

Note: LWE = Live weight equivalent, HOG = Head-on gutted.

According to Solsletten (2017) the largest cage-based salmon production site in Norway at that time had an annual production capacity of 8,580 tonnes. In Scotland the largest licensed capacity is 2,635 tonnes[11]. Companies planning land-based RAS units with production capacities between 3,000 and 10,000 tonnes is therefore broadly comparable with the current operational scale of the larger salmon companies. However, the major difference is that the large companies own many sites and can gain further economies of scale through shared well boat, shore-base, processing and other infrastructure.

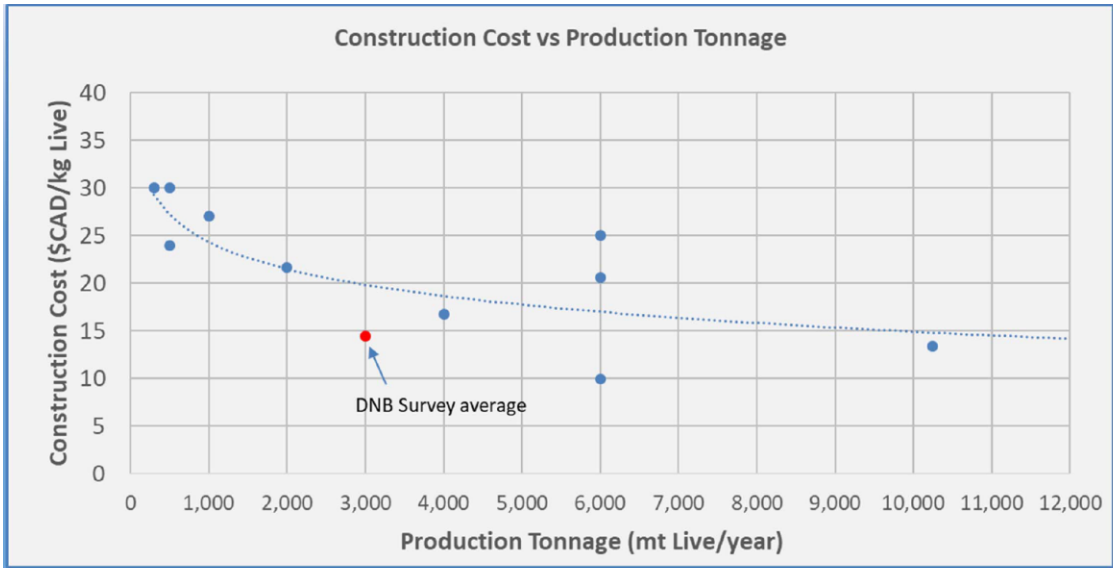

Figure 2: Effect of scale on capital cost per kg of production capacity (Reproduced from Robinson 2017)

In addition to scale efficiencies capital cost per unit of production can be lowered through efficiency of design; for instance, using shared tank walls. The standardisation of component design and size allowing cost savings through multiple production efficiencies can also be expected. Many suppliers already base their designs around standard modules such that large production units simply consist of more standard units. An example of this approach is Nofitech, a Norwegian company specialising in Atlantic salmon RAS smolt units (http://nofitech.com).

A critical factor for competitiveness could be the cost of marine site licenses. Anders Milde Gjendemsjø, Head of Seafood with Deloitte AS suggested in 2015 that restrictions on new site licenses are eliminating the cost advantage of sea cage farms in Norway. He calculated the cost of establishing a 5000 t farm as 325-400 million NOK (including licenses) whilst a land-based farm of that capacity would also be in the range 300-450 million NOK. Production costs are also estimated to be similar at 26.50 NOK/kg in cage farms and 26.75 NOK/kg in RAS (Gjendemsjø, 2015).

11 http://aquaculture.scotland.gov.uk

3.3 Availability of Experienced RAS Operators

Experienced RAS operators, especially in application of marine RAS technology, are in very short supply. Certainly, technicians and managers cannot be trained adequately by the university sector. Equally, experience on large RAS farms in excess of several hundred tonnes annual production is essential to get to grips with RAS operation. Decades of experience within the cage sector does not equate to competence in RAS operation. Equally, experience with operation of freshwater RAS farms, low biomass fingerling or smolt farms does not equip a manager to safely manage a marine RAS unit without significant risk.

A RAS is a combination of different aspects and interactions such as biology, chemistry, physics and engineering. The understanding of all of them separately is common in the industry but there is a need for people being able to understand the system as a whole (Badiola et al. 2012).

Several workshops, conferences and short courses are specifically RAS related (examples listed below). However, the teaching of practical skill is still lacking, and courses mostly draw on experience of freshwater systems with limited biomass.

- The NordicRAS workshop[12] has been successfully gaining importance since its beginning in 2011. Moreover, apart from the conference, there is a Nordic network on RAS with the aim to co-ordinate and strengthen research and development of RAS in Nordic countries.
- International conference in RAS (ICRA)[13], which is held in Roanoke (US)
- Aquaculture Innovation Workshops (AIW)[14] are focused on discussing the technical, biological and economic performance of land-based RAS for production of market sized fish
- International Patagonic RAS workshop (Chile)
- RAS Technology Workshops hosted by Pentair Aquatic Eco-Systems[15], some in partnership with the Fish Vet Group

12 http://www.nordicras.net/
13 http://www.recircaqua.com/
14 https://www.conservationfund.org/our-work/freshwater-institute/aquaculture-innovation-workshop
15 https://pentairaes.com/workshops

- Different workshops hosted by the Freshwater Institute[16]
- AQUAEXCEL RAS short-course[17]
- Cornell University annual Recirculating Aquaculture Systems Short Course[18] (RAS, Aquaponics and Hydroponics technology).

3.4 Environmental Credentials

3.4.1 Introduction

RAS are frequently promoted as "environmentally friendly" operation units: less water usage; more biosecure; no escapees and therefore, no interaction with the surrounding environment. RAS decrease potential environmental impacts such as eutrophication as well as water dependence (Verdegem et al. 2006; d'Orbcastel et al. 2009a; Eding et al. 2009), aiding waste management (i.e. reduced waste volumes) and boosting nutrient recycling (Piedrahita 2003). Moreover, such technology enablesa "green" (recommended food choice) label within the Monterey Bay Aquarium's Seafood Watch program. This evaluation is based upon seven different criteria: data, effluent, habitat, chemical use, feed, escapees, disease pathogen and parasite interaction; source of stock and mortalities (Albaum et al, 2014).

The main issue potentially undermining the sustainability credentials of RAS in most reviews is their relatively high energy requirement, although overall sustainability improves with increased use of renewable rather than carbon emitting energy sources (Section 3.4.2 below). Relatively few systematic integrated environmental impact systems have been commissioned on RAS. One notable Life Cycle Analysis (LCA) study by Ayer & Tyedmers (2009) comparing salmonid cage, floating-bag, shore-based flow through and RAS observed that: '*while the use of closed-containment systems may reduce the local ecological impacts typically associated with net-pen salmon farming, the increase in material and energy demands associated with their use may result in significantly increased contributions to several environmental impacts of global concern, including global warming, non-renewable resource depletion, and acidification.*' Further discussion of LCA work on RAS is presented in Section 0 below.

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16 https://www.conservationfund.org/our-work/freshwater-institute/events/1659-water-recirculating-aquaculture-systems-ras-course
17 http://www.aquaexcel2020.eu/training-courses/aquaexcel2020-training-courses
18 https://blogs.cornell.edu/aquaculture/)

Other potential problems for land-based RAS include disposal of solid wastes (Section 3.4.3) and issues around water consumption (briefly considered in section 3.4.4) and nutrient discharge.

3.4.2 Energy Requirements

Little has been published regarding the direct energy used in RAS. Published values include 5 kWh/kg (Robinson, 2017), 6.1 kWh/kg (calculated from data in Bjørndal & Tusvik, 2017), 4.6 kWh/kg (Vinci et al 2015), 5.4 kWh/kg (Liu et al 2016), 8.1 kWh/kg (Rainbow trout, Dekamin et al 2015) and a very optimistic 1.3 kWh/kg (Holm 2011) in projections for the Atlantic Sapphire, Langsand Laks farm. Merino et al (2013) suggested RAS smolt farms in Chile have reduced power consumption from 5 kWh/kg of feed to 2 to 2.5 kWh/kg of feed (equivalent to kWh/kg production at an FCR of 1:1). A more detailed examination of these figures would be required to determine if there are substantive methodological differences in the way the power requirement is calculated. Some further discussion of this can be found in the work done by Colt et al. 2008; d'Orbcastel et al. 2009; Buck 2012; Ioakeimidis et al. 2013 and Badiola et al. 2017. As discussed in Section 4.3, a significant focus of system design is to optimise energy use and ensure efficient process operations.

3.4.3 Solid Waste Disposal

Current RAS technology focuses on removal of suspended solids from the culture water. The subsequent disposal of that organic matter is a separate problem that becomes a greater issue with scale of production. For instance, if the entire Scottish salmon production was carried out on land (approx. 160,000 tonnes per annum), the dry solids waste produced would be in the region of 8,000 to 32,000 tonnes (based on data from Bergheim & Fivelstad, 2014). With optimised feeds and feed control that figure could be towards the lower end. As a point of comparison, even the worst case calculation is less than 5% of solid waste produced by sheep farming in Scotland (based on a sheep population of Scotland of around 6.57 million (2013)[19] with average adult manure production of 907 kg/year[20] which is approximately 75% water[21] giving an output of 1.49 million tonnes of dry matter which can perhaps be halved again to account for a large proportion of juveniles to give around 745,000 tonnes[22]).

19 http://www.bbc.co.uk/news/uk-scotland-highlands-islands-25638723
20 https://wikifarmer.com/sheep-manure-production-and-waste-management/
21 http://adlib.everysite.co.uk/adlib/defra/content.aspx?id=2RRVTHNXTS.88UF90DE8XRAN
22 These simple calculations are included to provide some quantitative point of reference and do not imply any direct equivalence between either the composition or environmental implication of each waste

The first consideration in further management and disposal of the solids waste from RAS is that the water content of the removed sludge can be very high (up to 95%), so various stages of dewatering are required, each with cost implications in terms of space, equipment and power, before some disposal options become practical. Typical dewatering processes include the use of coagulants, flocculants, fine filtration, centrifuges and driers. Common options for disposal of various levels of dewatered sludge are shown below.

Table 8: Solid waste disposal options

Solids content of sludge	Potential disposal or treatment options
10%	**Soil injection (e.g. agricultural)** **Septic tank & municipal waste water treatment** **Anaerobic digestion for energy production**
30%	Spreading on Agriculture land Landfill Compost Incineration with energy recovery
80%	**Fertilizer** **(+ previous options including incineration, land application and landfill)**

Source: Adapted from Maitland, 2018

Each disposal option also has associated costs (financial and environmental). Waste from existing freshwater RAS is sometimes spread on agricultural land as fertilizer23, but partly due to salt or other chemical additions is more often taken to landfill. Sludge from marine RAS would have a higher salt content and would not be suitable for direct land application or some of the alternative disposal routes shown in the above table unless diluted by mixing with other waste streams (e.g. in large anaerobic digesters). Other options for disposal that have been proposed include the rehabilitation of coastal salt marshes (Joesting et al 2016) or the culture of marine worms (Brown et al 2011).

23 Disposal of organic material on land is regulated through the Sludge (Use in Agriculture) Regulations 1989, which control the spreading of sewage sludge and the Waste Management Licensing Regulations 2011, which control all other materials. Sludge from RAS is classed as waste under these regulations when it is transported off-site for disposal. However, unless contaminated, it is in a low-risk category and can be used for agricultural purposes within certain limits with registration rather than full licensing and associated controls. Around 15 million tonnes (wet weight) of organic waste is spread on agricultural land in Scotland each year (Cundill et al 2012).

The economics of waste collection and processing might improve as further opportunities develop to incorporate them into the wider circular economy for nutrient and energy rich waste materials. The Norwegian company Scanship AS is now marketing comprehensive technical solutions for aquaculture waste management from RAS (Rohold, 2017).

3.4.4 Land and Water Use Issues

Using data presented in Vinci et al (2015). Conversion of the present Scottish salmon production of 160,000 tonnes per annum to RAS (growout from smolt) would involve the following:

- 124 ha of building area
- 1.9 million cubic metres of rearing tank volume
- 43,000 m^3 of water pumped per minute for RAS flow
- 95,000 – 190,000 m^3 water per day (at 5-10% replacement per day)

Water supplies are less constrained in Scotland than most other countries in the world. The water for salmon grow-out RAS can potentially be anything between freshwater and full-strength seawater with various performance trade-offs with any particular salinity. To put the above numbers in some context, water abstracted and supplied for public consumption in 2015/16 was around 1.8 million m^3 per day[24], around ten times the hypothetical demand from RAS aquaculture. In practice, aquaculture would not compete for any of this supply, particularly if 100% seawater, although it may be useful to note that freshwater water abstraction has fallen in Scotland over the past 10 years by over 30%

The main issue for water would be the corresponding 95,000 to 190,000 m^3 per day of effluent containing elevated levels of dissolved nutrients such as nitrite and phosphate which could require further management.

24 http://www.gov.scot/Publications/2016/10/7565/334167

3.4.5 LCA

Useful perspectives on overall sustainability can be obtained from Lifecycle Analysis (LCA). A small number of studies have examined the credentials of intensive aquaculture systems. As the methodology used, and boundaries that are set for the system under consideration vary, it is difficult to directly compare between the outputs from different studies. However, those conducted show that the predominant impacts are related to the feed used; i.e. ingredients selected, manufacture process and feed conversion efficiency (Liu et al 2016). Differences between growout in RAS and growout in net cages is largely linked to electricity consumption and consequently the means used to generate the electricity and the related output of carbon dioxide. Liu et al (2016) found carbon footprints of 3.39 and 3.73 kg CO_2/kg salmon live weight for RAS and open net pens respectively if the electricity for the RAS was generated from a hydro scheme. For a more normal US mix of energy dominated by fossil fuels, the carbon footprint for RAS increased to 7.01 kg CO_2/kg salmon live weight. A high level use of non- renewable energy indicates that the Acidification Potential and Global Warming Potential impact categories in LCA are significantly higher in RAS than in traditional flow-through systems (e.g. Aubin et al., 2006).

Fossil fuels currently supply 80% of the total energy demand worldwide, although renewables are the fastest growing energy sources (a growth rate of 2.5% per year) (EIA, 2014). Scotland is already well ahead as renewable energy projects have reduced the share provided by fossil fuels to 46.2% with renewable energy providing the equivalent of 53.8% of Scotland's energy consumption in 2017[25].

Although very few examples have been reported (Toner, 2002; OPP, 2015), there is some potential for the combination of renewable energy generation within a RAS, e.g. through energy recovery from solids waste (e.g. anaerobic digestion) or from more conventional technologies such as solar panels on building roofs or hydro power from gravity-fed water supplies. Design considerations should already include a focus on energy efficiency, e.g. through minimisation of pumping head and conservation and recovery of thermal energy. The use of waste energy (usually heat) from other industries has also been tried, albeit with substantial problems in practice. Further discussion of these issues can be found in (Worrell et al. 2003 and 2009).

25 http://www.scottishrenewables.com/sectors/renewables-in-numbers/

3.5 Welfare Credentials

Farmed animal welfare has become a greater focus of attention in recent years. Most of the salmon production in Scotland now complies with the RSPCA Freedom Foods Standards[26]. These standards are regularly reviewed and revised where appropriate. Currently, there are no standards for salmon grow-out in RAS, so fish produced in this way could not be certified as compliant.

Perhaps the most discussed issue for fish welfare is acceptable stock densities, and the criteria by which acceptable stock densities can be defined. This was first reviewed for rainbow trout by Ellis et al (2002) where a range of welfare related factors were identified, including water quality, fish density, culture space and fish behaviour. Adams et al (2011) conducted trials with Atlantic salmon in seawater tanks with stock densities between 15 and 35 kg/m^3. They found welfare indicators (body condition, fin condition, plasma glucose, and cortisol) could be adversely affected by low as well as high stock density. They suggested that social interactions between the fish could be an important factor in welfare. Calabrese et al (2017) used specific growth rate, food conversion efficiency, incidence of fin damage and cataracts as primary welfare indicators in tank-reared post-smolts (flow-through). Secondary physiological indicators included plasma concentrations of cortisol, sodium and carbon dioxide, and also plasma pH. They found food conversion ratio deteriorated with increasing stock density, specific growth rate reduced above densities of 50 kg/m^3. More serious primary and secondary impacts were found in fish stocked above 100 kg/m^3. They concluded that post-smolts could be reared at up to 75 kg/m^3 without significantly compromising welfare or performance.

Stock density is a significant parameter for commercial production in RAS. Due to high capital costs, the greater the production per cubic meter of culture volume, the faster the investment can be paid back and the more profitable the operation in the long-term. If welfare considerations force comparatively low stock densities, the financial viability of RAS production becomes more challenging. The current Freedom Foods standard for grow-out salmon in sea cages is 15 kg/m^3 for a site and 17 kg/m^3 for a single cage. For juvenile salmon in tanks there is a sliding scale from 10 kg/m3 for fry up to 1g up to 50 kg/m^3 for fish between 30 and 50g average weight. There is a note that for larger fish, up to 60 kg/m^3 may be possible. For short-term transport in well boats, stocking densities up to 125 kg/m^3 (5 kg fish) is permitted, with lower stocking densities for smaller fish.

26 https://science.rspca.org.uk/sciencegroup/farmanimals/standards/salmon

This suggests that stock densities of at least 75 kg/m^3 may be considered suitable for grow-out salmon in RAS in the future, although this is an evolving field. As fish behaviour is better studied, it might be that other factors become important parameters for welfare. Examples include:

- Swimming space (a minimum diameter swimming circle is already defined for cages as 5 m)
- Water depth
- Quality, quantity, diurnal patterns and variations in light
- Noise levels, frequencies and patterns
- Water temperatures, variability and choice for the fish
- Wide range of other water quality parameters
- Ability of fish to express innate behaviours
- Visual and textural environment
- Water velocities, patterns and choice for the fish
- Feeding methods and frequencies
- Potential for interactions with other species

Some of these parameters may be easier to satisfy in RAS than in cage farms. For instance, the fish would be much better protected against potential predators. Development of improved sensor technology (e.g. cortisol) to monitor stress levels in real time and the ability to better control environmental conditions will also improve welfare management.

A further welfare (and economic) consideration is freedom from disease. This is impossible to guarantee, but well designed and managed RAS create very stable environments which are optimal for fish performance. Disease outbreaks are significantly reduced under such conditions. Proper treatment of incoming water can greatly minimise the risk of pathogen entry. However, this is not always the case and poor design and/or management have not only enable access to stock by parasites for instance, but also create ideal conditions for disease outbreaks. Under high stocking densities the impact of such events can be significant.

Overall, it will be increasingly important for companies using RAS to demonstrate, and have independently certified, their welfare credentials.

3.6 Potential Regulatory and Market Responses

3.6.1 Eco-certification as a Market-based Driver of Future Salmonid RAS Adoption?

The global growth and intensification of salmonid production in 'open' net-cage systems has been accompanied by a sustained campaign by often well-resourced civil society and other interest groups lobbying against the environmental impacts of salmonid farms in marine and freshwater bodies. Many such campaigns promote shore-based production, including RAS as more sustainable alternatives. Approaches range from more polemical 'worst-case scenarios' deployed by individual and activist groups (e.g. the Global Alliance against Industrial Aquaculture, Greenpeace etc.) to more 'evidence-based approaches' deployed for example by environmental NGOs seeking to drive change through strategic collaboration with industry. Over the last 2 decades, co-development of voluntary environmental/ social certification standards auditable by independent 3rd party 'conformity assessment bodies' (CABs) has become and an increasingly common form of 'market-based governance'. Such schemes simultaneously offer an out-sourced means of defending brand-reputation and seeking social license around industry strategic planning e.g. expansion.

Four dominant certification bodies serve the aquaculture sector; GlobalGAP, the Global Aquaculture Alliance-Better Aquaculture Practice (GAA-BAP), Friends of the Sea (FoS) and the Aquaculture Stewardship Council (ASC). In the first three instances, development of the standards held by these bodies were driven foremost by industry actors (including producers, retail and food service companies), whilst the World Wildlife Fund (WWF) facilitated 'multi-stakeholder dialogues' that gave rise to the ASC standards; with marine and freshwater salmonid production covered by 2 separate ASC standards. Consistent with this origin, time-bound phasing out of cage production in fresh water bodies, viewed as a pragmatic near-term option by WWF became a particularly contentious discussion point during the initial 'Salmon Aquaculture Dialogue' (SAD). Although eventually deferred for potential inclusion in future standard revisions, compromise was also supported by a commitment of major producers to have 100% of their grow-out sites achieve ASC certification by 2020. Members of this 'Global Salmon Initiative' (GSI) together account for >65% of global salmon production. Furthermore, under an ethos of 'continuous improvement', compliance threshold limits set on a wide range of environmental indicators (e.g. sea-lice transmission, chemotherapeutant use, N & P discharge etc.) are likely to become increasingly stringent in future standard revisions.

Together these observations point to 'metrics based' certification schemes (i.e. specifying threshold performance limits) such as the WWF/ ASC standards becoming proportionately important drivers of a transition to future shore-based production. GAA-BAP standards are similarly metrics-based.

Analysis of data presented on the websites of the four standards bodies cited above indicated a total of 1,214 salmonid aquaculture production sites certified as of 8 March 2018, 83% of them marine salmon sites and the balance trout sites, predominantly land-based freshwater operations.

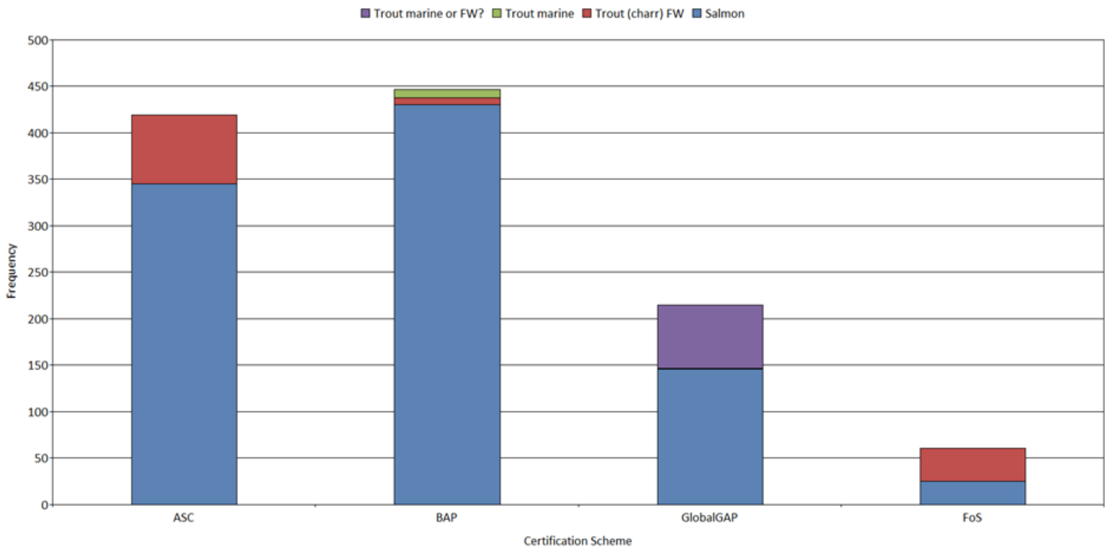


Figure 3: Number of salmonid farms certified under four dominant aquaculture certification schemes as of 8 March 2018 (Source: certification body websites).

Only the ASC clearly differentiate production system types in their publicly available data i.e. including RAS and other land-based systems. Unlike the other schemes ASC also currently only certifies grow-out farms i.e. thus excluding smolt RAS.

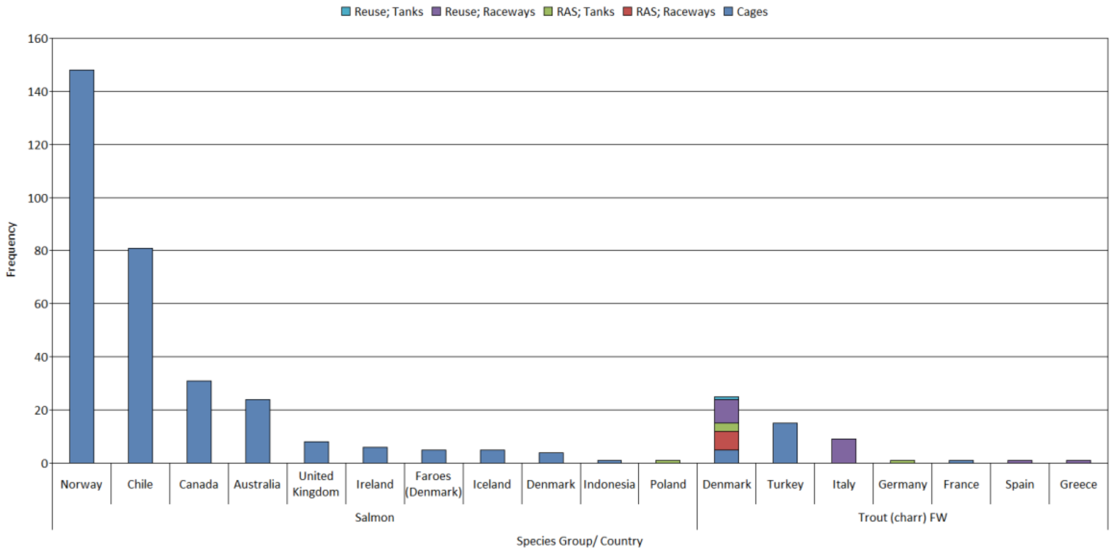


Figure 4: Number of grow-out farms certified under the Aquaculture Steward Council (ASC) marine and freshwater salmonid standards, by species group, country and system-type as of 8 March 2018 (Source: ASC audit database)

At the analysis point, a total of 12 RAS grow-out sites operated by 7 companies were ASC certified. The following figures show that despite the global distribution of ASC salmonid certification, certified RAS grow-out sites essentially remain limited to trout sites in Denmark (10 sites, 7 of them raceway systems) with a single salmon grow-out RAS 'Jurassic Salmon' located in Poland.

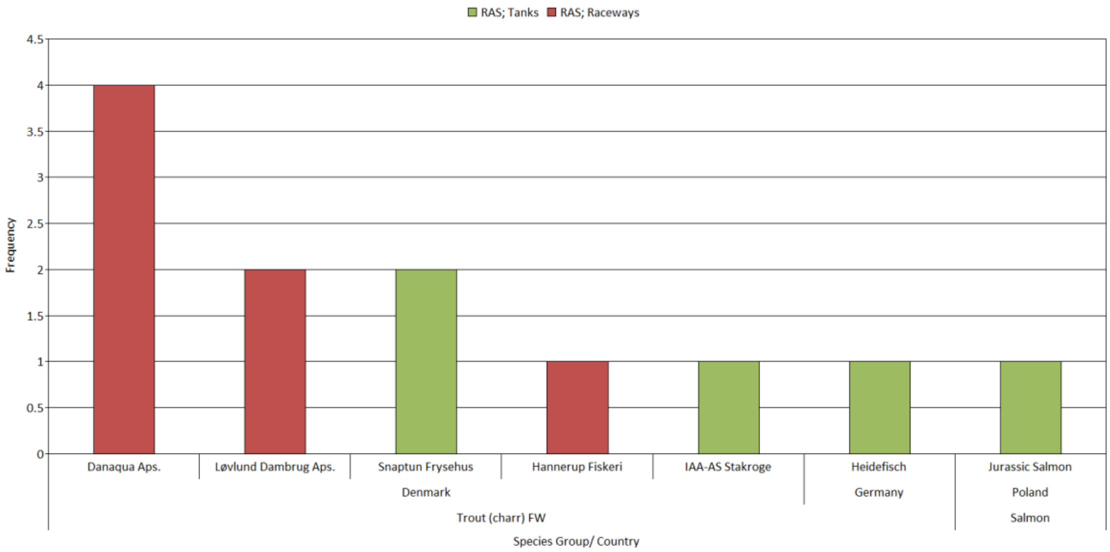


Figure 5: Number of RAS grow-out farms certified under the Aquaculture Steward Council (ASC) marine and freshwater salmonid standards, by species group, country and company as of 8 March 2018 (Source: ASC audit database)

The current output from certified grow-out RAS is marginal with annual output of individual farms ranging from only 250-1,000mt, Jurassic Salmon being the largest.

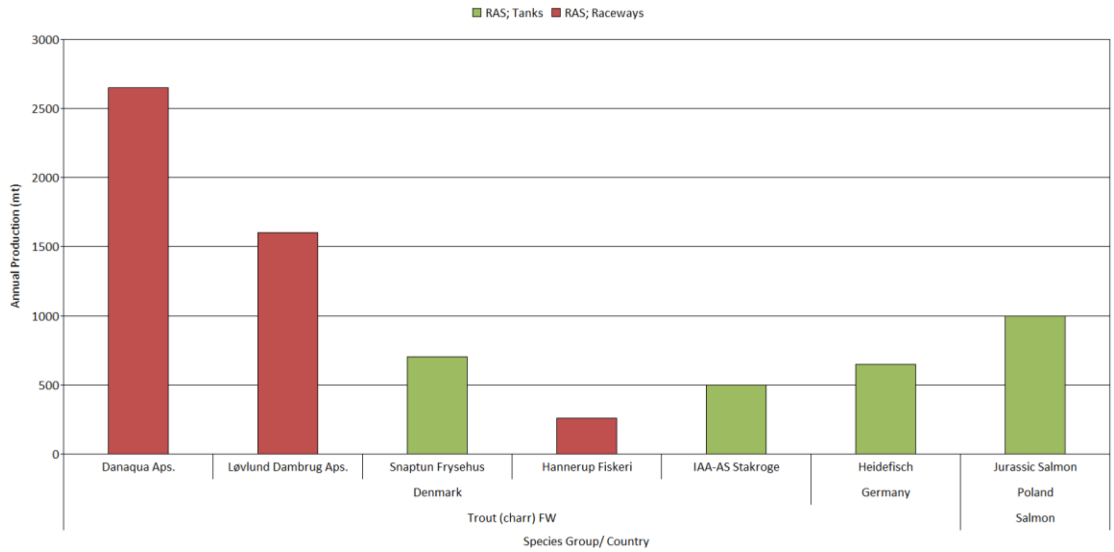


Figure 6: Annual production (tonnes) of RAS grow-out farms certified under the Aquaculture Steward Council (ASC) marine and freshwater salmonid standards, by species group, country and company as of 8 March 2018 (Source: ASC audit database)

3.6.2 Potential for Market Premium

Most promotors of RAS have projected higher market prices for their product based on either its sustainability credentials, or localness and perhaps associated freshness. Financial projections by SINTEF and The Freshwater Institute (Liu et al 2016) for instance, assumed a price premium of 30% for RAS produced salmon (assumptions usually range between 10 and 30%). There appear to have been no widespread surveys of consumer willingness to pay extra for fish produced in RAS.

Surveys on related criteria have been conducted. Roheim et al (2011) found a 14.2% price premium for MSC certified frozen Alaskan pollock products in the UK, suggesting this level of premium is attainable for independently certified and well promoted ecolabels. Olesen et al (2010) surveyed the willingness of Norwegian consumers to pay extra for organics and freedom food certified salmon over non-certified salmon. This showed a willingness to pay 15% extra for these certifications. However, this premium was lost, and indeed became negative when the salmon flesh of the organic salmon was pale in comparison with conventional salmon. Hence conventional indicators of quality tended to override any specific labelling. Ankamah-Yeboah et al (2016) found a 20% premium for organic salmon in Denmark, but in subsequent follow-up work (Ankamah-Yeboah et al 2017) found the picture to be rather more complex as 50% of consumers were unwilling to pay any premium and the remainder segmented into groups who would pay more for organic farmed salmon but not MSC labelled wild salmon and others where the inverse was the case (only paying a premium for MSC labelled wild salmon). A further generic challenge of such 'willingness to pay' or stated preference survey approaches is their often-poor correlation with so-called revealed preference methods i.e. their translation into real consumer purchasing decisions at the checkout.

A critical question is therefore the potential size of the premium market. Conventional supply-demand economics would predict a declining premium as supply increases. As an indication, the UK production of organic salmon in 2008 was around 4% of total production at 5,500 tonnes (The Fish Site, 2009). The overall market for organic food in the UK fell during the subsequent recession, only recently recovering to 2008 levels (Soil Association, 2016). In Scotland the number of cage sites certified for organic production fell from ten in 2011 to five in 2016. Organic salmon production has fluctuated slightly during that period, but totalled 3,903 tonnes in 2016 (2.4% of total Scottish salmon production).

So far, the public perception of fish produced from RAS compared with fish from sea cages has not been widely tested. As environmental groups have been promoting RAS as the solution to sustainable aquaculture it might be assumed that they will be willing to support suitable ecolabelling (as discussed above). However, there is also the risk that RAS farms will be tagged as factory farms and any concerns about welfare used to undermine the sector. As an example, planning permission for a proposed RAS farm for sturgeon in Scotland was opposed by the animal rights group PETA on welfare grounds[27]. However, the certification of Jurassic Salmon in Poland by the Aquaculture Stewardship Council (ASC) indicates potential for positive market responses (Fischer, 2017).

In summary, it is not certain that the farming method alone will guarantee a premium price for fish from RAS. The most important factor may be the actual product quality experienced by the consumer in the kitchen and dining room. Even if a premium is obtained for RAS production, it may only be sustainable whilst it contributes a small proportion of the total supply and will require substantial marketing investment to ensure differentiation.

3.6.3 Regulatory Responses

A range of policy options are available to industry regulators that would help or hinder the development of RAS-based aquaculture. On the positive side, these might include funding in support of technology development, or the establishments of special development zones etc. Production costs in RAS would also be more competitive with cage farms if the latter were more heavily regulated in a way which added to the cost of establishment or operation (e.g.

27 https://www.peta.org.uk/media/news-releases/thousands-join-peta-opposing-scotlands-first-caviar-farm/

on waste discharge). However, this would also make the industry internationally uncompetitive and would need to be implemented fairly with due consideration taken to other industries that might be impacted.

Another issue that is likely to arise is the farming of genetically modified fish. The potentially advantageous combination of GM and RAS technologies was discussed in the previous 2014 report. In the last year, AquaBounty Technologies have received marketing authorisation for genetically modified salmon in North America. These are currently farmed in a closed containment system in Panama with a second production facility planned in Canada (Higgins, 2017). Public resistance to GMOs is likely to prevent transfer of this technology to Europe and especially to Scotland in the foreseeable future. However, genome editing as a technique may provide a greater range of opportunities for breeders to develop strains specifically for RAS (Ye et al 2015; Zhu & Ge 2018), and face less public resistance in the long term. However, the legislative framework covering implantation of the technology requires further development (Kelly 2017) although the situation for the EU was recently clarified to class gene editing as a form of genetic modification[28]. In the longer term, the ability for precise environmental management conferred by RAS offers far greater potential for focussed and rapid selection of production and post-harvest traits relative to highly heterogeneous cage-production environments. The example of the highly consolidated primary breeding sector supplying much of the broiler industry in the UK provides a potential scenario of future development.

28 https://www.theguardian.com/environment/2018/jul/25/gene-editing-is-gm-europes-highest-court-rules

4. Advances in RAS Technology

4.1 Introduction

The production of fish in a recirculated aquaculture system is a complex biological and chemical process. A typical RAS will include equipment to achieve the following objectives:

- Deliver the correct quantities of feed to the fish in an efficient manner
- Remove uneaten feed and faeces from the culture water
- Detect and remove mortalities
- Supply sufficient dissolved oxygen to meet the metabolic requirements of the fish
- Remove carbon dioxide from the water to maintain suitable concentrations
- Maintain appropriate temperatures
- Control potentially toxic metabolites, especially ammonia and break-down products including nitrite and where necessary nitrate
- Control pH and related water quality parameters especially alkalinity
- Control levels of potential pathogens including virus, fungi, bacteria and parasites
- Control concentrations of dissolved organic compounds, especially those likely to lead to tainting of fish flesh, the production of toxic compounds, the influencing of fish health, or which might affect the performance of other processes
- Maintain overall environmental conditions that promote growth, ensure welfare, protect against disease and minimise early maturity or other unwanted biological factors
- Provide monitoring and back-up systems to ensure the above objectives are consistently met

A mix of biological and chemical treatment systems are used, which were described in more detail in the 2014 report. The focus of this update is therefore limited to more recent and notable advances. A general observation however, is that with increasing scale of installations and investment, there is greater sophistication overall in the design and engineering of the systems. Expertise has come in through the entry of companies such as Veolia – a major multinational company involved in many water and waste treatment sectors which has now been involved in the construction of over 29 RAS; in addition to the expansion and consolidation of established aquaculture engineering groups such as AKVA. Such companies are developing standardised modules that are highly integrated and enable ready scaling of production. The following illustration is of the Veolia RAS2020 system which is designed as a module capable of up to 1,200 tonnes of production per year with a tank volume of 5,000 m^3, a standing stock of up to 400 tonnes, a feed capacity of 4 tonnes per day and a water consumption of between 100 and 350 litres per kg feed per day. The technical performance is not exceptional, but the novelty of the tank design and integration of process equipment and monitoring systems is illustrative of wider trends within the sector.

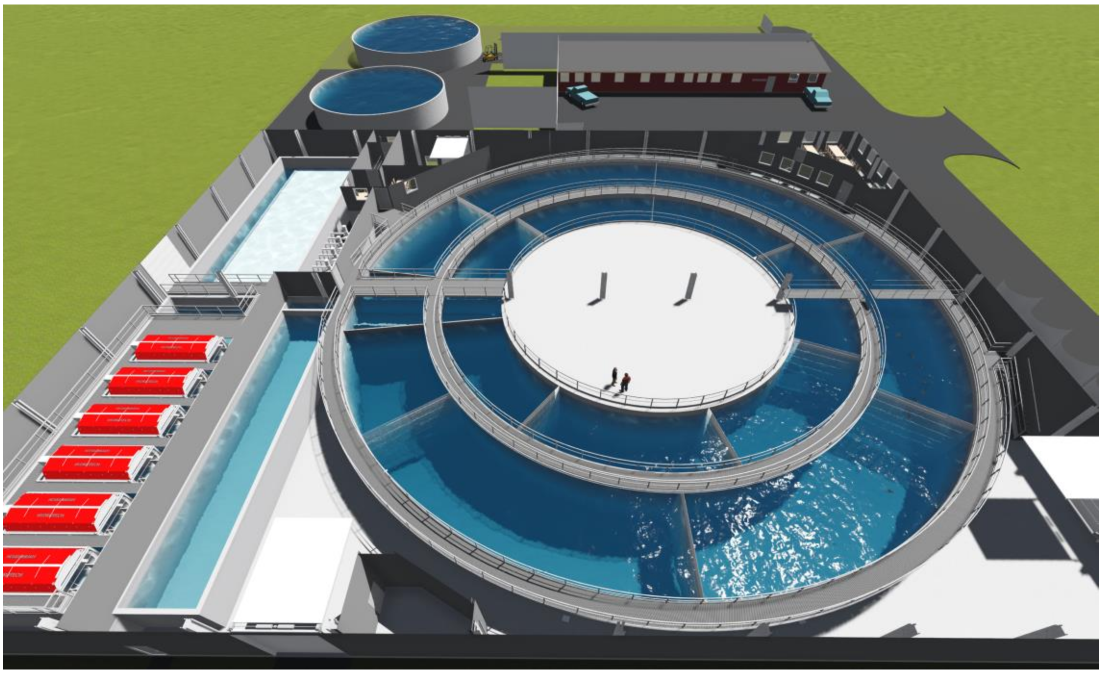
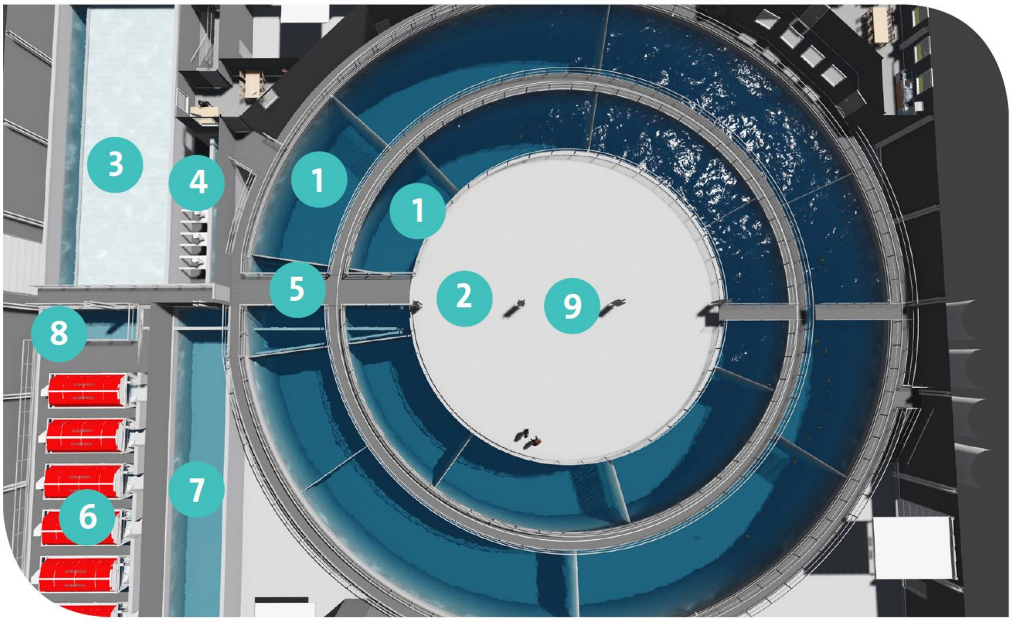


Figure 7: Veolia RAS2020 concept29

29 Source: http://www.veoliawatertech.com/vwt-latam/ressources/files/1/49733-Brochure-RAS2020.pdf



1. *Fish tanks with movable compartments*
2. *Biofilter MBBR reactor (Krüger Kaldnes – Veolia)*
3. *CO_2 and N_2 Degasser – (Krüger Kaldnes – Veolia)*
4. *Propeller pumps into level weir*
5. *Inlet channel and circulation propeller*
6. *Drumfilters (Hydrotech – Veolia)*
7. *Purging tank*
8. *UV filter*
9. *Denitrification chamber (optional)*

Figure 8: Veolia RAS2020 - plan of tank and associated water treatment infrastructure29

4.2 Management of Salmonid Early Maturation in RAS using Sex and Photoperiod Control

Considerable R&D effort has been focussed on the problem of early maturation in pen-farmed salmon (Atlantic and Pacific) over recent decades. For Atlantic salmon, maturation times can vary by as much as 2 years between different strains and cohorts with maturation possible at weights as low as 50g for precocious male smolts. Although RAS offers greater scope for environmental control to address this problem, knowledge of optimal culture conditions and their interactions with salmon strain types in RAS remains very limited. Furthermore, management of maturation is essential as by the time maturing animals can be readily identified and (potentially) be graded-out, quality can already be severely compromised as flesh pigmentation and oil levels decline with maturation.

Three factors have been identified as key determinants of maturation (Henry, 2018):

i) Whilst lowered **water temperature** delays maturation it can also slow growth. For example, RAS researchers in BC Canada reduced maturation rates from 10 to 2.3% by lowering water temperature from 15ºC – 13ºC (during part of the cycle), restricting feeding, whilst improved turbidity management potentially aided photoperiod control

ii) **Photoperiod**; a recent study implemented by the University of British Columbia found that 25-30% of mixed sex Atlantic salmon smolts cultured in RAS for 10 months under 24 hr lighting (being common practice in net-cages) and restricted feeding matured prematurely; whilst levels were significantly reduced using a 12:12hr (light: dark) photoperiod. In the same trial maturation rates for all-female coho salmon were considerably lower; 1-17% under 24 hr lighting and 0% under a 12:12 photoperiod.

iii) **Monosex populations**: In a recent trial implemented by the Freshwater Institute Virginia, the performance of two Atlantic salmon strains were compared under continuous lighting in RAS culture. The first all-female ('Gaspe River') strain grew to 4 kg with no maturation, 50% of males from a second mixed-sex (St Johns River) strain matured early. No females matured prematurely in either case.

Thus sex-control appears a highly promising option for future RAS production. Whilst the commercial availability of all-female Atlantic salmon remains limited, all female coho salmon are already in production. Under optimal photoperiod and temperature and without restricted feeding, such stocks cultured in RAS can reach harvest size prior to maturation after around 18-20 months. This is a year earlier than under 'ambient' conditions (i.e. typically 3 years to maturation). This takes advantage of the fact that coho growth rates increase significantly prior to maturation. Harvesting can therefore be planned to optimise production of both meat and roe. Conversely, salinity levels appear to have little influence on maturation outcomes in RAS (Henry, 2018).

4.3 Thermal & Energy Management

RAS are up to 1.4-1.8 times more energy intensive than traditional flow-through tank systems (d'Orbcastel et al., 2009a,b). Power supply is required on a continual basis supported by automatic power back-up supplies in the event of mains failure. RAS farms will naturally generate heat from pumping systems, fish metabolism and bacterial activity in biofilters which will encourage water temperature increases. The extent of, and cost of controlling, water temperature rises in RAS can be managed by good advance feasibility studies and detailed planning. This applies to species selection, site selection, availability of cooling water supplies, use of heat exchange pumps and quality of building insulation. Maintaining optimum temperatures in RAS can be challenging irrespective of whether ambient temperatures vary seasonally or are relatively stable throughout the year. The ambient temperature range of the source waters during different seasons need to be assessed during the feasibility study together with the availability of additional cooling or heating water supplies e.g. from underground reservoirs. The availability of heated or cooled water supplies from neighboring industries is often considered an asset to a planned RAS farm. In practice, such sources rarely prove to be trouble free and have led to RAS farm failure. However, there are some examples of successful aquaculture in regions where prevailing conditions are unsuited to the farming of target species such as tilapia and shrimp culture in the Arizona Desert where the use of geothermal energy enables cost-effective production (Buck, 2012).

Greater attention is now being paid to designing low-head and low-pressure systems to minimise pumping costs. Examples include drum filters rather than pressurised sand filters, submerged rather than trickle biofilters and UV illuminated channels rather than pressurised tubes. Variable speed pumps are also used to optimise flow rates and minimise the need to stop and start or pump to overflow (Timmons and Ebeling, 2010) and more efficient LED lighting is being adopted. Krogh (2016) suggested that improvements in the design of RAS for smolt production in Chile had led to a reduction from around 6-8 kW of power per kg of feed used in 1998 to around 2-2.5 kW/kg in 2015.

Energy consumption must also be considered as a multi-faceted target as the headline total energy consumption does not provide information on the cost and different sources of that energy and hence performance with respect to economic or environmental objectives. Measuring energy consumption along the production cycle through an energy audit and thus differentiating consumption peaks (i.e. maximum and minimum) could help in the design on an energy-cost-environmental-efficiency plan (e.g. finding an optional mix of energy sources at different times (including renewables) and contracting best energy rates in the maximum energy consumption periods). Such design and management measures could save an average of 20% of the consumed energy (Badiola et al., 2012; OPP, 2014).

4.4 Gas Exchange

Several new gas exchange technologies are reaching the market, particularly from Asia or North America. These are based around either nano or micro bubble diffusers, or membrane-based diffusers. So far there is little independent verification of enhanced efficiency, cost or other health benefits, but specific advantages could emerge and drive further adoption.

In RAS-based production of salmonids, the removal of carbon dioxide has become a priority for technology development. The principle aims are to:

i) Reduce systems' water CO_2 levels to 3 ppm while ensuring no build-up of CO_2 within the farm building

ii) Combine CO_2 degassing with technology to ensure optimal flow patterns within the culture tank

iii) Preheat the air used for CO_2 degassing to avoid system water cooling

iv) Avoid nitrogen super saturation.

Recent research has attempted to define acceptable CO_2 levels for RAS farmed salmon but there remains uncertainty. Perhaps this reflects the problem of identifying responses of salmon to specific water quality criteria under variable experimental conditions. Mota et al., (2017) report no mortalities, cataracts, nephrocalcinosis or poor external welfare issues in Atlantic salmon exposed to 5 – 40 ppm CO_2. However, low CO_2 exposure <12 ppm impacted growth and this problem had a carry-over effect on performance at later stages. CO_2 up to 5 ppm was considered safe. Nephrocalcinosis developed when Atlantic salmon post smolt were exposed to ambient CO_2 concentrations above 15 ppm (Fivelstad et al., 2018). Krogh (2016) reported that in Chile, the mean water turnover time in salmon smolt RAS culture tanks had been reduced from 1 to 1.5 times per hour (2004 data) to 2 to 2.5 times per hour with degassing of the system flow to reduce mean CO_2 concentrations from 20-25 mg/l to 10-12 mg/l.

4.5 Solids Control

Warrer-Hansen (Quoted in Dodd, 2017) raised an issue that has unfortunately been ignored by many key players involved in the design and management of both freshwater and marine RAS. Very simply, the primary function of biofilters is to efficiently remove ammonia. However, biofilters are often used for both ammonia plus fine suspended solids removal that have passed through the primary drum filters. This approach applies to RAS farms utilising biofilters of a specific design and operation. This dual approach seems to break the first cardinal rule of optimum RAS design and operation - 'remove all suspended solids as rapidly and gently as possible' (Fernandes et al., 2016) prior to the biofilter. Depending on the design, operation and daily management of the system, these solids can accumulate within the biofilter, blocking flow and providing organic nutrients for heterotrophic bacteria. This can lead to the development of anaerobic pockets within the filter which harbour anaerobic bacteria which produce toxic gases such as methane and hydrogen sulphide in freshwater and marine RAS respectively. Ideally, freshwater fish should not be exposed to more than 0.002 ppm of hydrogen sulphide for long periods with 0.001 ppm maximum exposure level being recommended (Tucker, 1993). Even chronic exposure to low levels can influence fish performance at levels below the detection threshold of (gas-chromatographic) analytical methods (0.025 mg/l). H_2S concentrations greater than 0.5mg/l are acutely lethal to most adult fish species (Wedemeyer, 1996). Mortalities and sub-lethal health impacts due to development of Sulphate Reducing Bacteria (SRB) in sludge deposits in static biofilters can occur in seawater systems with high naturally occurring sulphates levels of around 2,700 mg/l or higher. In addition to anaerobic conditions SRBs can thrive and divide at oxygen levels up to 40% saturation i.e. in mildly aerobic sludge, making them particularly difficult to control in conventional system designs (Dodd, 2017).

Inefficient solids removal, combined with the mineralisation of fine solids within some biofilters can, in the absence of additional fine solids and dissolved organics removal, also lead to the commonly observed RAS water discolouration reflecting increased organic enrichment and bacterial loading i.e. so-called "Brown Water" systems. This is an all too common feature of stocked RAS farms producing salmon smolts and marine and freshwater fish species direct for market. Ultimately, this leads to the common problem of flesh tainting of fish stock - especially in species like salmon with high fat content. Taints are due to release of substances like geosmin (GSM) and 2-methylisorboneol (MIB) by specific bacteria whose proliferation is encouraged by sub-standard water quality due to inefficient system water purification. Fish taint in RAS should not be presented as an "unavoidable characteristic" of RAS technology (Warrer-Hansen, 2015) when it really reflects a particularly inefficient approach to processing the circulating water. Such RAS systems accumulate increasing levels of fine particulates and dissolved organics leading to discoloured water and tainted product. Unfortunately, such conditions are often blamed on the RAS farm management and while this may be a contributory factor, weak RAS design usually makes the most significant contribution.

Flesh taint likely explains why depuration units are such a common feature of some RAS finfish farm design (usually involving purging with a clean water supply for several hours or days). Investors in RAS projects are often advised that the inclusion of depuration systems to reduce the taint levels of market product to acceptable thresholds is a secure solution. Henry (2018) noted the need for RAS farmers to stop sending tainted fish to market especially as it does the product, seafood market and RAS technology a disservice. The solution he believes is to perform regular taste tests and delay sending product to market if the slightest taint is detected. This approach may well suffice for low level volumes of annual production but will hardly be applicable for the industrial scale salmon RAS farms under construction where annual production may be measured in the thousands of tonnes. Apart from the many 'tasters' that would be required to taste test each harvest, such RAS farms simply won't be able to afford the backing-up of stock within the system simply because a batch of fish fail a quality test. The taint problem should be avoided in the first instance with improved RAS design and management so avoiding the conditions that encourage taint producing bacteria.

Depuration procedures also leads to weight and lipid loss with an increase in moisture content of the fillets. Since salmon fillet quality assessment parameters for producers of RAS-cultured salmon are flavour, texture and lipid levels (Burr et al., 2012) depuration is a questionable approach to solve a clear weakness of RAS design. It should also be emphasised that variable flesh lipid levels in any population of fish results in different taint removal rates between individuals over a specific depuration period. Failure to appreciate this fact has already resulted in the failure of both small and large - scale commercial RAS installations in the UK which clearly had little control over organic enrichment of system water. Not only is depuration a less than secure solution to ensure delivery to market of a non-tainted product, the construction and operation of depuration facilities increases initial investment required and raises production costs in terms of additional labour, power and resources simply to produce a lower quality product.

Meanwhile, research focuses on improving taint depuration techniques for salmon (Davidson et al., 2014), methods of removing taint substances in RAS water (Nam-Koong et al., 2016; Pestana et al., 2014; Guttman & van Rijn, 2008) or even modelling the "safe" period during which fish can be cultured in tainted water before the flesh absorbs unpalatable quantities of taint substances (Hathurusingha & Davey, 2014 & 2016). A far more useful line of research relates to the development of new sensors actually capable of detecting low quantities of gesomin in water (see section 4.6). This technology could provide farmers with early warning of detectable levels of geosmin before stock becomes tainted. It would also encourage RAS technology providers to improve their farm design and eliminate solids accumulation within the RAS.

It needs to be appreciated that problems of taint substances and toxic gases like H_2S in RAS reflect poor water quality conditions. They are clear indicators of the likely presence of other accumulating metabolic by-products that will reduce fish performance and product quality, encourage disease outbreaks, reduce animal welfare and deliver sub-standard products. Research needs to refocus on pollutant detection and improving solids removal technology in RAS rather than techniques that simply raise the production costs to deliver an inferior product and are ineffective when applied across the global field of RAS farm operation. Rather than simply accepting more expensive and less sustainable approaches to dealing with the side effects of inefficient solids removal in RAS improved solids removal technology is needed to reduce organic enrichment associated with "Brown Water" systems. It is not as if the technology doesn't already exist and has been successfully applied on commercial scale RAS farms selling non-depurated fish at premium price to the UK Korean sashimi market.

Evolving technologies more applicable to the aquaculture sector may have potential for improving solids removal. These include membrane filtration (Wold et al., 2014), sustainable bio-electrochemical reactor technology (Lin & Wu, 1996; Mook et al., 2012), Electro-Fenton (Virkutyte & Jegatheesan, 2009) and electrocoagulation technology (Majlesi et al., 2016). These methods have been tested on aquaculture waste streams and have been shown to have potential to treat some, if not all, RAS aquaculture metabolic by-products of the fish and suspended solids. Electrocoagulation (EC) technology is particularly attractive since the process removes solids through the addition of a precipitation agent to the contaminated stream. This agent, typically iron or aluminium, binds to contaminants that are dissolved or in suspension and the compounds settle into a sludge. The process is like chemical coagulation, which is the industry standard for various waste streams, but differs in the way that the agent is added to the stream. Whereas chemical coagulation does this via chemical dosing, EC does it electrochemically. As a result, the system has a significantly reduced environmental footprint and the need for chemical handling and storage is reduced or even eliminated. These features enable the technology to be safely used in a range of applications and environments.

EC has already been demonstrated to rapidly remove suspended organic solids from RAS effluent streams with only low energy consumption. Similarly, removal of heavy metals and phosphate, both significant issues in RAS farms, are also removed effectively with EC technology. EC technology also acts as a disinfectant agent reducing bacterial levels directly and indirectly by removal of dissolved organics. A 3-year UK research programme commenced in July 2018 to assess the impact of EC technology on disinfection rates, solids, metals and phosphate on commercial RAS farms. Nitrate can accumulate to excessively high levels in RAS without denitrification technology. However, EC technology has demonstrated its potential to reduce nitrate levels at the laboratory scale (Majlesi et al., 2016; Pak, 2015). Ensuring minimal nitrate, ammonia and sex hormone levels are all relevant to optimising salmon production in RAS. The UK programme will assess the impact of EC technology on commercial RAS farms and will report on potential positive and negative side effects of EC technology.

4.6 Enhanced Monitoring Systems

Intermittent system water sampling and laboratory analysis remain the most widely used tools for monitoring specific parameters in RAS. However, because of its non-continuous nature and the delay in obtaining laboratory results this approach is unsuited to managing significant biomass held at high stocking densities. Sub-lethal levels of some metabolic pollutants can have a subtle impact on fish physiology, suppressing appetite and growth. In large RAS farms this leads to significant production losses and possible disease outbreaks. There is the added concern that some accumulating substances can act synergistically to have an even greater impact than might be expected from one pollutant alone. Many potential RAS water pollutants such as hydrogen sulphide, taint substances, nitrate and heavy metals may not even be considered as relevant to managing RAS. Considering the very large RAS farms being planned or under construction then very much more refined, real time in-line sensors are needed. At high stocking densities approaching 50-60 kg/m^3 a water quality parameter that moves outside its optimal range should be detected immediately to avoid fatalities or impact feed intake and growth. Even where fatalities are avoided, a single day of lost growth due to appetite suppression can translate to a significant financial loss. More elaborate sensors that can monitor a range of water quality parameters on a continual real time basis 24h per day are needed.

Online UV/Vis spectroscopy has proven itself as a tool that allows the collection of specific information on the removal efficiency and subsequent concentrations of (organic) substances in water. For example, total suspended solids, chemical oxygen demand (COD) and nitrate can be readily monitored with UV/Vis spectral measurements (Langergraber et al. 2004). The use of two on-line spectrometer instruments, placed before and after a treatment step, and the calculation of the differential spectrum between these two sites could open a further area in water quality monitoring and process control as it allows calculation and prediction of water quality parameters previously unavailable. A major benefit in RAS management of such a setup would be the high measurement frequency.

Companies like DCM Process Control Ltd produce scan spectrolyser which is delivered with a predefined set of parameters called a ‘global calibration’. Parameters such as nitrate, nitrite, hydrogen sulphide and ozone can be measured on a continual basis. Sensitivity to any parameter depends upon the path length used. A 35mm path length is the standard but it can be setup with a 100mm path length, the 100mm path length is particularly useful when it comes to low level ozone detection (<0.1mg/l) although this level of sensitivity may be insufficient for RAS farms and similarly for hydrogen sulphide.

Fundamentally, scan sensors are a very flexible platform that allows measurement of any number of parameters that can be derived using UV-Vis spectroscopy. Extra sensors may be added for physical parameters (pH, DO etc) to create a comprehensive water quality monitoring system. Other advantages are that it requires minimal maintenance with automated cleaning using either a brush mechanism or compressed air and no recalibration. The system can be housed in a titanium body for use in saline environments.

Similarly, SINTEF Ocean has initiated the MONMIC[30] project to develop a system that alerts operators of RAS when dangerous bacteria are in the process of blooming. Bacterial blooming associated with unstable water quality conditions is a common cause of fish and crustacean larval mortalities in hatcheries. Until mid-2019, researchers at SINTEF Ocean will receive weekly samples of water from three different land-based salmon RAS hatcheries. The researchers will analyse the samples to map bacterial communities in the hatchery water, and to find out what happens when there are outbreaks of bacteria that can lead to disease, to develop the warning system.

The University of Liverpool (UoL) has a history of sensor development. The Mass Spectrometry group in the Department of Electrical Engineering and Electronics, working with the UoL spin-out company Q Technologies, developed a membrane inlet mass spectrometry (MIMS) system for detection and analysis of petrochemical compounds in seawater (Brkić et al., 2011; Maher et al., 2014). It consisted of a quadrupole mass spectrometer (QMS) connected to the capillary probe with a silicone-based membrane capable of measuring petrochemical pollutants in seawater and distinguishing between different types of oil and, potentially, where they originated from. The MIMS system was adapted in AQUAMMS (EU FP7 for SMEs http://aquamms.com) to provide a real-time online multi-sensor monitoring device for the aquaculture industry. The MIMS device was developed for measurement of a wide range of parameters, including gases, petrochemicals, Polycyclic Aromatic Hydrocarbons (Jjunju et al., 2015) and chlorinated hydrocarbons (Giannoukos et al., 2016) and contaminants that can affect the water quality in fish farms, more specifically in RAS to provide immediate warning and allow the farmer sufficient time to take a management decision like increasing oxygen flow or suspending water extraction.

The MIMS technique is simple (no need for sample pre-concentration), sensitive (detection limits are often in the low ppb range) and can rapidly analyse multi-component mixtures simultaneously. However, the membrane interface restricts the range of substances that can be sampled, particularly large and polar molecules. Ambient Ionisation (AI) approaches also offer the advantages of being simple, sensitive and requiring very little/no sample preparation (Maher et al., 2015). Ions are formed outside of the mass spectrometer at ambient pressures. Paper spray (PS) ionisation is a relatively new AI-MS method, successfully applied in the quantification of complex molecules, ranging from small organics to large biological molecules, including dried blood, under ordinary ambient conditions (Wang et al 2010). The sample is usually loaded onto paper cut to a fine tip. The paper is wetted with a solvent and charged liquid droplets are emitted from the paper tip when a high DC voltage (± 3.5 kV) is applied. Analysis by PS-MS requires little or no sample preparation and the entire experiment can be completed in a few seconds. PS integrates three analytical steps: sample collection,

30 https://thefishsite.com/articles/water-quality-warning-system-in-the-pipeline

separation, and ionisation into a single experimental step making it more attractive for rapid and direct analysis of analytes in complex mixtures. In addition, the technique can be used with portable MS in the field. UoL have proven this technology for the measurement of Metaldehyde, extensively used worldwide as a contact and systemic molluscicide for controlling slugs and snails and now a problem contaminant of surface waters due to run-off (Maher et al., 2016). This technique has been further enhanced by refinement of the paper substrate incorporating printed microfluidic channels (Maher et al., 2015; Damon et al., 2016). UoL is now developing the same approaches to measure taste and odour compounds such as Geosmin found in surface water. Geosmin at present cannot be detected on site nor in real time.

5. Appraisal of Short and Medium-term Prospects for RAS in Scotland

5.1 Recent Developments in Scotland

Globally the momentum towards recirculated aquaculture production systems continues to increase with larger scale investments and better developed technologies. A very small proportion of global aquaculture production uses RAS for grow-out but use in hatcheries is quite common for many species.

5.1.1 Salmon Smolts and Post-smolts

With Scottish aquaculture dominated by Atlantic salmon production, developments in this sector are particularly relevant. Recirculated aquaculture systems have been used for commercial rearing of salmon parr and smolts for over twenty years, with a gradually increasing proportion coming from such systems. With investments over the past five years the Scottish industry appears to be on a clear trajectory of increased reliance on these systems. Data on salmon smolt production is collated by Marine Scotland, but at present, data on smolt production from RAS is combined with production from other non-cage systems (mostly flow-through and semi-recirculated tank systems) and cannot easily be disaggregated. Data for 2012 to 2016 shows smolt production relatively constant at between 40 and 50 million per year. However, an increasing proportion of the smolts are from tank-based system (63% in 2016 compared with 40% in 2012).

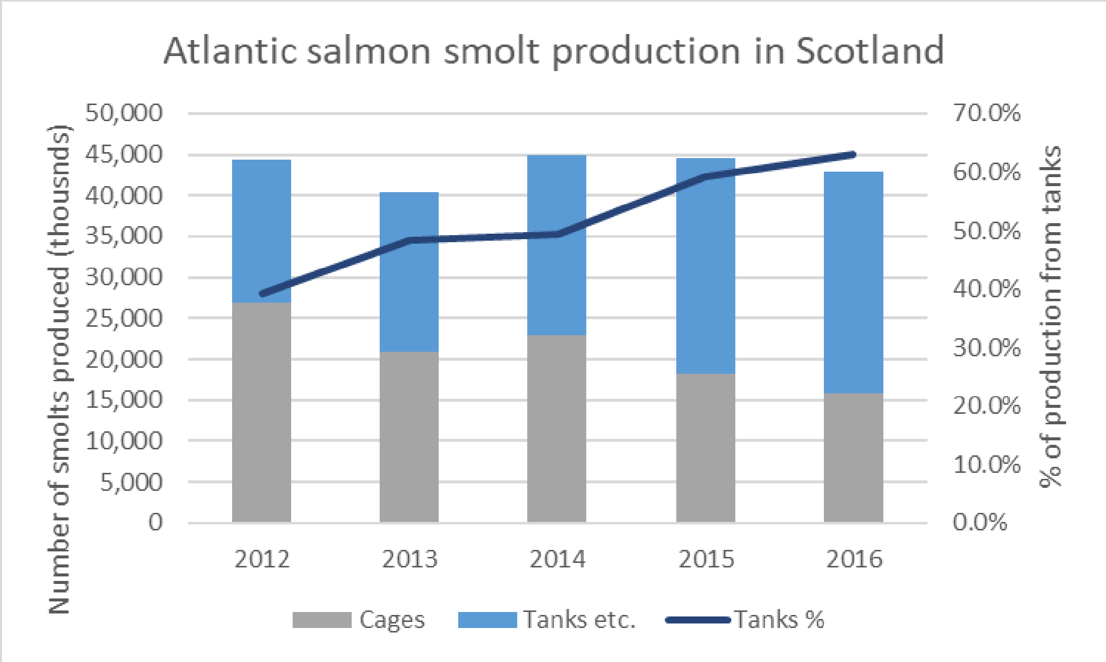


Figure 9: Development of Atlantic salmon smolt production in Scotland by system (Source: Data from Marine Scotland Science, 2017)

The number of freshwater cage sites has only reduced slightly over this period from 43 sites to 38 sites although total capacity has increased slightly. The fall in production from freshwater cages shows in the statistics as reduced stocking densities (from 77 to 40 fish per cubic meter).

The number of tank (and similar) sites has also reduced over this period – from 57 to 49 and so has total capacity (from 51 to 46 thousand cubic meters) indicating an increase in stock density (342 to 578 fish per cubic meter) which at least indicated greater use of oxygenation and other water treatment technology typical of RAS. The trend towards fewer larger production units is also reflected in the proportion of sites producing over 1 million smolts, which increased from 21% in 2012 to 25% in 2016. RAS smolt units currently in construction by Marine Harvest and Scottish Sea Farms should contribute at least 10 million smolts per annum when production commences later in 2018 or 2019.

So far, no post-smolt projects in Scotland are known to have been initiated, although are potentially economically viable (Jeffery et al 2015) and anticipated before 2030 (IMANI Development 2017). Marine Harvest have indicated an intention to develop a post-smolt project on Skye[31].

31 https://issuu.com/fishfarmermagazine/docs/ff_october_2017/32

Table 9: Recent RAS Salmon Smolt Units in Scotland

Company	Location	Approx. Production	Investment estimate
Cooke Aquaculture (Scotland) Ltd.	**Furnace**		**£6M**
Grieg Seafood ASA	Shetland	5 million	£15 Million
Marine Harvest	**Loch Ailort**	**5 million**	**£16.1 Million**
Marine Harvest	Inchmore	4.5 million smolts + 6.5 million parr	£26 Million
Scottish Sea Farms	**Barcaldine***	**6 million**	**£35 Million**

***Still under construction in early 2018**

5.1.2 Salmon Grow-out

Whilst numerous technical problems have been encountered, Scottish salmon producers are investing in RAS and clearly perceive it to be a technically and economically viable solution for smolt production. However, these companies have not yet indicated a willingness to invest in RAS for full grow-out of salmon in Scotland. Some other companies perceive this to be a missed opportunity and are either promoting or actively investing in RAS for salmon grow-out in Scotland. Two companies have initiated developments, although as of February 2018, both are seeking investors to proceed.

Table 10: Salmon grow-out projects in Scotland using RAS

Company	Location	Web address	Production	Published Investment requirement
Niri Scotland Ltd	**Machrihanish**	**http://niri.com**	**1000T**	
FishFrom	Tayinloan	http://www.fishfrom.com	3000T	£20 million

Niri is a Norwegian based company established in 2006 to develop land-based aquaculture. Niri Scotland Ltd was established in December 2013. The Niri RAS system is integrated within the rearing tank and a single system was installed at the old US Airforce base in Machrihanish during 2015 and was stocked in 2016. The tank is 1600 m^3 and was stocked with 26,000 juvenile salmon (Anon, 2016) suggesting it could produce around 100 -120 tonnes at harvest depending on assumptions concerning mortalities and final harvest weight. This appears to contrast with initial plans given to HIE for two 8000 m^3 tanks each capable of producing 1000 tonnes each per year (HIE 2014). The stocked fish were reportedly farmed to market size but were destroyed rather than sold to market. The reason for this was given as contamination with detergent, although a number of other technical problems were encountered including pH control and hydrogen sulphide. The company was taken over by new management in 2017 and the now empty facility is being promoted as an investment opportunity with potential for substantial expansion and integration with algae production, processing, and bioprocessing of waste for use in horticulture or energy production (Moore 2018a).

FishFrom Ltd was incorporated in 2012 and published plans for a 3000 tonne RAS production plant in Tayinloan in 2013. There has been little publicity since this time, but it is understood the company has established commercial partnerships and secured necessary development permissions. It has commenced site clearance but has not yet secured the full investment required (January 2018).

The authors are aware of other companies looking into the potential of salmon growout in RAS in Scotland, but not at the time of writing, firm proposals.

5.1.3 Cleaner Fish

Marine Management Organisation (MMO) figures show that between 40 - 89 tonnes of wrasse species valued at £1.1 – 5 million were caught in inshore waters of the South West of England during 2015 to be used as cleaner fish[32]. Wrasse are highly important recreational angling species which supports thousands of jobs throughout the South West of England valued at £165m to the regional economy in 2005. Landings data shows that the value of live, wild-caught wrasse at prices as high as £150 per kilo has converted a former 'trash fish', or one only used as pot bait, to the single most valuable wild capture fishery in the UK compared to wild sea bass and lobster that can fetch only £15 -17 per kilo.

In the UK, little is known about the sustainability of wrasse populations and what impact commercial scale harvesting will have on marine ecosystems where wrasse play an important role. Similarly, wrasse fisheries in Norway have also increased markedly since 2010 (Halvorsen et al., 2017). As in the UK, basic knowledge on the status of the targeted wrasse populations in Norwegian waters is weak, and the consequences of harvesting at the current intensity have not been assessed. Halvorsen et al. (2017) suggest that despite its short history, the wrasse fisheries have had a considerable negative impact on target wrasse populations. They also suggested that small MPAs might be important as a management tool for maintaining natural population sizes and size structure.

32 Reported in blog article - https://www.anglingtrust.net/news.asp?section=29&sectionTitle=Angling+Trust+News&page=4&itemid=3690

The demand for cleaner fish has stimulated the development of both wrasse and lumpsucker hatcheries in the UK with new facilities being constructed in Scotland and Wales. However, the complicated lifecycle of wrasse, slow growth rates and need to establish hatchery protocols suggests that a dependency on wild supplies will continue for several years. More sustainable approaches to lice control in the salmon sector need to ensure that wild cleaner fish stocks and communities remote from the salmon farming sector don't pay the cost.

Currently there are four main production sites in Scotland with Marine Harvest announcing a second development at Machrihanish:

Table 11: Cleaner fish production sites in Scotland

Company	Location	Species	Notes
Marine Harvest & Scottish Sea Farms	**Machrihanish**	**Wrasse**	**Joint Venture at University of Stirling site, 200,000 per annum**
FAI Farms	Aultbea, Wester Ross	Lumpsucker	Target production approx. 1 million
FAI Farms	**Sandwick, Shetland**	**Lumpsucker**	**Target production approx. 1 million**
Otter Ferry Seafish	Tighnabruaich	Wrasse & lumpsucker	Approx.. 200,000 wrasse & 650,000 lumpsucker
Marine Harvest	**Machrihanish**	**Wrasse**	**Not yet built – target 800,000 per year (£6 million investment)**

There are also developments in England (Portland, linked with the Native Marine Centre) and Wales (Marine Harvest is taking over the old Anglesey Aquaculture farm to farm wrasse and "Ocean Matters" located nearby is farming lumpsucker). The estimated demand for cleaner fish is around 3 to 4 million per year. Current developments in Scotland are therefore on course to achieve this so it is unlikely there will be many additional farms. The need for cleaner fish will also depend on what alternative solutions to sea lice are developed and adopted in the future.

5.1.4 Other Species

At present, the main opportunity for RAS in Scotland is probably for salmon smolts and potentially post-smolts for subsequent cage production providing sea site leases continue to be granted. However, potential new entrants to the sector are likely to find significant barriers to entry due to the scale and degree of consolidation of the existing industry. An alternative strategy is to focus on niche species for which alternative production methods are not suitable. This might include Mediterranean sole, *Solea senegalensis*, (Morais et al., 2016), European spiny lobster, *Palinurus elephas*, (Fletcher, 2015) and Siberian sturgeon (*Acipenser baerii*) for caviar production (e.g https://www.kccaviar.co.uk/products/caviar). All these species have specific attributes that make them attractive to farming using RAS technology.

As an example, The Fynest Caviar Company Ltd., has been granted planning permission to develop a RAS based sturgeon farm in Argyll after initial objections raised on grounds of animal welfare by PETA (Paterson, 2018). The stated production target is 50 t of sturgeon and 10 t of sturgeon products per year; although at start-up, only 10% of the capacity is expected to be reached (Moore, 2018b).

The UK is developing the hatchery technology for *P. elephas*. It has a 5-10-fold higher market value compared to *Homarus gammarus*, is not aggressive and has potential to be grown at higher temperatures than clawed lobsters. *P. elephas* is also in critical decline through much of its EU range including the UK and has a red (avoid) rating from the Marine Conservation Society. However, it still has very high unitary value and a strong market within the EU and export market to China. The EU *P. elephas* fishery is described as residual (ICES, 2006) and the species is on the ICUN Red List of Threatened Species[33]. As an ecological keystone species with high socio-economic value, recovery of *P. elephas* is vital to achieving Good Environmental Status (GES) under EU Marine Strategy Framework Directive and to improve opportunities for coastal fishermen. Many global lobster fisheries are in decline and showing little sign of recovery while the Asian markets continue to expand. This is a UK BAP Priority Species (BAP species are now Species of Principal Importance/Priority Species) and species of principal importance for the purpose of conservation of biodiversity under the Natural Environment and Rural Communities Act 2006. As such it could be a strong candidate for further aquaculture development.

There have also been some developments with whiteleg shrimp (*Litopenaeus vannamei*) farming in several European countries as well as the USA. Some of these use RAS and others biofloc technology. The authors are aware of one recent commercial initiative of this type in Scotland.

The first consideration for companies investing in new species is the timescale and expertise required to develop and up-scale the culture technology to commercial levels. Smaller companies with less capital to invest often collapse before adequate returns on income can be achieved (see previous 2014 report). Such risks might be reduced as RAS plants become more standardised and the skill base in operating them expands. Secondly consideration needs to be given to the potential market and long-term business model. High value niche products have limited scope for growth without impacting on market price. This can make them less attractive to larger-scale investors who are likely to prioritise long-term growth potential. The ideal candidate would be a species that has potential mass market appeal but for which prices are currently high due to restricted supply from the wild (as was the case

33 http://www.iucnredlist.org/details/169975/0

when salmon was first farmed). If this could be produced profitably in RAS with improving efficiency counteracting expected decline in sales prices there would be good prospects for growth, especially if there is also a competitive advantage to locating in Scotland.

5.2 Prospects for Commercialisation of Salmonid RAS Grow-out from an Under-writer's Perspective

Three insurance professionals servicing the salmonid farming industry were interviewed regarding their views on risk auditing and wider propensity of the industry to under-write the RAS sector.

Three key risk areas are prioritised during RAS audits; presence and effective operation of (i) alarm-systems, (ii) effective back-up systems in the event of a system failure (including power generation, pumping capacity and system modularisation) (iii) water quality treatment systems (particularly in respect of suspended solids removal, O_2 and CO_2 gas exchange).

The underwriters looked most favourably on RAS operated for smolt-production by larger vertically integrated companies. This was both a consequence of their now established commercial track record (i.e. compared to grow-out RAS) but also due to the fact that under-writing costs tended to be embedded as elements of larger contracts covering other production nodes i.e. thereby masking relatively higher RAS risk compared to cage-production.

The informants also highlighted an enduring reluctance of the sector to under-write dedicated grow-out RAS, despite the current wave of speculative investments in the same. Were they to become involved, they added that established 'vertically-integrated' salmon producers with long-term experience in RAS smolt production would be viewed more favourably in terms of under-writing propensity and cost. However, they also observed that to date there has been no real investment interest by such companies, which has instead mainly originated from private investment consortia with limited production and marketing experience. A trend for investment by the water and sanitation sector (e.g. Veolia) was highlighted. However overall risk was still only partially offset by lower operational risk associated with their core industry water treatment competence. Furthermore, the main strategic interest of such companies is likely to be in marketing turn-key operations i.e. rather than moving into aquaculture production themselves beyond pilot-scale R&D efforts.

This lack of investment by established salmon farming companies might then be viewed as an indicator of on-going poor commercial feasibility of salmonid grow-out RAS. However, this reluctance may also be due in part to the disruptive potential of such technology to the established norm (and substantial investment) in cage-production in open-water cage-sites. Furthermore, it is arguably the role of public regional development funding to support such innovation transitions during critical phases when they remain priced out of under-writing markets.

In a 2001 Seafish report (Epsilon Aquaculture Ltd. 2001), the authors estimated fish stock insurance for a small-scale turbot (*Psetta maxima*) RAS likely to be around 4% of the value of standing stock (88 tonnes at £4.00/ kg). Comparable rates for salmon in sea cages range from 1.5 to 2%.

5.3 Potential Impact on Scottish Aquaculture of RAS Developments Elsewhere

The global market for salmon is expected to continue to grow in line with population growth and increasing prosperity. If scope for expansion using sea cages is limited through regulatory controls, prices are likely to rise, and land-based farming will become more financially attractive. Alternative scenarios involve further moves by the cage-based sector to less environmentally sensitive offshore locations, or the development of floating closed containment systems which are already under pilot trials.

If land-based RAS develop as many anticipate, the key determinants of location will be access to (and cost of) land and suitable water supplies; proximity to markets (or at least distribution infrastructure) or possibly to feed supplies; and marketing related attributes such as the "Scottish salmon" brand or linkages with renewable energy or aquaponic projects.

At the present time it is probably more attractive for RAS companies to locate salmon production in Scotland than elsewhere in the UK due to the service infrastructure (e.g. access to smolts, feed supplies, processing and transport), access to water and relevant husbandry skills, and access to the Scottish salmon brand. Long-term, increased development of RAS-based salmon production in more distant markets (China, Middle East and probably elsewhere in Europe) could substantially limit the potential for further growth in Scottish salmon production. More substantial loss of market (i.e. to well below current production) is highly unlikely, but remains a long term risk if RAS based production of salmon in other locations becomes more economic, or regulatory action is taken in Scotland to remove the industry from coastal waters.

6. Conclusions

This report update focuses primarily on the use of RAS for salmon production. This is due to the particular economic and social importance of Atlantic salmon production in Scotland, and because it has become a key driver species for RAS development in general.

RAS technology is being increasingly applied for the production of juvenile fish (and in this context especially salmon). Its use for production to market size fish (or other species) remains relatively niche, with more commercial failures than successes, although there is now a little more confidence that lessons are being learned and knowledge is being applied to overcome past constraints.

There are probably over 100 RAS salmon hatcheries and smolt units worldwide and investment in this technology in Scotland is in the order of £100 million since 2012 (including ongoing builds). The salmon industry is increasingly producing larger smolts in these systems to shorten the grow-out period in sea cages, however, none of the major producers has invested in RAS for full salmon grow-out. The reasons for this are reflected in the discussions in earlier sections of the report, but most importantly the economics are not yet sufficiently attractive.

This analysis is not shared by all engineers and investors who see the future of aquaculture as being in RAS. Steve Summerfelt of the US Freshwater Institute was quoted as saying in 2014 that there were nine land-based salmon farms working to produce 7,000 tonnes per year (Schonwald, 2014). Moving forward, Fiorillo (2017) cites a combined production of around 10,000 tonnes of salmon from RAS. With the global production of farmed salmon around 3.1 million tonnes[34], production from RAS represents just 0.32% of the total. However, in research for this report we found 26 recent or proposed salmon RAS farms globally (Atlantic and Pacific salmon species). If all were developed and performed at design capacity, the production would be over 100,000 tonnes (3.2% of the global total). On these figures it is hard to conclude there is an immediate threat to cage-based salmon farming on purely commercial and economic grounds. However, economic factors can change and more importantly, social attitudes and policy changes could change and push the industry away from coastal cages.

34 http://globalsalmoninitiative.org

The president of the International Salmon Farmers Association, Trond Davidsen is quoted as saying “To my knowledge there are no examples of successful commercial land-based salmon farms yet. I am not arguing against it, just stating facts, but it will happen, maybe not tomorrow or 10 years or 15 years from now, but it will happen eventually. Someday the challenges will be overcome, and the technology will exist. It can’t be stopped.” (Welling, 2018).

Kjetil Lye (an analyst with Handelsbanken Capital Markets, Norway) is quoted as saying “Land-based edible fish production is a technology that has not yet been sufficiently tested, and there are technological and biological risks connected to the project”. With that caveat he also suggested land-based production could be a supplement to sea-based production. “It’ll take time, and I don’t consider it posing any threat to sea-based production. On the contrary, I see it as a necessary supplement to achieve the growth required in supply to satisfy the market” (Furuset, 2018).

Michal Kowalski of Jurassic Salmon (Active salmon producer from RAS) is quoted as saying “Salmon farming on land is not yet fully understood. Lessons are drawn every day. The most important thing is humility. Over the past few years we have learned a lot of lessons, but we are also looking forward to the future because we know that a lot of work is ahead of us” (Fischer, 2017).

There are an increasing number of commercial RAS developments in Scotland. For the foreseeable future these are expected to support and enhance the development of the Scottish salmon industry and potentially open the door to some further diversification of Scottish aquaculture production. The technology should not be viewed as either a threat to established producers, or a simple solution to the challenges of good environmental and natural resource management.

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Appendix A: RAS Technology Suppliers

NB. The following list is not exhaustive and implies no endorsement by the report authors. It is intended as a resource for anyone wishing to conduct further research into the sector.

Company Name	**Company web address**
AgriMarine Technologies	http://agrimarinetechnologies.com
AKVA Group	http://www.akvagroup.com/
Akvaplan Niva	http://www.akvaplan.niva.no/
Aqua EcoSystems	http://www.aqua-ecosystems.com/
Aquabiotech	http://www.aquabt.com/
Aquacultur Fischtechnik GmbH (EMF)	http://www.aquacultur.de/
AquaMaof	http://aquamaof.com
Aquatech Solutions	http://aquatec-solutions.com/
Artec Aqua AS	http://www.artec-aqua.com/
Atlantech Companies	http://www.atlantech.ca/
Atlantic Sapphire	http://www.atlanticsapphire.com/
Billund Aquaculture	http://www.billund-aqua.dk/
DHTED	https://www.linkedin.com/company/dhted/
Grow Fish Anywhere	http://growfishanywhere.com/
Hesy Aquaculture	http://www.hesy.com/
HTHaquaMetrics LLC	www.hthaqua.com
IDEE	www.ideeaquaculture.com
INACUI S.A.	http://www.indura.net/web

Inter Aqua Advance	http://www.interaqua.dk/
International Aqua-Tech	http://www.iat.uk.com/
Krùger Kaldnes (Veolia)	http://www.krugerkaldnes.no/
Landing Aquaculture	www.landingaquaculture.com
Llyn Aquaculture	http://www.llyn-aquaculture.co.uk/
Nofitech	http://www.nofitech.com/
PRAqua	http://www.praqua.com/
RecircInvest Biotech	http://www.recircinvest.com.cn/index_en.php?mod=index
Steinsvik	https://www.steinsvik.no/en/

Appendix B: Non-exhaustive list of farms using RAS

Country	Location	Species	Company	Type	Web address
Canada		Atlantic salmon	Kuterra (Namgis First Nation)	On-growing	http://www.kuterra.com/
Canada	British Columbia	Pacific coho salmon/ pacific Sockeye salmon and rainbow trout	West Creek Aquaculture	On-growing	https://www.westcreekbc.ca/
Canada	Nova Scotia	Atlantic salmon	Sustainable Blue	On-growing	http://sustainableblue.com/
Canada		Coho salmon	Golden Eagle Aquaculture	On-growing	
Canada		Steelhead salmon	Little Cedar Falls	On-growing	http://www.littlecedarfalls.com/home.html
Canada		Halibut, Arctic Char, Atlantic salmon smolts	Canaqua	Mix	
Canada			Agri Marine Holdings Inc		http://agrimarine.com

Country	Location	Species	Company	Type	Web address
Canada	Big Tree Creek, Sayward, B.C.	Atlantic salmon	Marine Harvest	Smolt	http://marineharvest.ca/about/blog-marine-harvest-canada/2017/big-tree-creek-turns-on-the-tap/
Canada	Dalrymple, Sayward, B.C.	Atlantic salmon	Marine Harvest	Smolt	https://youtu.be/EJBUw5D6Sso
Chile	Petrohue	Atlantic salmon	Camanchaca	Smolt	http://www.camanchaca.cl/en/
Chile	Rauco, Chiloe	Atlantic salmon	Marine Harvest	Smolt	http://marineharvest.com
Chile	Santa Juana	Atlantic salmon	Humboldt	Smolt	
Chile	Pargua	Atlantic salmon	Sealand	Smolt	
Chile	Lago Verde	Atlantic salmon	Invertec	Smolt	http://www.invermar.cl/index.aspx
Chile	Pargua	Atlantic salmon	Novofish	Smolt	http://www.novofish.cl
Chile	Rauco 2, Chiloe	Atlantic salmon	Marine Harvest	Smolt	http://marineharvest.com
Chile	Ampliacion, Chayahue	Atlantic salmon	Novofish	Smolt	http://www.novofish.cl
Chile		Atlantic salmon	Cupquelan	Smolt	http://www.cookeaqua.cl/en
Chile	Natales, Pto. Natales	Atlantic salmon	Acuimag	Smolt	
Chile	Reproductores, Trainel	Atlantic salmon	Marine Harvest	Smolt	http://marineharvest.com
Chile	Puelo, Rio Grande	Atlantic salmon	Aquachile	Smolt	http://www.aquachile.com
China		Atlantic salmon	Shandong Oriental Ocean Sci-Tech Co.	On-growing	http://en.orientalocean.com

Country	Location	Species	Company	Type	Web address
China		Atlantic salmon	Urumuqi	On-growing	
China	Goatang Island, Ningbo City	Atlantic salmon	Seafood Dragon	On-growing	
Denmark		Atlantic salmon	Danish Salmon	On-growing	www.danishsalmon.dk
Denmark		Yellowtail	Sashimi Royal	On-growing	http://www.nordicaquafarms.com
Denmark		Pike-perch	Aquapri	On-growing	http://aquapri.dk
Denmark	Vinderup	Hybrid striped bass	Biofarm	Growout	http://biofarm.dk/index.php/frontpage
Denmark		Atlantic salmon	Langsand Laks	On-growing	http://langsandlaks.dk/
England	Portland	Wrasse	Native Marine Centre	Hatchery/ Nursery	http://www.nativemarinecentre.com
Estonia	Pihtla, Saaremaa	Trout	Osel Harvest	On-growing	http://www.oselharvest.ee
Faroe Islands	Laxa MH Faroes	Atlantic salmon	Marine Harvest	Post-smolt	http://marineharvest.com
France		Atlantic salmon	BDV SAS	On-growing	http://saumondisigny.fr
France		Sea bass & Meagre	LPDS	On-growing	
Germany	Grevesmühlen	Whiteleg Shrimp	Cara-Royal (Green AquaFarming)	Growout	http://www.cara-royal.de
Iceland		Atlantic salmon	Arctic Fish	Smolt	http://www.arcticfish.is
Netherlands	Zeeland	Yellowtail	Kingfish Zeeland	Growout	https://www.kingfish-zeeland.com

Country	Location	Species	Company	Type	Web address
Norway		Atlantic salmon	SalmoBreed AS and Salten Stomfisk AS	Breeding company	http://salmobreed.no/en/
Norway	Steinsvik	Atlantic salmon	Marine Harvest	Smolt or Post-Smolt?	http://marineharvest.com
Norway	Fjaera	Atlantic salmon	Marine Harvest	Smolt or Post-Smolt?	http://marineharvest.com
Norway	Nordheim, Aure	Atlantic salmon	Marine Harvest	Post-smolt	http://marineharvest.com
Norway		Atlantic salmon	Grieg Seafood ASA		https://www.griegseafood.no/en/
Norway		Atlantic salmon	Fredrikstad Seafoods	On-growing	http://www.nordicaquafarms.com
Norway	Sagvag, Hordaland	Atlantic Salmon	Stord Havbrukspark	On-growing	https://www.facebook.com/ERKO-Settefisk-As-201249463646938/
Norway	Oygarden, Bergen	Atlantic salmon	Salmo Terra	Growout	http://www.salmoterra.com
Norway	Rjukan, Telemark	Atlantic salmon	SalmoFarms	Growout	https://www.facebook.com/Salmofarms/
Norway	Sjotroll	Atlantic salmon	Leroy Sea Food Group	Smolts and post-smolts	https://www.leroyseafood.com/en/
Norway	Vindafjord	Atlantic salmon	Marine Harvest	Smolt	http://marineharvest.com
Poland	Janowo, West Pomerania	Atlantic salmon	Jurassic Salmon	Full cycle	http://jurassicsalmon.pl/en/
Poland	Plonsk	Atlantic salmon	AquaMaof	Growout	http://aquamaof.com

Country	Location	Species	Company	Type	Web address
Russia	Kaluga Region	Trout	F Trout	Growout	
Scotland	Furnace	Atlantic salmon	Cooke Aquaculture (Scotland) Ltd.	Smolt	http://cookeaquaculturescotland.com
Scotland	Machrihanish	Atlantic salmon	Niri	On-growing	http://niri.com
Scotland	Tayinloan	Atlantic salmon	FishFrom	On-growing	http://fishfrom.com
Scotland	Shetland	Atlantic salmon	Grieg Seafood ASA	Smolt	https://www.griegseafood.no/production/grieg-seafood-hjaltland-gsfh/
Scotland	Loch Ailort	Atlantic salmon	Marine Harvest	Smolt	http://www.marineharvestscotland.co.uk
Scotland	Machrihanish	Wrasse	Marine Harvest/Scottish Sea Farms	Hatchery/ Nursery	http://www.marineharvestscotland.co.uk
Scotland	Inchmore	Atlantic salmon	Marine Harvest	Smolt	http://www.marineharvestscotland.co.uk
Scotland	Barcaldine	Atlantic salmon	Scottish Sea Farms	Smolt	https://www.scottishseafarms.com
Scotland	Machrihanish	Wrasse	Marine Harvest	Hatchery/ Nursery	http://marineharvest.com
Scotland	Sandwick, Shetland	Lumpsucker	FAI Farms	Hatchery/ Nursery	http://www.benchmarkplc.com/articles/the-curious-looking-lumpfish-is-proving-its-worth-in-the-fight-against-sea-lice/
Scotland	Aultbea, Wester Ross	Lumpsucker	FAI Farms	Hatchery/ Nursery	http://www.benchmarkplc.com/articles/the-curious-looking-lumpfish-is-proving-its-worth-in-the-fight-against-sea-lice/

Country	Location	Species	Company	Type	Web address
Scotland	Tighnabruaich, Aryll	Wrasse & lumpsucker	Otter Ferry Seafish	Hatchery/ Nursery	http://www.gighahalibut.co.uk/tag/otter-ferry-seafish/
Slovakia		Catfish	Rybia Farm		http://sumcekomega.sk
Spain		Atlantic salmon	Rodsel		https://www.rodsel.com/projects
Spain	Cadiz	Amberjack	Futuna Blue	Growout	http://futunablue.com
Switzerland		Atlantic salmon	Swiss Alpine Fish AG	On-growing	http://dev.swisslachs.ch/en/
UAE		Atlantic salmon	Asmak		http://www.asmak.biz
UAE	Abu Dhabi	Sturgeon	Emirates Aquatech	Growout	http://www.emiratesaquatech.ae
US	Hixton, Wisconsin	salmon and trout	Superior fresh	On-growing	www.superiorfresh.com
US		Steelhead Pacific salmon	Hudson Valley fish farms	On-growing	http://www.hudsonvalleyfishfarms.com/our_feed.html
US		Atlantic salmon	AquaBounty	On-growing	http://aquabounty.com
US		Atlantic salmon	Freshwater Institute	On-growing	https://www.conservationfund.org/our-work/freshwater-institute/
US	Belfast, Maine	Atlantic salmon	Nordic Aquafarms Inc	On-growing	http://www.nordicaquafarms.com
US	Mianmi, Florida	Atlantic salmon	Atlantic Sapphire	On-growing	http://www.atlanticsapphire.com/
US	Bucksport, Maine	Atlantic salmon	Whole Oceans	On-growing	https://wholeoceans.com

Country	Location	Species	Company	Type	Web address
US	Waterbury, Connecticut	Sea bass	Great American Aquaculture	Growout	https://www.greatameraqua.com
Wales	Anglesey	Wrasse	Marine Harvest	Hatchery/ Nursery	http://marineharvest.com
Wales	Penmon	Lumpsucker	Ocean Matters	Hatchery/ Nursery	http://www.oceanmattersltd.co.uk