Strategic Innovation Ltd.

SIF Baseline Review

A Global State-of-the-Art Review of Seafood Industry Innovation

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1 Preface from the SIF Executive Board

The £10 million UK Seafood Innovation Fund (SIF) is supporting the UK's fishing, aquaculture, and seafood industries to deliver cutting-edge technology and innovation. Launched in 2019, for an initial three-year period, the overall aim of the SIF programme is to kick-start a step-change in the productivity and sustainability of UK seafood into the future.

This SIF programme is administered by the Centre for Environment, Fisheries and Aquaculture Science (Cefas) on behalf of the Department for Environment, Food and Rural Affairs (Defra). The governance of SIF is provided through the Cefas secretariat, a Steering Group comprising of experts across the UK seafood and innovation sectors, and an Executive Board that includes members from Defra, Cefas, and representatives from the Scottish, Welsh and Northern Irish Governments with expert knowledge in the UK seafood sector.

At the commencement of SIF, the Executive Board commissioned, through an open tender process, a Baseline Review of innovation in the seafood sector. The output from the review is given in this report. The content of this report does not necessarily reflect the views of Defra or Cefas. The report includes a brief overview of UK fisheries, aquaculture and seafood industry and a review of the state-of-the-art technologies and innovations from around the world which are relevant to the UK fisheries, aquaculture and seafood industries, in the context of the challenges faced by these sectors. This work was carried out prior to the COVID-19 outbreak and the effect of the COVID-19 lock-down on the industry or markets has not been considered.

This report is intended to be used by those making applications to SIF, to help inform them of the relevance to SIF of the project being considered. It will also be made available to the independent assessors performing evaluations of SIF proposals to help with their assessments. Applying the review in this way is intended to increase the confidence that funding is awarded to truly innovative projects. The review will also form part of the overall evaluation of the success of the SIF programme in meeting its objectives.

It should be noted that, due to the wide scope of the commissioned task, the review was not anticipated to include all innovations in all sectors. The approach that was agreed in producing the review has generated extensive examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently occurring. It is expected that a successful innovation programme will fund projects associated with known areas of innovation, but also lesser known areas and completely new ideas. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

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2 Introduction to the SIF Baseline Review

2.1 Background

This report presents a global state-of-the-art review of seafood industry innovation. The report has been prepared in the context of the Seafood Innovation Fund (SIF), a £10 million UK Government fund to support seafood research and innovation. The SIF aims to foster, encourage and financially support innovative technologies to support more sustainable and productive fisheries, aquaculture and seafood production. Through stimulating the development of new transformative technological innovation, it will contribute to both the government's ambition for UK world-class sustainable fisheries and aquaculture and, more broadly, contribute to economic growth by improving the productivity of the sector and helping create new markets and products from innovative and sustainable fisheries both in the UK and overseas.

The SIF is administered by the Centre for Environment, Fisheries and Aquaculture Science (Cefas) on behalf of Defra. Further details of the SIF can be found at: https://www.seafoodinnovation.fund/

2.2 Aims, objectives and scope of this review

The overall aim of this review – the 'SIF Baseline Review' - was to generate an overview of the state-of-the-art technologies and innovations from around the world that are relevant to the UK fisheries, aquaculture and seafood industries.

The outputs of the SIF Baseline Review are intended to:

1. Guide the assessment of submitted SIF proposals through providing wider context on the state of innovation.
2. Inform on priority areas for funding.
3. Ensure funding is awarded to truly innovative projects.
4. Identify gaps in specific topics on which proposals will be encouraged.

The scope of the review covered 22 topics within four themes: 'marine and land-based aquaculture', 'onshore supply chains and added value production', 'climate change' and 'marine fisheries'. Innovations from around the world since 2015 were captured for each of the challenge areas. Further details of the challenge areas and scope definition can be found in the methodology chapter.

2.3 Structure of this report

Chapter 2 of this report provides a brief overview of the UK fisheries, aquaculture and seafood industry and identifies links to ‘challenges’ discussed in the report.

Chapter 3 provides details of the research methodology applied during the SIF Baseline Review.

Chapter 4 provides background information on how innovation is defined and evaluated and goes on to explain how this was applied during the assessment of innovations within the SIF Baseline Review.

Chapters 5 to 26 present the review results for the 22 challenge areas, organised alphabetically within the four themes. To aid navigation and quick reference, each challenge area includes:

- A table of contents for the chapter.
- A ‘blue box’, which summarises the challenge for the UK, the most promising innovation categories identified and any significant knowledge gaps.
- An ‘innovation matrix’, which summarises all the innovations captured for the challenge and their rating in terms of potential performance impact and technical risk (see chapter 4 for further details of the innovation matrix).
- Brief descriptions of each of the innovations identified.
- References, providing details of the source from which the innovation was identified.

Chapter 27 presents a top-level summary and the conclusions.

3 Brief overview of UK fisheries, aquaculture and seafood industry

Seafoods are some of the most traded food items in the world today. The world's largest fish producer and exporter is China, whereas the world's largest consumer market of fish and fish products is the European Union, followed by the United States and Japan (FAO 2018). In 2016 the global fish production from marine capture fisheries was around 90 million tonnes, of which about 35% entered international trade in various forms for human consumption or for non-edible purposes (FAO 2018). The value of this fish production export was around £110 billion. Global aquaculture production (including aquatic plants) in 2016 was 110.2 million tonnes, with the first-sale value estimated at £188 billion (FAO 2018).

This chapter seeks to give a top-level overview of marine wild-capture fisheries and the aquaculture industry in the UK.

3.1 Wild-capture marine fisheries

The Marine Management Organisation published the following figures for marine fisheries in the UK 2018. A total of around 698,000 tonnes of fish and shellfish were landed in 2018 and sold into the UK market and abroad with a value of £989 million. This equates to a 4% decrease in quantity of fish and shellfish landed by UK vessels compared to 2017. In 2017 the UK exported fish and fish-derived products for around £1.3 billion. In 2018 exports fell by 12,000 tonnes to 448,000 tonnes and imports of fish and shellfish into the UK were also down by 31,000 tonnes to 674,000 tonnes (Marine Management Organisation 2019b; 2019a).

The UK fleet landings abroad fell to 272,000 tonnes compared with 291,000 tonnes in 2017, almost entirely down to a decrease in mackerel landings. Mackerel landings fell to 191,000 tonnes from 227,000 thousand tonnes in 2017, but still made up a substantial 27% of UK fleet landings. The Scottish and Northern Irish fleets caught mainly pelagic fish. The English landed mainly demersal species and the Welsh caught mostly shellfish (Marine Management Organisation 2019a).

In 2019, around 12,000 fishermen were active in the UK, of which approximately 2,400 were part-time. The UK fishing fleet remained seventh largest in the European Union (EU) in terms of vessel numbers, with the second largest capacity and fourth largest engine power. In January 2020, a total of just over 3400 licensed vessels of 10 metres and under overall length and just over 1000 licensed vessels of over 10 metres overall length were registered in the UK (excluding islands). In 2018 there were 4,512 active registered vessels in the UK fishing fleet. In addition, there were 1,733 inactive vessels, most of which were small-scale vessels under 10m in length. The number of active and low activity vessels decreased in 2018 by 3.7% and 5.1% respectively, compared to 2017 (Seafish 2018a). In comparison, in 2014, the UK fishing industry had around 4,600 active vessels.

Based on the 2012-14 average and rounded to the nearest £10m, these vessels earned £800m in revenue each year from landing fish into the UK and abroad (House of Commons Committee 2017). England has the largest number of vessels (49%) followed by Scotland (32%), although Scotland has the highest share of capacity due to having larger vessels on average. The UK fleet is very diverse, with considerable variety in the size of vessels, the fish species they catch and their routes to market.

Scottish vessels accounted for 64% of the quantity of landings by the UK fleet while English vessels accounted for 27%. A total of 74% of the quantity landed by the UK fleet was caught by vessels over 24 metres in length which accounted for 4% of the total number of UK vessels. These vessels tend to catch lower value pelagic fish (Marine Management Organisation 2019b).

Table 3-1 below from the Marine Management Organisation (Marine Management Organisation 2019a) shows the top five species landed by UK vessels in each of the four major zonal divisions in 2018. Mackerel from UK waters is by far the largest with an estimate of 186,000 tonnes live weight.

From UK waters	**Lower bound**	**Spatial estimate**	**Upper bound**
Mackerel	185,255	185,647	185,989
Herring	96,026	99,122	100,945
Haddock	29,275	30,066	30,704
Edible crab	24,426	27,752	28,520
Nephrops	22,820	24,115	25,072
From OMS	**Lower bound**	**Spatial estimate**	**Upper bound**
Blue whiting	62,001	63,209	63,793
Plaice	4,471	5,616	7,805
Edible crab	4,431	5,200	8,525
King Scallops	1,240	4,972	9,075
Mackerel	4,296	4,296	5,030
From 3rd C waters	**Lower bound**	**Spatial estimate**	**Upper bound**
Cod	N/a	13,856	N/a
Squid	N/a	4,196	N/a
Haddock	N/a	4,067	N/a
Herring	N/a	2,582	N/a
Saithe	N/a	2,280	N/a
From International waters	**Lower bound**	**Spatial estimate**	**Upper bound**
Northern Prawn	N/a	1,247	N/a
Haddock	N/a	861	N/a
Mackerel	N/a	796	N/a
Cod	N/a	570	N/a
Swordfish	N/a	523	N/a

Table 3-1: UK top five species by major zonal division in 2018, by tonnage (Marine Management Organisation 2019a).

From UK waters	**Lower bound**	**Spatial estimate**	**Upper bound**
Mackerel	196,087,377	196,396,155	196,661,340
Nephrops	73,970,811	77,221,283	79,493,999
Edible crab	58,032,247	66,372,923	68,202,537
King Scallops	45,482,107	54,833,407	63,398,918
Cod	46,532,083	46,785,681	46,930,485
From OMS	**Lower bound**	**Spatial estimate**	**Upper bound**
Blue whiting	13,373,408	13,569,337	13,663,949
Monks or anglers	10,835,373	11,760,128	14,792,270
King Scallops	2,886747	11,451,796	20,803,300
Plaice	8,459,138	10,554,823	14,753,631
Edible crab	6,833,629	8,663,027	17,003,867
From 3rd C waters	**Lower bound**	**Spatial estimate**	**Upper bound**
Cod	N/a	26,454,565	N/a
Squid	N/a	11,343,944	N/a
Haddock	N/a	6,956,540	N/a
Hake	N/a	3,840,579	N/a
Saithe	N/a	1,893,610	N/a
From International waters	**Lower bound**	**Spatial estimate**	**Upper bound**
Northern Prawn	N/a	3,750,006	N/a
Mackerel	N/a	2,223,156	N/a
Haddock	N/a	1,302,374	N/a
Swordfish	N/a	1,244,037	N/a
Cod	N/a	1,167,993	N/a

Table 3-2 below shows the same as above but for landed value instead of tonnage; e.g. illustrating the lower value pelagic species herring being overtaken by higher priced Nephrops, crabs, scallops and cod (Marine Management Organisation 2019a).

From UK waters	**Lower bound**	**Spatial estimate**	**Upper bound**
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Swordfish	N/a	1,244,037	N/a
Cod	N/a	1,167,993	N/a

Table 3-2: UK top five species by major zonal division in 2018, by landed value (Marine Management Organisation 2019a).

Figure 3-1 below shows landings made by UK vessels in 2018 split by length group and those groups' five most valuable gear groups (Marine Management Organisation 2019a). Specifically, it shows the proportion of those group landed coming from each major zonal division. The figure shows an increase in landing value originating in non-UK waters as vessel size increases, with a high seen for over 40m beam trawlers in other European Union Member States (OMS). Statistics for OMS were obtained from publicly available datasets and as such the Marine Management Organisation takes no responsibility for their quality; they are provided for context only.

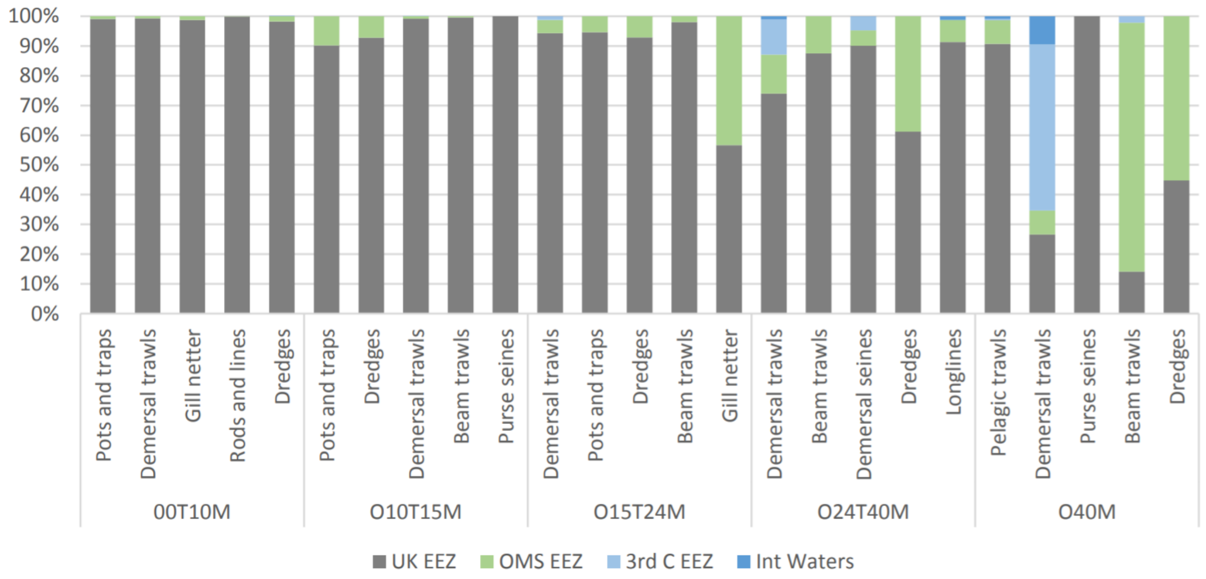


Figure 3-1: UK vessel top five gear types by length group by major zonal division in 2018, by landed value (Marine Management Organisation 2019a).

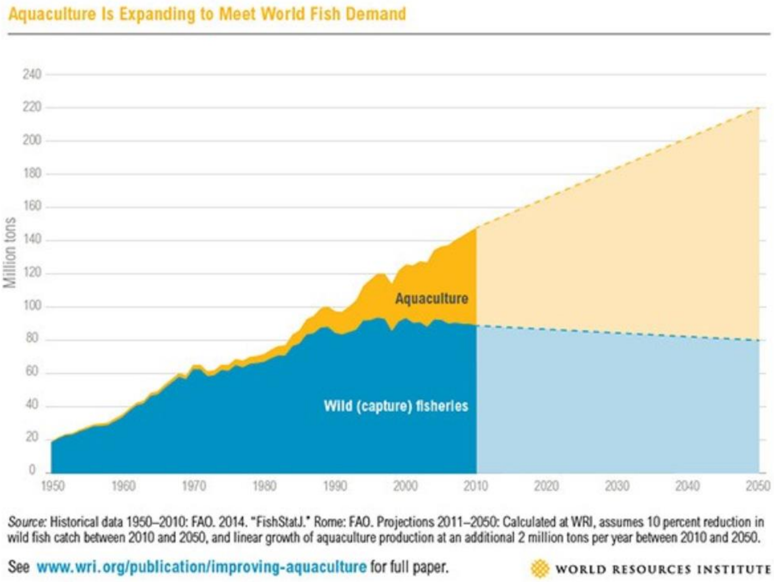
Major challenges in wild-capture fisheries include bycatch, ghost fishing and improvement of targeted harvesting, as well as the larger scale issues such as habitat loss from coastal development. Innovations from the past five years, related to these key issues, are listed in the following wild-capture fisheries focused chapters.

3.2 Aquaculture

Aquaculture continues to be the world's fastest growing and most diverse food production sector, with over 95.6% of total aquaculture production being realised within developing countries and the sector growing at an average APR of 6.64% per year, compared with 1.15% for economically developed countries (FAO 2018; Guillen *et al.* 2019).

In 2015, the world reached the point where at least half of all seafood consumed globally (~160 million metric tonnes, Mmt) was grown in farms, rather than from wild-capture fisheries (World Resources Institute 2014). This 80 Mmt of farmed seafood comprised fish, shellfish, crustaceans and seaweed, with around 90% produced in Asia. By 2050, global production from aquaculture is forecast to at least double with well-managed fisheries expected to flatline or even decline over the same period (Figure 3-2 below). Clearly, aquaculture will be making an increasingly important contribution as a source of protein to the future global diet.

Figure 3-2: Aquaculture is Expanding to meet world demand (source: World Resources Institute 2014).



Aquaculture Is Expanding to Meet World Fish Demand

Source: Historical data 1950–2010: FAO. 2014. "FishStatJ." Rome: FAO. Projections 2011–2050: Calculated at WRI, assumes 10 percent reduction in wild fish catch between 2010 and 2050, and linear growth of aquaculture production at an additional 2 million tons per year between 2010 and 2050.

See www.wri.org/publication/improving-aquaculture for full paper.

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In 2016, the European Union's (EU) aquaculture sector represented only about 1.7% of the world production in volume and 3.1% in value. The UK remains a leading aquaculture producer within the EU, with the Atlantic salmon production in Scotland dominating the UK aquaculture (Ellis *et al.*, 2015.; FAO n.d.). Scotland's salmon farming accounts for Britain's biggest single food export, yet it represents merely 6% of global production (Fraser 2019). Figure 3-3 below shows the evolution of table aquaculture production in the UK over the last four decades.

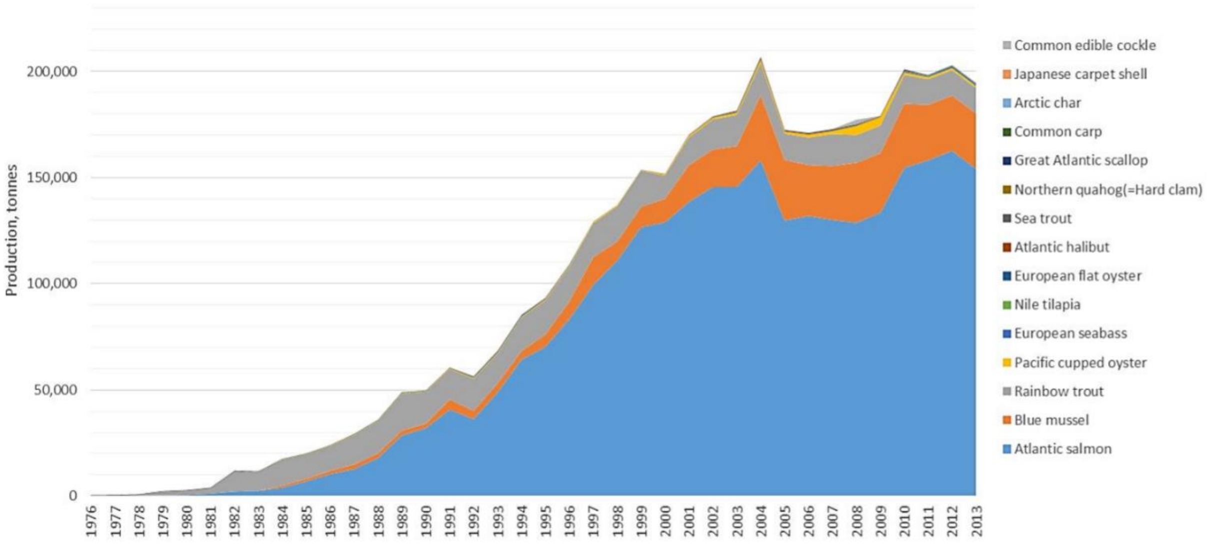

Figure 3-3: Historic development of aquaculture in the UK (Hambrey and Evans 2016; based on FAO data).

Salmon farming in Scotland started production in the early 1970s and the aquaculture in the UK has since been dominated by Scottish aquaculture, primarily in the form of Atlantic salmon farming, which accounts for approximately 80-90% of the production both in volume and value. In 2019, global salmon exports from Scotland generated £700m of income from industrial activity in Scotland in a sector that supports over 12,000 jobs and with a current estimated value of over £1bn per annum (SAIC n.d.). However, the UK fish and seafood market continues to be dominated by imports (43%) and capture fisheries (40%) with aquaculture making up only 17% of domestic supply in 2017 (Black and Hughes 2017).

Scottish salmon is renowned for its quality, and operators have been uncompromising in ensuring that all salmon farmed in Scotland is of a high standard. Accordingly, Scottish salmon was the first non-French product to be awarded a Label Rouge quality mark, which it achieved in 1992 (Scottish Salmon 2018).

The main export markets for UK salmon in 2017 were the USA (34%), France (23%) and China (12%) (Black and Hughes 2017). This was still the case in 2018, with a value of just under £505 million, around 16% less than the record-breaking year of 2017 (Moore 2019). The fall in earnings was primarily a direct consequence of a decrease in export volumes to 74,816 tonnes in 2018 from 92,350 tonnes in 2017, where salmon farmers produced a record-high 189,707 tonnes (Moore 2019). Chile also re-emerged as a competitor after overcoming biological issues. In 2018 exports to the EU amounted to 38,980 tonnes, with a value of £250 million (Moore 2019).

The interests of the UK aquaculture sector are represented by various advising bodies and interest groups, such as Seafish and the Scottish Aquaculture Innovation Centre (SAIC), and the industry is directly represented by a range of influential trade bodies and organisations, such as the Scottish Salmon Producers Association, Association of Scottish Shellfish Growers, Scottish Shellfish Marketing Group, Shetland Aquaculture, British Trout Association, British Aquaponics Association, Shellfish Association of Great Britain, Welsh Aquaculture Producers' Association, and the British Marine Finfish Association amongst others.

In October 2016, the Scottish salmon aquaculture industry set out a strategic plan which would see output reach around 350,000 tonnes per year by 2030, with an estimated £3.6bn in value (Fraser 2019). To reach this target, the industry wants to raise capacity, securing licences which would expand the maximum size of a fish farm site, bringing that closer to the more efficient Norwegian scale.

Salmon farming in the UK is followed by mussel production. Europe is responsible for around 6% of the world production of marine bivalves, with a significant decrease in production since 1998 (Wijsman *et al.* 2019). This decrease is mainly due to a decrease in mussel production by aquaculture activities from about 600 thousand tonnes per year in 1998 to about 465 thousand tonnes per year in the period 2010 to 2015. Production is limited by a reduction in physical space due to competing claims with nature conservation and occasional recruitment failures.

Production of oysters, clams and scallops in Europe is much lower than the mussel production. The oyster production decreased from 150 thousand tonnes in 1998 to about 94 thousand tonnes per year (average 2010–2015), with the largest production in France (ca 78 thousand tonnes per year). In Ireland, however, the production of oysters is increasing. Almost 25% of the marine bivalve production in Europe, yearly about 205 thousand tonnes per year, comes from the fishery. The highest capture production is in the UK (scallops and cockles), Denmark (blue mussels), France (scallops) and Italy (venus clams) (Whiteley 2016).

Shellfish farming is a significant and growing aquaculture sector in Scotland, feeding demand in a growing market both in the UK and abroad (Scotland's Aquaculture n.d.). The majority of production is centred on mussels, but oysters and scallops are also grown. It is regarded as a promising, low-impact, sustainable industry producing a range of different products (Hambrey and Evans 2016).

Still, a recent snapshot from 2019 indicated that the majority of Scottish shellfish farms produce less than 200 tonnes per year, which means that the industry is likely susceptible to financial shocks if/when commodity markets fluctuate. Production needs to be scaled up sustainably in order to insulate producers from market pressures (The Fish Site 2019).

According to a recent presentation by Seafish, the UK aquaculture industry produced 24,157 tons of shellfish per annum with a value of around £37m (Brooks 2018). Species included sea mussels making up nearly 80% of the total, common edible cockle represents nearly 13% and Pacific cupped oyster represents around 7%. Other farmed species incl. European flat oyster, Japanese carpet shell (or Manila clam), great Atlantic scallop, northern quahog (or hard clam) and Queen scallop, which together only account for around 0.2% of total production (Brooks 2018).

The mussel production is followed by trout production, dominated by the production of rainbow trout and a much smaller production of brown trout. Rainbow trout aquaculture is done mostly in England and produced for both restocking and consumption (Franco n.d.; Munro *et al.* 2016).

UK rainbow trout farming took off very rapidly in the early 1980’s but has remained almost constant and at a relatively low level since at around 8,000 tons produced in recent years (Hambrey and Evans 2016). The demand for trout (predominantly rainbow trout) is relatively flat, and producer margins slender. Demand for the traditional whole, plate sized trout in the UK is limited and easily met by existing suppliers. Internationally the UK is in competition with high-quality production from Denmark, and volume supply from Iran, Turkey, and Chile. Growth in the trout market appears to be confined to the production of large seatrout in marine cages, which now takes place in Norway, Denmark, Scotland and Chile. There may be some growth potential for this sub-sector in Northern Ireland (perhaps in association with salmon production) but lack of competitive sites will significantly limit growth opportunities in other parts of England, Wales and Northern Ireland. Stimulating demand for trout through value-added products may have more potential (Hambrey and Evans 2016).

The farm gate value of trout production in 2012 was estimated at around £23 million, omitting the value of egg and juvenile production (Ellis *et al.*, 2015). Wales produced roughly 250 tonnes of rainbow trout, worth around £0.5 million, of which around 60% went to the table market and the rest for stocking. Northern Ireland produced 563 tons of rainbow trout worth around £1.2 million. Brown trout production in England amounted to just over 300 tonnes, worth around £0.75 million, and modest amounts of Arctic char (7 tonnes) and Atlantic salmon (4 tonnes) were produced for restocking. Small amounts of brook trout were also produced in both England and Wales for stocking purposes. Northern Ireland produced some 44 tons of brown trout worth £0.1 million.

Historically, in the UK there has been a number of attempts of aquaculture developments for both native and exotic species in a variety of systems. Between the late 1980s up to 2018, examples included (but are not limited to): Haddock, signal crayfish, whiteleg shrimp, Atlantic cod, chub, rudd, Mozambique tilapia, queen scallop, North African catfish, brook trout, barramundi, turbot, Mediterranean mussel, tench, grooved carpet shell, freshwater bream, crucian carp, roach, cupped oyster and more recently, sea bass can be added to the list (Hughes 2015; Hambrey and Evans 2016).

The majority of those attempts have failed and the most successful aquaculture species in the UK remain Atlantic salmon, a few species of shellfish and bivalves and trout. However, seaweed is gaining traction and there are a few small-scale seaweed farms operating in Devon and Cornwall.

One promise of aquaculture was that it would relieve fishing pressure on declining wild stocks and help to restore natural ecosystems. This has happened to some extent, but aquaculture has also led to issues related to e.g. the escape of exotic species, eutrophication, habitat destruction, the conversion of scarce protein feed to luxury commodities, and the spread of marine diseases, many of which have significant economic consequences for the fishing or aquaculture industry (Lafferty *et al.* 2015). Innovations from the past five years, related to these key issues, are listed in the following aquaculture focused chapters.

3.3 Seafood processing

Overall, the UK is a net importer of fish - it exports most of what it catches and imports the majority of the fish that are processed or consumed within the UK. The UK seafood processing industry is larger than both the aquaculture and fishing industries, with a turnover of around £3.8 billion in 2015. This makes the UK seafood processing industry one of the largest in the EU, with only the French industry generating more income with a turnover of £4.0 billion (Scottish Parliament 2019).

While seafood processing and other fishing related industries make up a very small proportion of the Scottish economy as a whole, they are a significant part of the marine economy and make an important contribution to many coastal communities. In 2016 there were 377 fish processing sites in the UK, operated by 347 companies and deriving over 50% of their turnover from fish processing (Seafish 2018c). Of these processing sites a total of 139 were in Scotland in 2018, providing 8,900 Full-Time Equivalent (FTE) jobs - this adds up to approximately 39% of the sites in the UK and 46.3% of the jobs. Figure 3-4 below shows the number of processing sites and jobs against fish species categories from 2008 to 2016 (Seafish 2016).

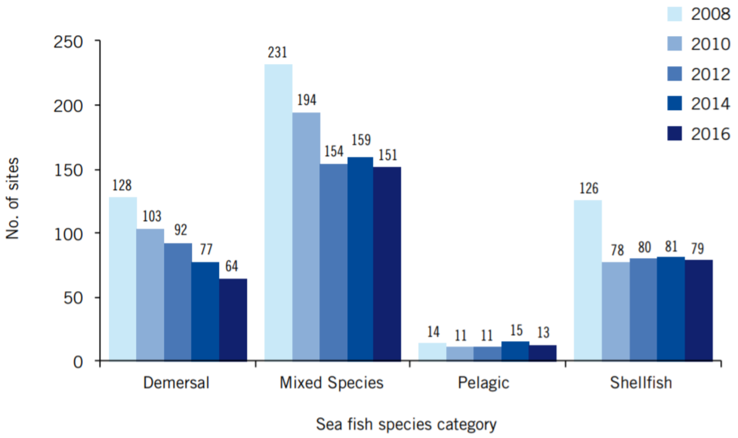

Figure 3-4: Sea fish processing: sites and jobs by fish species category (2008-2016) (Seafish 2016).

In Scotland, the sector is primarily based in the North-East, the Highlands and Islands and on the West Coast, and makes a significant contribution to the local economies in these areas. The Grampian region has the largest share of Scotland's processing sector, with 4,327 FTE jobs (48.6% of the Scottish total) based at 55 sites in 2018. In 2015 alone, it is estimated that processing businesses in the region generated more than £725 million in turnover (Scottish Parliament 2019).

The turnover of sea fish (saltwater species) processing companies in 2014 was £3.13 billion and gross value added (GVA) was £554 million (N.B. these figures exclude the turnover and GVA of salmon-only processing companies). In 2016 fish processing sites accounted for 17,999 full-time equivalent (FTE) jobs, 13,455 of them in majority-sea fish processing sites and the remainder in salmon processing sites.

The seafood processing sector in the UK relies heavily on workers from other European Economic Area (EEA) countries. This trend is even more pronounced in Scotland - based on survey data, Seafish has estimated that, in 2018, 59% of those employed in the sector in Scotland were from non-UK EEA countries, compared with 51% in the UK as a whole (Danielsen 2019; Seafish 2018c).

Research conducted by Seafish in early 2017 revealed significant variability in reliance on EEA staff by region within the UK (Seafish 2018c). In the Grampian region 70% of reported workers were citizens of other EEA countries; in comparison, processors in Humberside reported the lowest proportion of EEA workers at 17% (Danielsen 2019).

The seafood processing industry is continuingly facing challenges from rising costs as these cannot be directly passed on to consumers in full, due to competition, including competition from producers and processors of cheaper sources of animal protein such as chicken (personal communications). Further, with a few exceptions, UK landings comprise relatively small volumes. Thus, apart from basic filleting and freezing services, the value added by UK primary processors may not meet the format, quantity and species demands of large-scale food manufacturers. Also, the UK's decision to withdraw from the European Union presents the sector with fresh challenges, particularly around workforce and future immigration arrangements, sources of funding and international trade opportunities.

3.4 Retail and consumers

According to Seafish (Seafish 2018b), in the year ending 7 October 2017, a total of 321,000 tonnes of seafood was bought for £3.22bn from the major multiple supermarkets in Great Britain. Price inflation has increased the average price per kg by 5.7% to £10.03, resulting in almost £100m value growth. With over £2bn of sales, the chilled sector dominates the category but only the frozen sector is reporting growth of both sales value and volume. The ambient sector (shelf-stable tins, jars, pouches) is also reporting an 8.9% increase in the average price paid per kg, which is now £6.62, however the sector remains in overall decline (Seafish 2018b).

By overall volume, the two largest product segments within retail are natural (seafood with no additional ingredients) and prepared (seafood prepared by any other means not specified by the other segments). Combined, these account for just below 55% of all sales, however they are experiencing a decline along with sauce and breaded segments. The segments that are reporting an increase in sales volume are meals, fingers, batter, cakes, sushi and dusted (Seafish 2018b; Mowi 2019).

The 35 top species by sales value remain the same as last year with salmon, cod, tuna, warm-water prawns, haddock and cold-water prawns maintaining their top six rankings. In fact the only species which have changed their ranks are: mackerel +1, pollock -1, basa +1, scampi -1, sea bream +1, scallops -1, squid (calamari) +1, anchovy +1, lobster -2, pilchards +1, cockles +1, shrimps +2, crayfish -3 and monkfish -1 (Seafish 2018b).

In 2016 a total of 72% of UK adults did not know that it is recommended they eat two portions of fish a week, one of which should be oily (Dish 2020). It was also reported that 32% of UK adults who eat one or less portions of fish a week claim that it is the cost of fish that prevents them from eating more fish. This explains why in June 2019, budget supermarkets combined took a 19.6% volume share of the total UK seafood (Seafish 2019). Of those UK adults who eat at least one portion of fish a week, 43% are doing so as they “try and have a balanced diet" and 35% do so because of the "general health benefits of eating fish". When told of the multitude of health benefits of fish, 66% of UK adults agree that they are encouraged to eat more fish than they already do and 78% agree that they feel encouraged to specifically eat two portions of fish a week (Seafish 2020). This demonstrates that once people are made aware of the many health benefits of eating fish, they are encouraged to up their intake.

In 2017, over 467,000 tonnes of seafood were purchased by consumers in Great Britain, which was 0.4% less than the previous year (Seafish 2020). In 2015, each person in the UK ate an estimated 161g of seafood per week. This amounted to an average of 1.15 portions per person per week (based on a 140g portion size) (Defra 2015).

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4 Methodology

This chapter provides details of the methodology applied for the SIF Baseline Review. The overall aim of the SIF Baseline Review was to generate a “review of the state-of-the-art technologies and innovations from around the world that are relevant to the UK fisheries, aquaculture and seafood industries.”

The outputs of the review are intended to:

1. Guide the assessment of submitted SIF proposals through providing wider context on the state of innovation.
2. Inform on priority areas for funding.
3. Ensure funding is awarded to truly innovative projects.
4. Identify gaps in specific topics on which proposals will be encouraged.

With these practical objectives in mind, it was agreed with Cefas that the research approach should focus on generating an overview of the main innovations and research avenues currently being pursued, to address high priority challenges for UK seafood sector. It should be noted that the aim of the review was not to produce a systematic literature review as such in-depth reviews can take many person months for each topic – which was not compatible with the time and resource available for the Baseline Review and was not necessary for the applications listed above.

4.1 Process overview

An overview of the SIF Baseline Review process is shown in Figure 4-1, which is described briefly here.

A long list of challenges facing the UK seafood sector was presented to the SIF Steering Group. From this long list, 20 challenges were selected for the review through discussion with the SIF Steering Group. For each challenge, a range of primary and secondary sources of information were reviewed in order to understand recent innovations and research developments. Draft chapters covering each of the 20 challenges were submitted to Cefas and the SIF Steering Group for feedback. A further round of interviews was conducted with external experts as part of the ‘ground truthing’ exercise to ensure that no significant innovations had been overlooked. Further details of each of these activities can be found in the following sections.

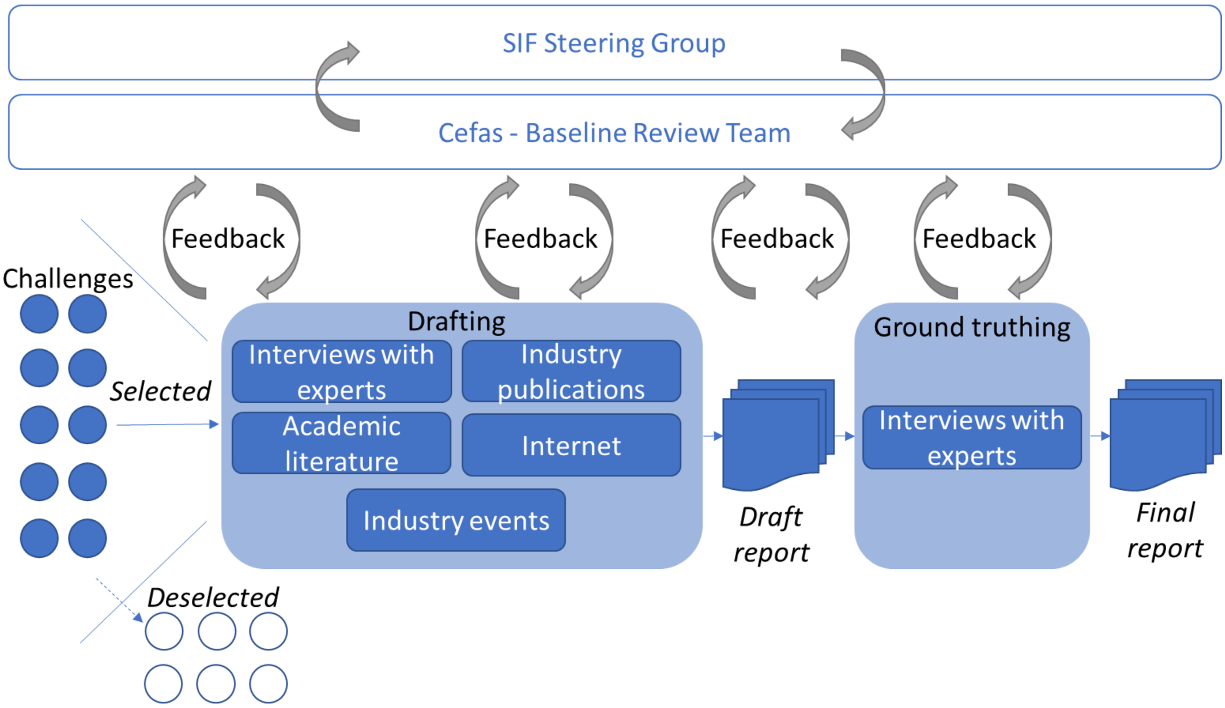


Figure 4-1: Overview of the methodology applied during the SIF Baseline Review.

4.2 Scope definition

At the start of the review, a long list of over 40 ‘challenges’ facing the UK seafood sector was identified by Strategic Innovation, covering the themes of ‘marine and diadromous fisheries, ‘marine and land-based aquaculture’, ‘onshore supply chains and added value production’ and ‘policy and cross-cutting issues’. Through discussion between the SIF Steering Group and Cefas, 20 challenges were identified for investigation, taking into account the main objectives and aims of the SIF programme. The ‘policy and cross-cutting issues’ theme was replaced by the theme of ‘climate change’ after the mid-term review meeting, and two new challenges added: ‘climate change mitigation’ and ‘climate change adaptation’. In total 22 challenges were addressed under the SIF Baseline Review and are shown in Table 4-1 below.

Table 4-1: Themes and challenges selected and deselected from the scope of the review.

Marine and diadromous fisheries	Marine and land-based aquaculture	Onshore supply chains and added value production	Policy and cross-cutting issues (Climate change*)
Selected Challenges - Illegal, unreported and unregulated (IUU) fishing and vessel monitoring - Fishing effort and fuel consumption - On-board processing - Selectivity of gear and reduction of unwanted catches - Fish welfare - Habitat, environment and ecosystem impact - Ghost fishing and marine litter **Deselected Challenges** - Biodiversity and ecosystem effects - Stock assessment - Stock management - Fleet management - Fish finding technologies - Freezing and cold storage - Vessel design - Bycatch and discards - Worker welfare	**Selected Challenges** - Species diversification - Nutrition and feeding - Farmed animal health and welfare - Pest and disease management - Environment and ecosystem monitoring and impacts - Production and handling technologies - Genetic improvement - Management and valorisation of wastes **Deselected Challenges** - Precision farming - Resource management and the circular economy - Improvements to production efficiency - Resilience to climate change	**Selected Challenges** - Processing technologies - Sustainability accreditations/labels - Quality and food safety management systems and accreditations - Waste reduction and valorisation - Packaging technologies **Deselected Challenges** - Blue clusters - Changes in consumer preferences - Freezing and cold chain management	**Selected Challenges** - Climate change mitigation* - Climate change adaptation* **Deselected Challenges** - Impact of Brexit - Traceability - Marine planning and development - Emerging Technologies - Governance (e.g. of aquaculture) * Renamed/added after mid-term review

4.3 Innovation identification strategy

A variety of primary and secondary data sources were used to identify relevant innovations. The use of a broad range of sources was necessary to ensure that the review covered all the major types of innovation and research developments for each challenge. Here we present further details of how each of the data sources were used to identify relevant innovations.

General internet research - For each challenge, research was initially conducted using information freely available on the internet. This enabled the researcher to get a good overview of the challenge, including identifying key manufacturers, research organisations and recent news stories related to the challenge. This overview was then used to inform a list of keywords and search terms that were used to search academic publication databases.

Academic publication databases - Searches were conducted using the following academic publication databases:

- Aquatic Science & Fisheries Abstracts – 2.5 million references within the aquatic science domain.
- Google Scholar – Approximately 160 million references from all fields of science.
- DeepDyve – 18 million full paper articles covering all fields of science.

Challenge-specific search terms were generated based on the keywords identified from the general internet research. The primary exclusion criteria for these searches were articles published before 1st January 2015. Some references from before this date were included where they present key examples of innovations that had not been launched commercially by 1st January 2015 or where they provided useful background information for a challenge.

Beyond publication date, no other hard exclusion criteria were applied as the aim was to identify as many relevant innovations as possible. However, when selecting which abstracts to access and read full papers for, priority was given to:

- Articles that appeared to describe a novel technology to address the challenge (rather than articles discussing policy measures or methodological issues).
- Review articles – which were helpful in efficiently capturing a wide range of innovations.
- Articles with a high number of citations.
- Articles published in journals with a high ‘impact factor’.

Interviews with experts – People with relevant expertise in each of the challenge areas were identified from scientific publication records, internet research, recommendations from the SIF Steering Group, and recommendations from other interviewees. A total of 25 academic experts from reputable universities in the UK, the USA, Scandinavia and Asia were interviewed as well as eight experts from different NGOs and associations. A total of 18 experts from industry, across manufacturing, processing and packaging were also interviewed. Interviews typically lasted between 25 and 60 minutes and focused on:

- The recent innovations and research developments they had personal experience of.
- Any other innovations in the field that they were aware of.
- The current status of the innovations mentioned in terms of technology readiness or adoption in the seafood sector.
- Their opinions as to the most promising innovations and research developments.
- Identification of any significant knowledge gaps.

Typically, one or two experts were interviewed per challenge. Additional interviews with experts were conducted as part of the ‘ground truthing’ activity, which is described in section 4.5.

Patent databases – Patent searches were conducted using the patentinspiration.com patent search portal. The search terms created for the academic publication databases were re-used for these searches. For relevant patents, further research was conducted to establish the commercialisation status of the technology; for example, by looking up the organisation that registered the patent and searching for references to the technology in their product portfolio or news items.

Trade events - Members of the research team attended the “Aquaculture Europe 2019” (7-10th October 2019 in Berlin) and a meeting of the Seafish “Common Language Group”. A variety of innovations and relevant experts were identified from the presentations and exhibitors at these events.

Trade news publications – The news archives of trade publications including ‘Undercurrent News’ and ‘Intrafish’ were searched for each challenge. This source proved effective in identifying innovations being trialled in industry and recently launched innovations as innovators often seek publicity in trade publications as part of their marketing strategy.

4.4 Innovation evaluation

A basic evaluation of each innovation identified was performed to estimate the potential performance gain and technical risk associated with widespread adoption of the innovation in the UK seafood sector as well as the Technology Readiness Level (TRL). Further details of the innovation evaluation process and background are provided in the following chapter.

4.5 Reviewing and validation

The content of this report went through several rounds of review and validation before finalisation. Here we present an overview of the review and validation activities.

4.5.1 Reviewing during the initial research phase

Once a chapter on a challenge was drafted, it was submitted and presented to the SIF secretariat in bi-weekly meetings. The chapter then went out for review by the SIF Steering Group. When feedback and comments were received that identified gaps in the range of innovations covered or highlighted errors or lack of clarity in the language used, these comments were addressed. Some feedback and comments were not addressed as they represented personal opinions or anecdotes that could not be verified or requested additional information which was beyond the scope of this report.

4.5.2 Mid-term review meeting

The mid-term review meeting was held on 14 January 2020 in Bristol and was attended by the SIF secretariat, the SIF Steering Group and the report authors from Strategic Innovation. An overview of the draft chapters for each of the 20 challenges was presented. The two major outcomes from this meeting were:

- The addition of two challenges to the scope of the report - namely ‘climate change mitigation’ and ‘climate change adaptation’.
- A request for ‘ground truthing’ interviews to be completed with topic experts to reduce the risk of significant innovations or research developments being overlooked.

4.5.3 Ground truthing interviews

For the ground truthing interviews, typically one or two topic experts that had not previously contributed to the review were identified and interviewed for each challenge. Typically, the interviewees were sent an overview of the innovations captured in the draft chapter in advance of the interview. During the interview they were asked to identify any significant categories of innovation that were missing from the current list of innovations captured. In a few cases, the experts were sent the entire chapter to read and provide comments.

4.6 Summary statistics for the report coverage

A total of 51 interviews with experts were completed and over 2,000 secondary sources were reviewed as part of the SIF Baseline Review. This led to the identification of 613 innovations across the 22 challenge areas and four themes. Figure 4-2 presents the distribution of the innovations across the four themes and includes a breakdown by performance impact rating.

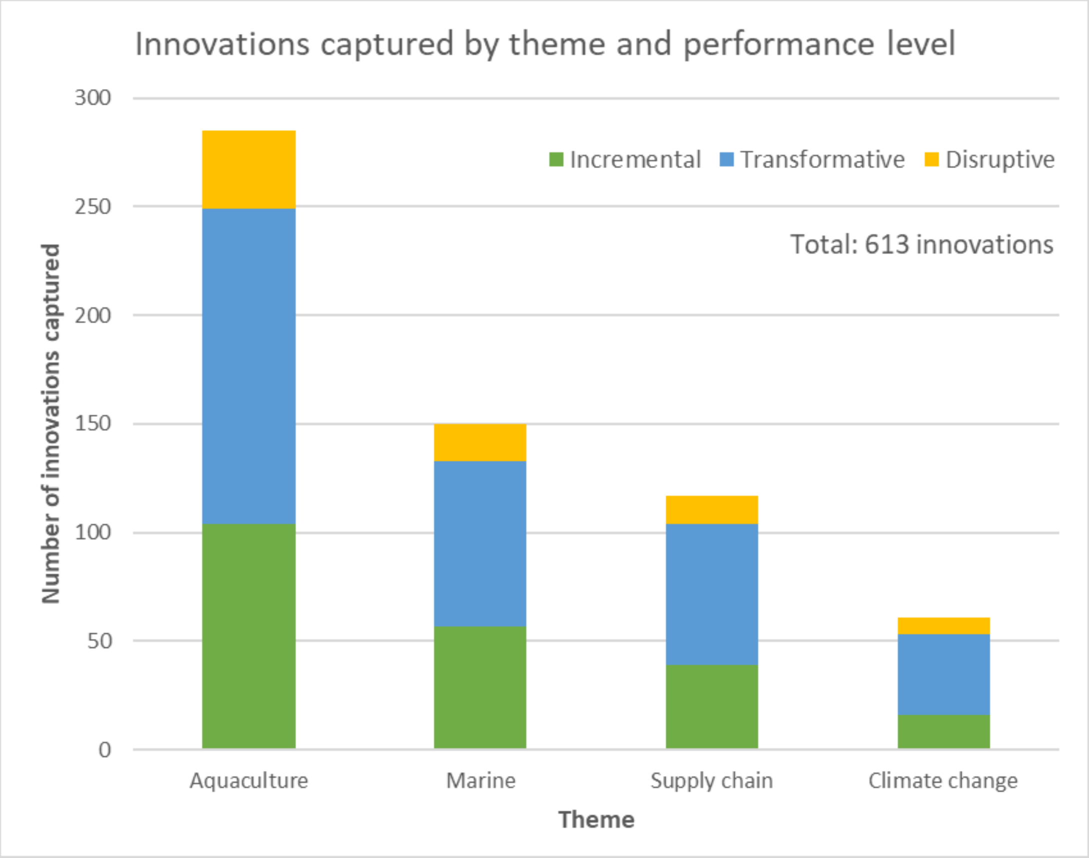


Figure 4-2: Breakdown of innovations captured by theme and performance level.

5 Innovation in the seafood sector

This chapter provides background information on how innovation is defined and evaluated and goes on to explain how this was applied during the assessment of innovations within the SIF Baseline Review.

5.1 Defining innovation

From SIF documentation, innovation "is considered here as new ideas, creative thoughts, new imaginations in the form of technology or method. Such innovation takes place through the provision of more effective products, processes, services, technologies, or business models that are made available to markets, governments and society. An innovation is something original and more effective and, as a consequence, new, that "breaks into" the market or society. The SIF programme is aiming to attract innovative ideas at Technology Readiness Levels (TRL) 3-7".

In literature there are many other definitions of innovation (Christensen 1997; Dorst 2011; Mann 2014; Tidd and Bessant 2018) and we can best explain in graphical form in Figure 5-1.

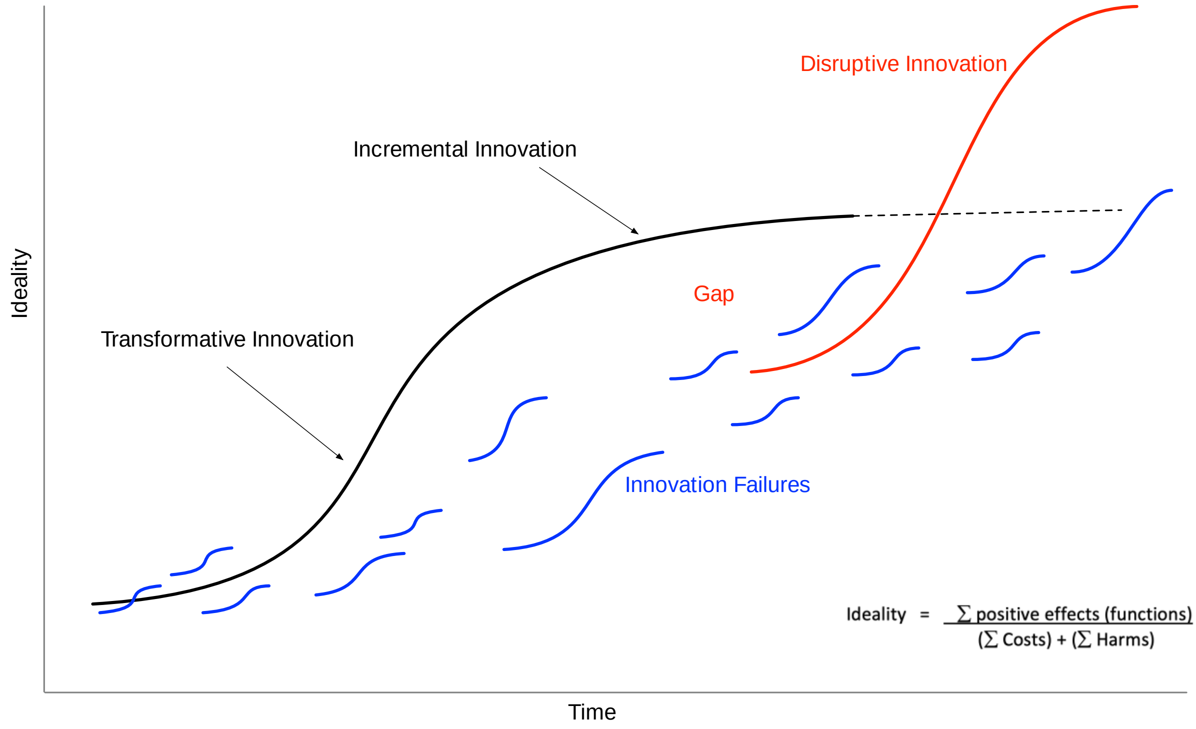


Figure 5-1: 'S-Curves' of innovation over time.

The y-axis “ideality” concept comes from the TRIZ systematic innovation approach. Ideality could be described as the “main parameter of value” in performing a **function** (Mann 2014). It is the balance between the positive and negative aspects of performing the function from the perspective of the consumer or decision maker:

$$\text{Ideality} \quad = \quad \frac{\sum \text{positive effects (functions)}}{(\sum \text{costs}) + (\sum \text{harms})}$$

The **black curve** in Figure 5-1 demonstrates how system ideality evolves over time in the manner of an S-Curve. The development steps that apply to the core principle / technology of the system can be considered sustaining, or **incremental innovation**. These developments are usually conducted by the players within the incumbent industry at the sub-system level. Technologies that make a significant improvement within the black curve paradigm, particularly in the fast-improving middle section of the S-Curve, can be considered **transformative innovation**.

The **blue curves** are attempts to fulfil the same function, but using an alternative core approach, technology or principle. These are often the “**innovation failures**” in a sector. They may fail before launch or fail in the market. These can also successfully create a small niche, which is commercially viable and survive, but ultimately not threatening to the incumbent black curve. They are typically introduced by start-ups or niche R&D based initiatives from large organisations. Analysis shows that many failures are not due to deficiencies in the technical idea itself but failures in marketing, operations, route to market or being ahead of their time.

At some point, a new technology or approach is introduced, that initially appears to be another blue curve, and less ideal than the incumbent, but is fundamentally more capable of achieving higher ideality. Although, initially suffering from a gap through disadvantages, such as lack of scale, limited market presence and under direct threat from the incumbent industry, this new innovation starts to outperform the incumbent technology and eventually dominates the market – becoming **the red curve**. There are many examples; communication (wired phone → mobile phone → smart phone), transport (steam → internal combustion → electric vehicles), vacuum cleaning (bags → bagless) etc. These are **disruptive innovations**.

When considering an innovation proposal, the first step is to understand the primary function being delivered, and secondly what type of curve the proposal likely represents:

- **Black Curves** – helping existing seafood players to deliver their core function in a way that enhances the positive effects/functions and minimises costs and harms.

- **Blue Curves** – identifying opportunities that can either find a niche to survive in or have the potential to turn into a red curve.
- **Red Curves** – helping innovations to progress up the red curve and prevent them from turning back to blue.

5.2 Modelling the innovation process

A lot of academic research on innovation has focused on describing and developing models of innovation with the aim of supporting organisations to reduce the number of failed innovation attempts and increase the likelihood of developing a disruptive, 'red curve' innovation. These models tend to focus on the sequential steps from insight or idea through to product launch (Design Council 2007; Dorst 2011; Tidd and Bessant 2018). There are many interpretations, that are often graphically represented as a pipeline, funnel, or diamond shape, such as Figure 5-2.

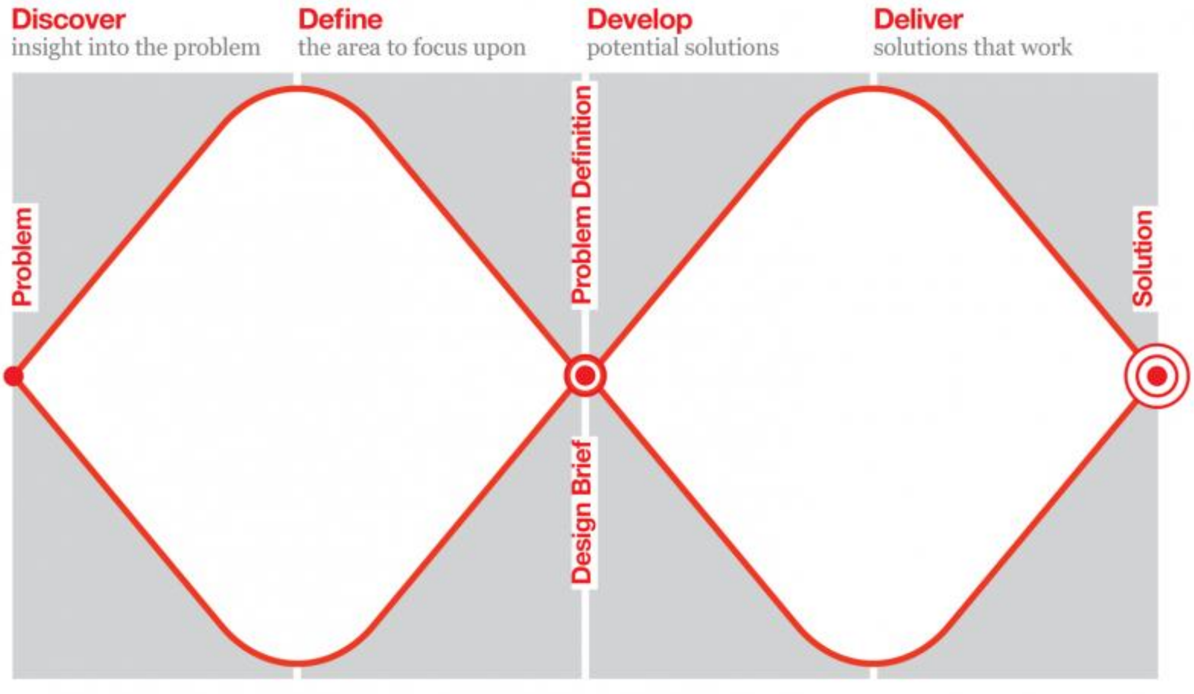


Figure 5-2 Double diamond model of the innovation process (Design Council, 2007).

These sequential models are useful in managing innovation projects at the operational level, but typically do not fully consider the strategic landscape or the capability of the organisation to deliver the innovation. Hence, although these sequential models of innovation may help to complete an innovation project faster and more efficiently, they do not always increase the probability of innovation success because, as the saying goes, “a great solution to the wrong problem is the wrong solution”. A seafood innovation project may appear to offer an elegant technical approach but would be of limited value or merit if solving the wrong problem. A more holistic systems approach is therefore needed to complete the understanding (Beer 1972). The ‘Box Model’ of innovation was developed by Frobisher (2010) to address this need.

Based on the IDEF0 functional modelling approach (KBSI Inc. n.d.), the Box Model describes innovation in terms of the inputs, controls, means/mechanisms and outputs of the ‘innovate’ process as shown in Figure 5-3.

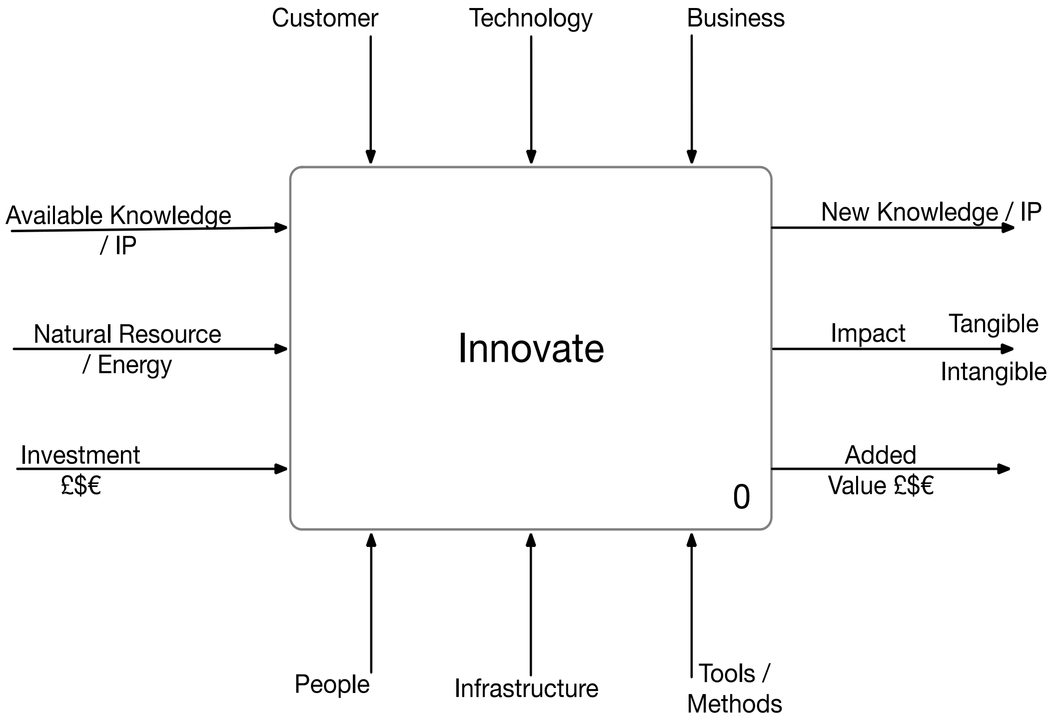


Figure 5-3: The ‘Box Model’ of innovation (Frobisher 2010).

It reveals that there are three categories of inputs to the innovation process: available knowledge (including e.g. Intellectual Property (IP)), natural resources (including e.g. energy), and investment. Through the innovation process, these inputs are transformed into the outputs of; new knowledge / IP, impact (tangible and intangible) (Amabile and Kramer 2011; Mann 2009) and financial added value.

In the context of SIF, the flexibility of the model means that it could be applied at the UK seafood sector level, as well as to sub-sectors and individual companies. The SIF Baseline Review could be considered to contribute primarily to the available knowledge/IP input arrow, expanding and making accessible the global state of knowledge. The purpose of the SIF could be described as taking this knowledge input along with the natural resources of the sea and using the investments by the fund in such a way as to maximize the desired outputs from the sector (e.g. nutritious and sustainable food, revenue, jobs etc.).

Figure 5-4 shows a summary level application of the Box Model to the UK seafood sector.

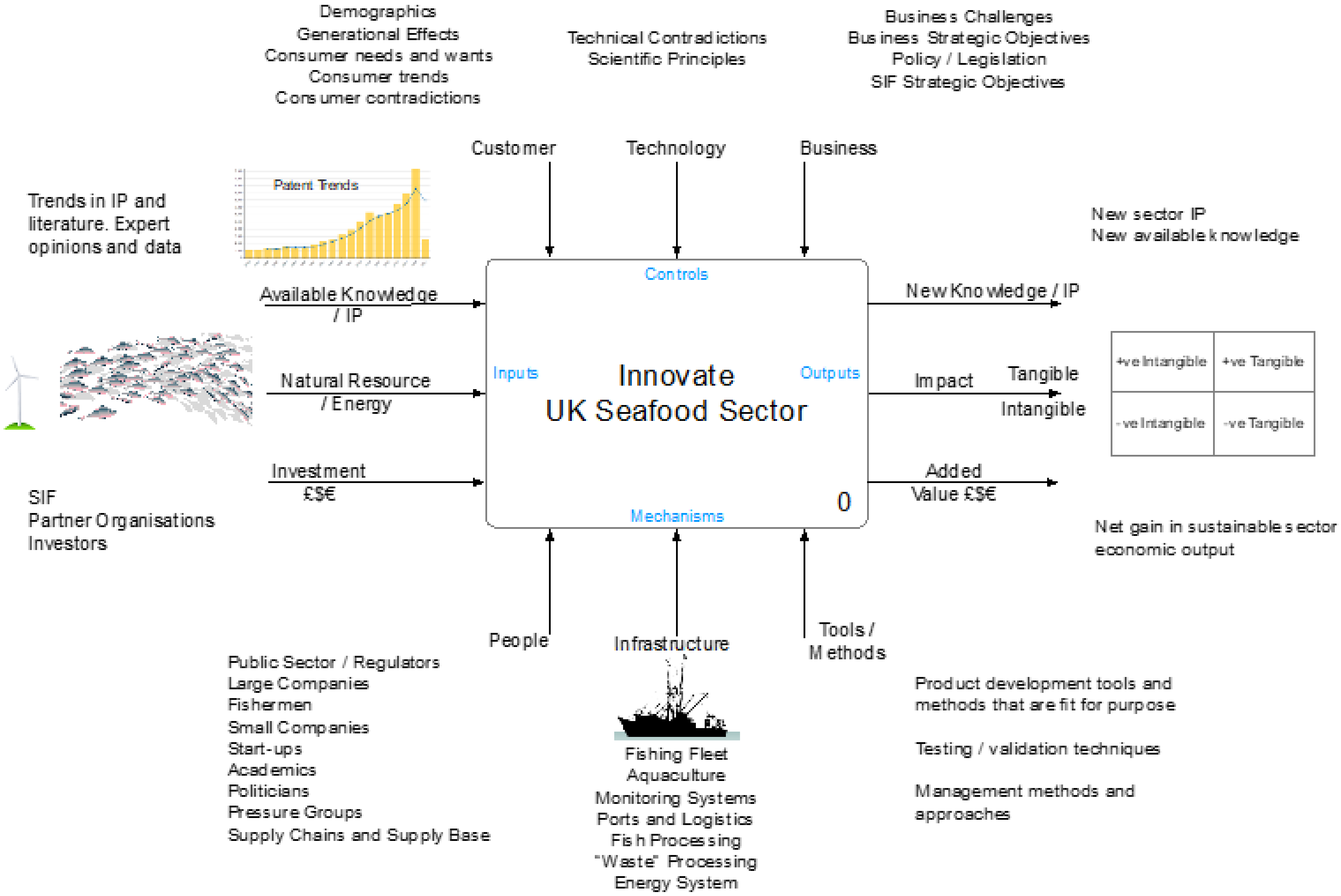


Figure 5-4: Summary of the Box Model applied to the UK seafood sector.

5.3 Understanding success and failure of innovations using the Box Model

The Box Model of innovation is a useful framework for understanding why some innovations are successful and why some fail.

Successful innovations are those which positively affect the majority of the box arrows, particularly those that match a trend or solve a contradiction within the control arrows (customer, technology, business) (Frobisher 2010). Successful innovations also have the means to execute the new idea, including the combination of capable people, infrastructure and tools/methods and access to sufficient funding, or a compelling cost advantage through increased revenue or reduced production costs (Mann 2014).

Unsuccessful innovations, that either fail completely or fail to scale, are those that either do not sufficiently address a contradiction in the control arrows or do not possess the means to execute them e.g. due to an insufficiently broad skill base of the people, inadequate infrastructure or insufficient funding. Many innovations also fail due to regulatory considerations that prevent implementation.

Hence, with the holistic overview provided by the Box Model, it is easier to evaluate and compare innovations by identifying the issues that might prevent an innovation from becoming widely adopted ('blue curves') and recognise the innovations that appear to hold a strong position (potential 'red curves').

Applying the Box Model requires information concerning the inputs, controls, means/mechanisms and outputs of the innovation activities in a particular field – as presented in more detail in

Table 5-1.

	Description
Inputs	*Available Knowledge / IP* – How quickly is new knowledge being generated in terms of scientific publications and patents? Is there significant "unavailable knowledge" e.g. trade secrets?
	Natural Resources / Energy – primary natural resources consumed by the activity, and if energy consumption is a significant factor.
	Investment – Trends in investment in the area where available data exists.

Controls	*Consumer / Customer* – To what extent are end consumers involved / affected by the technology, and if so, what are the primary related consumer trends and contradictions?
	Technology – What are the core technology approaches used? E.g. biological, chemical, physical, fields (i.e. laser, ultrasound etc.). Is the idea solving a technical contradiction?
	Business – What are the main influencing factors for business? E.g. legislation, cost reduction, production efficiency / yields and the strategic ambition of the management team.
Means/ Mechanisms	*People* – Key players – academics, companies, experts, suppliers - are these people / organisations credible? Demonstrating the required broad range of skills for development and introduction – execution.
	Infrastructure – key processes / plant / equipment required (can be multiple types for different approaches).
	Tools / methods – Notable methods / techniques required – such as diagnostics, testing methods, production methods.
Outputs	*New Knowledge / IP* – Is knowledge in the area likely to increase or decrease?
	Impact – What impact is the activity in the area already having and likely to have on the tangible or intangible outcomes? Most likely to be addressing the contradictions expressed in the controls.
	Added Value – Will it lead to increases in sales volumes, increases in prices, reduction in costs through lower energy use, less labour cost, increased yields?

Table 5-1: Details of the parameters used within the Box Model analysis.

The following sub-sections provide simplified examples of how the Box Model can be used to assess innovations, providing an indication of the characteristics of successful and unsuccessful innovation attempts.

5.3.1 Examples of recent successful innovations

The following are examples of innovation attempts that the Box Model analysis suggest are in a strong position. They have not necessarily yet taken a ‘red curve’ position but appear to be capable of doing so.

Steerable Trawling Systems. The ability to keep a constant distance from the seabed and hence not impact the seabed. **‘**Blue curve’ with potential for turning to red should the proponents be able to articulate the business case to potential customers given the significant upfront costs.	
Controls	Aligned with informed consumer and retailer requirements to reduce bycatch. Solves technical contradictions relating to the core function of capture, increasing efficiency and reducing bycatch, although increasing complexity. Aligned with business objectives and legislation.
Means	Technical teams are capable, although question marks over abilities to promote adoption. Using existing infrastructure and off the shelf core technologies adapted to a new purpose. Manufacturing capacity / capability unknown. Methods appear to have further scope for development.
Inputs	Adequate funding has been available for development. Built on knowledge from research and know-how. Relating to natural resource of demersal species.
Outputs	Reduces costs from fuel economy (drag), improved selectivity and catch value per trip. Tangibles - increases safety onboard, Intangibles – pride and sense of progress / control.

Processing boats for aquaculture. Processing boat enables slaughter and processing in large, converted “well-boats” on site. The next step towards red curve status will occur if smaller, more cost-effective boats are developed.	
Controls	Solves several technical contradictions concerning the speed and efficiency of slaughter, processing and logistics. Legislation and tax regime concerning may be more attractive after Brexit. In line with business objectives.
Means	Achievable with existing people skills, new infrastructure is modification from existing, but steps needed to “miniaturise” the processing boats.
Inputs	Funding not an issue so far – details unknown. Unclear if new, smaller boats are in development and the investment required.
Outputs	Smaller carbon footprint and improved disease control. Shortens processing time. No need for crowding, starvation, loading and unloading in order to transport the fish for slaughter. Improved animal welfare with very few mortalities.

Fish Protein Hydrolysate (FPH). Several companies have developed similar industrial processes to convert fish processing waste into silage products for animal feed (ruminant, poultry, fish) and organic soil improvers. Sold in liquid form but can also be dried to powder. Currently a blue curve in a successful niche. Opportunity for FPH to scale if an ambitious new entrant takes it on, or incumbents see an opportunity, potentially driven by legislation or initiatives centred around the environmental benefits.	
Controls	Aligned with consumer sustainability trend. End users (e.g. farmers) gain significant advantages over existing products. Solves multiple technical contradictions compared to fishmeal i.e. nutrition vs energy, aligned with business objectives and legislation.
Means	Capable teams, but limited ambition to scale. Using off the shelf processing technology/infrastructure. Scalable and cheap technology. Using in-house tools and methods. At the sector level, fishmeal (black curve) incumbent infrastructure is “locked in”.
Inputs	Developed from initial know-how and IP. Capital investment significantly lower than for fishmeal, scalable. Industrial enzymes are standard.
Outputs	New know-how / knowledge, with potential for considerable further product development. Shown to reduce enteric emissions from ruminants, increase fatty acid content in eggs, milk and meat, improve soil fertility and significantly reduce carbon footprint. New businesses are profitable.

5.3.2 Examples of innovations with limited implementation, failed to scale up and be brought to market

The following are examples of innovation attempts that the Box Model analysis suggests face one or more significant barriers that are currently preventing them from turning into a ‘red curve’. This does not mean that they will not become successful innovations in the future if they are able to address the barriers they currently face.

Insect protein-based feed. There has been considerable research and commercial interest in the potential of insect-based protein to support food production, either as a feed source or for direct human consumption. Research and development into the use of protein derived from insects such as the black soldier fly and meal worm has been gaining traction. This will remain a blue curve – potentially with successful niche players, until satisfactory input waste streams are established, and regulatory framework is favourably reconfigured.

Controls	Retailers are still unsure about the market acceptability of insect feed usage. Appears to resolve several important customer and technical contradictions concerning nutrition vs environment. Regulations – insect-based proteins are not allowed to be used as feed for poultry and pigs in the EU and were banned for fish until 2017, regulation prevent use of the lowest cost waste stream inputs.
Means	People directly involved appear to have required technical and business skills. Production processes and methods are established at scale, but demand is limited therefore not achieving full economy of scale.
Inputs	Waste streams such as supermarket and catering waste are the most ideal feed for insect larvae, but sources of consistent supply appear limited and problematic at scale. (brewery and distillery waste are already widely and directly used in poultry and salmon feed). Sufficient investment funding appears available for the concept.
Outputs	Significant knowledge and IP have been developed. Environmental impact is positive given the right inputs. Profitability is not sufficient to escape a blue curve categorisation. Cannot yet command premium pricing but cannot also achieve economies of scale to achieve competitive pricing.

<table>
<tr><td colspan="2">Pulse trawls for brown shrimp. Pulse trawling has been identified as a potential means to improve selectivity; startle pulses mitigate negative side-effects on non-target species. A blue curve that needs a fundamental shift in the ability to control fishing, as it is in effect too good.</td></tr>
<tr><td>Controls</td><td>Consumer preferences unknown, but theoretically is aligned with low impact fishing. Legislation - was banned in the EU in 1998 due to concerns about the very high fishing efficiency and effect on other demersal and benthic species. Partial exemptions to the EU ban were introduced in 2009, which has enabled further development of the gear and testing. High efficiency is in line with business objectives.</td></tr>
<tr><td>Means</td><td>Small number of people involved but with high technical skill. Question marks over business skills to manage the downsides of the technology. Gear appears well developed, as well as methods to achieve high efficiency, but lacking in surveillance techniques.</td></tr>
<tr><td>Inputs</td><td>High efficiency reduces fuel consumption per unit catch and reduces bycatch significantly. Investment appears forthcoming if allowed to proceed.</td></tr>
</table>

Outputs	New knowledge and IP have been developed. High trawl efficiency = high profitability. From 35% and up to 76% reductions in small shrimp and fish discards respectively. Significantly reduced benthic impact. Negative outputs are primarily due to ‘human error’ i.e. taking advantage of the exceptionally high technical efficiency. Legislators are likely fearful of reputation due to prior problematic implementations.

<table>
<tr><td colspan="2">AQUAPONIC SYSTEMS. In principle, aquaponics (fish in aquaculture and wastewater from fish used as fertiliser for plants) looks like a good system. There have been a multitude of inventions, trials and young start-up companies in this space over the last 10-15 years, but none of them really succeeded or “took off” - all blue curves. A significant shift in consumer demand specifically for aquaponic products at profitable price levels, favourable shift in legislation or breakthrough in production costs is required to take the market.</td></tr>
<tr><td>Controls</td><td>In line with consumer preferences. Technical contradictions appear to have not been adequately addressed. Principle is in line with business objectives, but profitability not established. No concerns on legislation.</td></tr>
<tr><td>Means</td><td>People seem technically competent but lacking in production / business skill. Infrastructure appears to need development, but there is nothing inherently new. Methods are probably insufficiently developed.</td></tr>
<tr><td>Inputs</td><td>Based on ancient technology and activity in the sector has been ongoing for many years to build a knowledge / IP base. Investment appears to be forthcoming but questions as to if it has been sufficient to achieve economies of scale.</td></tr>
<tr><td>Outputs</td><td>New knowledge / IP is being developed; impact is positive in terms of environmental considerations. But overall process efficiency is not sufficient to offer pricing to deliver sufficient profitability to escape the blue curve.</td></tr>
</table>

<table>
<tr><td colspan="2">Closed pens - Aquaculture. Improved physical containment at marine fish farming sites is a central recommendation of many international experts and forums on the environmental impacts of escapees and transfer of potential pest and disease (e.g. sea lice). Solutions piloted so far are bulky concrete pens.</td></tr>
<tr><td>Controls</td><td>Limited consumer awareness but may be associated positively with consumer trends. Technical contradictions are not resolved in an ideal manner. Not fully aligned with business objectives due to high investment costs and uncertainty.</td></tr>
</table>

	Legislation is neutral at present; future regulations may tip the balance towards this technology.
Means	Technical skills are sufficient but lacking in developing a clear business case and marketing plan. Infrastructure is simple, but costly. Methods are an improvement over incumbent systems, and some maintenance costs are avoided.
Inputs	Investment case is inadequate therefore funding is inadequate.
Outputs	Limited unique or protectable IP – simple to copy. Ecological impact is positive; reduction in escapes and transmissions between farmed and wild animals, installation further out to sea reducing coastal impact and eliminating issues with nets. High cost of the infrastructure is the main barrier to implementation, and the concept is stalled unless dictated through regulations or able to be marketed at a price premium through retailer / consumer preference as otherwise, the cost benefits are insufficient. A typical blue curve.

5.4 Evaluation of innovations within the SIF Baseline Review

A full 'Box Model' analysis of each of the 613 innovations identified was beyond the scope of this review. Instead, the focus has been on evaluating the technology aspects of the innovations. This section provides an overview of how a simplified evaluation system was developed with the aim of enabling the reader to quickly gain an understanding of the status of technical developments for each challenge.

Each innovation was assessed against two main parameters; the potential impact on the performance of the UK seafood sector in terms of the specific challenge addressed by the innovation and the level of technical risk. For each innovation, the performance parameter was evaluated by asking the question 'to what extent could this innovation have an impact on this challenge?' The potential impact on the UK seafood sector was then rated using the following guidelines:

- **Disruptive** – desired function is delivered using a novel solution principle to conventional systems and offers potential for step-change performance improvement or cost reduction compared to current performance in the UK
- **Transformative –** desired function delivered using existing solution principle but might provide significant performance improvement or cost reduction

- **Incremental** – desired function delivered using existing solution principle but might provide small performance improvement or cost reduction

The technical risk parameter was evaluated by assessing the Technology Readiness Level (TRL) and asking the question, ‘what is the risk that the innovation will not deliver the expected performance gains due to technical issues?’ The technical risk from the perspective of the UK seafood sector was then rated using the following guidelines:

- **Low** – If the global TRL is high, current research/development is focused on environments or species that are similar to UK (e.g. Norwegian salmon) and the technology is low complexity.
- **Moderate** – Anything in between the definitions for ‘high’ and ‘low’ risk.
- **High** – If global TRL is low, and current research/development is focused on environments or species that are dissimilar to UK (e.g. tropical shrimp) and the technology is high complexity.

N.B. Other types of risks (e.g. consumer acceptance, regulation, price fluctuations) are mentioned in the description of an innovation but were not considered in the assessment of the technical risk level.

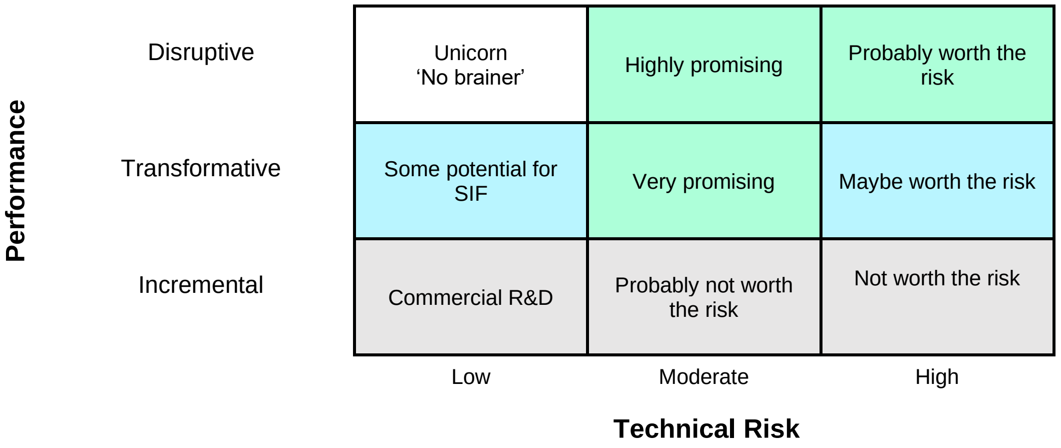
In many areas, a number of research studies and technology developers were identified that described similar innovations. Where possible, these have been clustered and captured as a single ‘innovation’ for the purpose of this report. In such cases, the performance and technical risk ratings assigned to these clusters are based on the leading example from those identified e.g. highest performance and lowest technical risk.

Table 5-2 provides an example of how the guidelines for assessing performance and technical risk of innovations can be applied to aquaculture fish feed. Relating this to the innovations S-Curves discussed earlier, the function of aquaculture fish feed is to provide nutrition, and the incumbent ‘black curve’ is fishmeal. An improvement to the efficiency of existing methods of fishmeal production, such as an improved screw cooker process, would classify as an **incremental,** black curve innovation. A new and fundamentally more efficient approach to fishmeal production may classify as **transformative**, as either a black or blue curve depending upon the core technology used. A new plant-based fish feed is likely to be a blue curve if it does not achieve the necessary nutritional function, but could be a **disruptive,** red curve innovation and eventually dominate the market if the nutritional functions are maintained together with reduced costs and reduced pressure on wild-capture fisheries.

Table 5-2: Application of the performance and technical risk rating guidelines to fish feed.

Fish feed for aquaculture			
Current solution	**Fishmeal production**	**Fishmeal production**	**Fishmeal production**
Proposed solution	**Improved screw cooker process**	**Improved fully automated fishmeal production system**	**Plant based feed**
Is solution principle different?	Yes, at the sublevel system	Yes, a system level	Yes, at supersystem level
Significant performance improvement or cost reduction?	Some cost reduction and lower energy use	Significant savings in energy, cost reduced plant size	Equivalent production costs, but addresses inherent strategic challenges in aquaculture sector
Performance improvement rating	**Incremental**	**Transformative**	**Disruptive**
Global TRL	7-8	5-6	3-4
Transferable to UK setting?	Yes, fully	Yes, fully	Potentially, species dependent
Technical complexity	Low	Medium	High
Overall technical risk	**Low**	**Moderate**	**High**

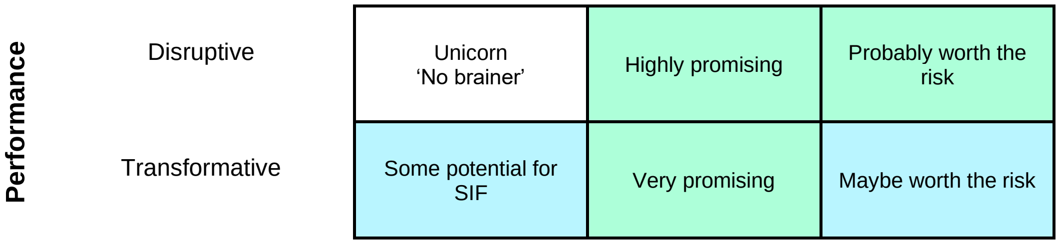
Having evaluated each of the innovations in terms of their potential performance gain and technical risk a summary table was created for each challenge in the form of an 'innovation matrix' – as shown in



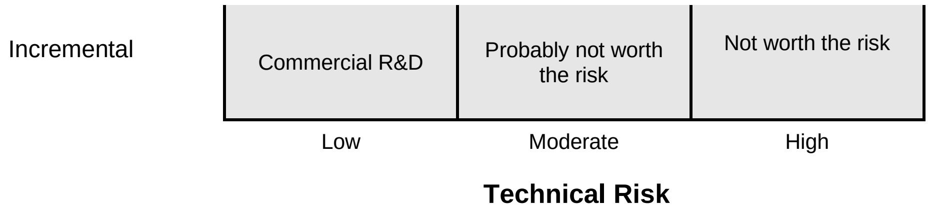
Performance	Low	Moderate	High
Disruptive	Unicorn 'No brainer'	Highly promising	Probably worth the risk
Transformative	Some potential for SIF	Very promising	Maybe worth the risk
Incremental	Commercial R&D	Probably not worth the risk	Not worth the risk

Technical Risk

Figure 5-5. The innovation matrix is used towards the beginning of each challenge chapter to summarise the innovations covered in the chapter and allow the reader to quickly identify the innovations that appear to be most relevant to the objectives of the SIF.



Performance			
Disruptive	Unicorn 'No brainer'	Highly promising	Probably worth the risk
Transformative	Some potential for SIF	Very promising	Maybe worth the risk



Incremental	Commercial R&D	Probably not worth the risk	Not worth the risk
	Low	Moderate	High

Technical Risk

Figure 5-5: Innovation matrix for the assessment of innovation in each challenge area.

The colour coding of the cells of the matrix provide an indication of the perceived fit to the objectives of the SIF:

- **Grey** - Innovations that deliver incremental performance gains are of great importance maintaining competitiveness in the context of ‘continuous improvement’ but are not the focus of the SIF as these opportunities can often be justified and implemented through commercial research and development activities.
- **White** - Innovations that have potential for disruptive performance gains and are low risk are very rare (‘Unicorns’) and are unlikely to be uncovered.
- **Blue** - Innovations that offer transformative performance gains but may be considered too low risk to justify public funding (e.g. technologies that are commercially implemented in other countries but have not yet been adopted in the UK) or are too high risk relative to the expected performance gains.
- **Green** - The best fit with SIF objectives. Innovations that would not ordinarily be self-funded through commercial R&D due to their technical risk but offer potential for transformative or disruptive performance gains.

It should be noted that the positioning of innovations within the innovation matrix are based on the existing examples of that type of innovation that were identified during the SIF Baseline Review. <u>These ratings will not be used as inclusion or exclusion criteria for SIF applications</u>. Each application to the SIF will be judged on its own merits in terms of its eligibility and fit to the SIF objectives.

5.5 Summary

- Innovations in the SIF Baseline Review are characterised as incremental, transformative or disruptive.
- Disruptive innovations deliver a core function in a fundamentally different way.
- Successful innovation always increases ‘ideality’ through resolving a contradiction.
- Unsuccessful innovation attempts mostly fail due to factors unrelated to the technical characteristics of the core idea, either due to unhelpful regulatory frameworks or poor execution.
- The ‘Box Model’ informs a more holistic understanding of the innovation process in comparison with traditional models and underpins the ranking approached used in the SIF Baseline Review.
- Interrogating each of the Box Model arrows helps to contextualise innovation opportunities.

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Theme 1: Marine and land-based aquaculture

6 Environment and ecosystem monitoring and impacts

Contents

From the SIF Executive Board

The method applied in this review has generated numerous examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently happening. It is recognised that there are existing innovations and research areas that are not included here, and new areas where future innovations may occur. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

6.1 Overview: environment and ecosystem monitoring and impacts

What is the challenge in the UK?

Main challenges with regards to environmental and ecosystem impacts are similar between countries with e.g. high scale production of farmed salmon in Norway, Chile and Scotland. For the UK, escapees, disease transfer from farmed to wild salmon, and the organic and foreign material outlet from marine aquaculture are the key challenges, antibiofouling material and medicines representing the biggest foreign material compounds.

What are the most promising innovation categories?

- Closed systems
- Biofloc technology
- Collection of fish farm waste
- Collection of biofouling cleaning waste
- Net grooming robots

Where are there important knowledge gaps?

- Cleaner fish welfare
- How to minimise the transfer of alien non fish species
- Biological control of biofouling

The phenomenal expansion of the aquaculture industry has not occurred without meeting a diverse array of sustainability-related challenges. Recent years increase in production has largely been achieved through intensification of existing marine based farming systems, resulting in a significant increase in feed requirements, higher risks of escapes, disease outbreaks and impacting surrounding environment and ecosystems. Globally, feed is still primarily fishmeal-based, which puts a strain on especially small pelagic fishes (Soliman, Yacout, and Hassaan 2017). Please refer to chapter 8 'Nutrition and feeding' for further information.

Over the years, there has also been a marked increase in the use of antibiofouling agents and antimicrobials with consequent antimicrobial resistance in many farming sectors and with that an increase in risks of antimicrobial resistance in humans through zoonotic diseases or through the transfer of antimicrobial resistance genes to bacterial pathogens of humans (Henriksson *et al.* 2018; Blanchard *et al.* 2017). This is particularly a problem in developing countries as in the West both the use of antibiofouling agents and antibiotics is controlled (personal communication).

An overview of the potential performance improvement rating of recent (2015-2019) innovations in environment and ecosystem monitoring and impacts of aquaculture are outlined in Figure 5-1.

Performance*	Low	Moderate	High
Disruptive		• Closed farming pens (deep-sea) • Biofloc technology	
Transformative	• Net groomers • Cleaner fish welfare • Modelling of pathogen transmission • Photodegradation • Electromagnetic wave sensing	• Improved digital monitoring and surveillance • Predator attack deterrents • Digital monitoring of bio-production • Cavitation based cleaning tech • Collection of cleaning waste • Advanced waste collecting systems	
Incremental	• Fish behaviour • Identification of farmed escapees • Non-biocidal coatings • Antibiofouling on farmed seaweed • Air exposure • Biofouling as a reservoir for pathogens • Reduce transfer of alien non-fish species • Indicator species & behaviour • Benthic Flux Sampling Device • eDNA • Dual Frequency Identification • Dispersion modelling software	• Cleaning regime management • Different netting material • Natural compounds • Biological control • Standardised methodology for hydrophobic contaminants • Construction of wetlands	• Biocidal Coatings

Technical Risk*

Figure 6-1: Performance and technical risk ratings of innovations in ecosystem impacts of aquaculture.

**See section 4.4 for definitions of performance and technical risk rating scales.*

6.2 Escapees

Farmed escapees (at all life cycle stages) may result in both ecological (Jonsson & Jonsson, 2006; Thorstad *et al.*, 2008) and genetic interactions with wild populations (Ferguson *et al.*, 2007; Hindar *et al.*, 1991). In addition, impacts may extend beyond problems with direct biological impacts, including socio-economic (Liu, Olaussen, & Skonhoft, 2011) and general ethical issues (Olesen, Myhr, & Rosendal, 2011), general effects on local ecosystems (Buschmann *et al.*, 2006), and transfer of parasites to native populations (Krkosek, Lewis, & Volpe, 2005; Torrissen *et al.*, 2013).

The potential escape of salmon and cleaner fish from aquaculture along the coast of Norway is considered one of the key risks in the industry (Grefsrud *et al.* 2018) and globally significant numbers of fish escape every year (Cordis 2012; Glover *et al.* 2017), with actual escapes likely underreported (Taranger *et al.* 2015; Hathaway 2018; Intrafish 2019).

Innovation with a potential for disruptive performance improvement

Closed pens: Recapturing escaped fish from marine aquaculture is largely unsuccessful (Dempster *et al.* 2018). Improved physical containment at marine fish farming sites, through research and development of fish-farming technology, is a central recommendation of many international workshops and forums on the environmental impacts of escapees. Scotland and Norway both have engineering standards that dictate the expectations on use of equipment (anchors, nets, tensioning systems etc.), all designed to optimise productivity and minimise losses through escapes (personal communication). Also, current developments to place the pens further out at sea will minimise coastal environmental impact. Examples of closed systems include raceways and recirculating systems on land (Eurofish Magazine 2019) but there are also further developments in closed pens at sea e.g. Aquapod. Please refer to chapter 10 ‘Production and handling technologies’. Typically, high cost is the main barrier to implementation.

Technology Readiness Level: 9; Technical risk: Moderate

Innovation with a potential for transformative performance improvement

Digital monitoring of pens: Aquaculture farms in Norway have seen the greatest advancement in containing escapes through the introduction of new netting techniques and other advanced technology such as the Deep Trekker underwater drone, known in the industry as a Remotely Operated Vehicle (ROV), and drop cameras ('The Ultimate Aquaculture Underwater Drone Package | Deep Trekker' n.d.). By using an ROV, such as the DTG2, site managers have the ability to dive below the water and quickly identify possible threats to their stock, mooring lines, and netting. With this immediate insight, they are able to respond quicker to any inherent situation before it progresses into a larger problem.

Technology Readiness Level: 9; Technical risk: Moderate

Predator attack deterrent systems: Attacks by predators typically lead to holes in the nets, large enough for fish to escape. There is a vast array of academic research on acoustic and other deterrent devices for marine mammals. Using ultrasonic transmission as e.g. developed by OTAQ, SealFence creates an acoustic "fence" of protection around cages as a deterrent against seal and sea lion attacks. Initial studies have shown that there is little effect on other animals as the ultrasonic waves are very local to the aquaculture pens and thus, little effect on the wider environment.

Technology Readiness Level: 6-8; Technical risk: Moderate

Digital monitoring of bio-production: Processes and systems enabling computing devices to assist with risk management of bio-production of livestock and/or aquatic animals, including obtaining bio-production data. The computing devices may establish baseline data based on the bio-production data and may receive additional bio-production data (e.g., real-time data), and calculate a deviation from the baseline data, based on the additional bio-production data. Systems are designed so that the computing devices can provide a recommendation to a user device in response to a deviation (SmartCatch n.d.; Evensen 2015). There are continued efforts to develop Google Earth technology in the aquaculture sector with the aim to develop simple methodologies to assist especially developing countries to inventory and monitor aquaculture (Aguilar-Manjarrez *et al.* 2017).

Technology Readiness Level: 6-8; Technical risk: Moderate

Innovations with a potential for incremental performance improvement

Fish behaviour and farm management: There are several escape-related behavioural repertoires that fish can exhibit when interacting with the cage wall including i) general net inspection behaviour, ii) overt net biting that weakens the net and potentially leads to hole formation, and iii) the exploratory or risk taking behaviour exhibited when fish pass through holes in the net. There is limited research into how fish behaviour can be altered but this is a potential strategy to reduce escape incidences, appreciating that a many behavioural traits are species-specific. With regard to Atlantic cod, several of the involved behavioural mechanisms differ between genetic strains, and some individual fish are repeatedly more prone to escape through small holes in the net wall, probably due to differences in so-called boldness or willingness to explore new environments. Factors that promoted escape-related behaviours included both physical net traits and the motivation to feed e.g. prolonged periods of starvation (ca. 1 week) and also short periods of feed restriction leads to escape behaviour. Escape behaviours can be reduced by environment enrichment within the cages and also by keeping the net clean.

Technology Readiness Level: 3-5; Technical risk: Low

Identification of farmed escapees: Typically identified based on external morphological divergence from wild fish (e.g. body condition and fin erosion). More recent developments in fatty acid profiling makes it possible to identify early (those salmon having been in the wild for some time, a year or more before entry to freshwater) as opposed to late (those having recently escaped, and certainly the same year in which they entered the river) escapees accurately (Skilbrei *et al.* 2015). However, most farmed escapees do not survive in the wild and efforts are made e.g. through breeding triploid trout so that these cannot interbreed with wild fish (please refer to chapter 7 ‘Genetic improvement’ for further details).

Technology Readiness Level: 9; Technical risk: Low.

6.3 Antibiofouling

Traditionally, four main concerns are highlighted with regards to the growth of biofouling organisms on fish cages and infrastructure in finfish aquaculture: (1) modified hydrodynamics in and around the cage affecting water quality and the cage’s volume and stability; (2) increased disease risk due to biofoulers and associated pathogens; (3) behavioural impacts to cleaner fish used as biological control against sea lice; and (4) reservoirs for non-indigenous species (Bannister *et al.* 2019).

Several biofouling removal methods have been tested experimentally and used commercially with varying levels of success, including manual removal (Li *et al.* 2018), exposure to air (Hopkins *et al.* 2016), freshwater (L. Fletcher, Forrest, and Bell 2013), vibration (Choi *et al.* 2013), heat shock treatment (Sievers *et al.* 2019), organic acids and bases, pressure washing, applying various coatings, adding a culture medium (a substratum within suspended bag culture that physically dislodges biofouling), ultrasonic, negative pressure, suctions, UV and cavitation (as reviewed by (Albitar *et al.* 2016) and employing biocontrol (Shin *et al.* 2019; Sterling, Cross, and Pearce 2016; Bannister *et al.* 2019). In the following section the most promising methods are listed, however, all of the methods listed above have the potential for further development.

An interesting avenue of continued research, which may prove useful for many cultured species, involves combining multiple treatments (Bannister *et al.* 2019 and personal communication). This approach has considerable appeal as (1) it may be more effective against a broader range of fouling species; (2) treatments will be effective using lower chemical concentrations or temperatures when applied simultaneously (safer for farmers and the environment); and (3) the effective exposure times are likely to be shorter. For example, recent evidence suggests that combining heat and acid treatments is more effective against numerous fouling species at lower intensities than either in isolation (Sievers *et al.* 2019).

Innovation with a potential for transformative performance improvement

Net groomers: Technology research and development continues to offer alternative and better performing net cleaning equipment e.g. net groomers, crawl belts (e.g. ‘RONC’ by MPI, ‘NCL-LX’ by Yanmar) or propulsion units (e.g. ‘FNC8’ by AKVAgroup, ‘Manta’ by Stranda Prolog, ‘Stealth Cleaner’ by Ocein). Alternative systems apply suction parallel to (and potentially independent of) high-pressure cleaning (e.g. ‘MIC2.0’ by PFG group).

Technology Readiness Level: 9; Technical risk: Low

Cavitation: Other net cleaning systems rely on cavitation-based systems. While cavitation is quite common on solid surfaces such as ship hulls, often used via handheld devices or ROV ad-ons, it is currently not used for biofouling removal from fish net-pens (with potential exception of the ‘Net Cleaner 3’ from Cavitator[1]). There are a few handheld devices on the market, but on such a small scale it is of no relevance to the Norwegian or Scottish market. There are a few companies starting to develop larger rigs (similar to today’s net cleaners) e.g. Cavitator Underwater Surface Cleaners but very little seen on the market yet. The use of cavitation was recently tested by Stiftelsen for industriell og teknisk forskning (SINTEF) Ocean as part of a bigger project on alternatives ways to clean nets. Typical cleaning with high pressure removes coating and shortens the life of the net. Using cavitation, where energy from the implosion of bubbles remove the biofouling, showed similar effect in terms of removing biofouling but didn’t remove any coating (personal communication).

Technology Readiness Level: 6-8; Technical risk: Moderate

Cleaner fish welfare: For further detail, please refer to chapter 6 ‘Farmed animal health and welfare’. Measures of stress inform us how effectively a fish resists death and resets homeostatic norms when faced with noxious stimuli and stress indicators in fish is an area of research that has steadily grown with the aquaculture industry (Sopinka *et al.* 2016; Davis 2010). There is a very high mortality rate amongst cleaner fish due to stress (physiological and behavioural) and diseases. It is common with a 100% mortality rate for each rearing cycle of salmon at Norwegian farms and with the increasing focus on fish welfare as well as environmental impact, it was mentioned by interviewed experts working with the salmon farm industry in Norway, that the use of cleaner fish may well become heavily regulated and potentially phased out in the foreseeable future (personal communication).

Research has shown that cleaner fish show stress responses during first encounter with Atlantic salmon, while stress responses are reduced in experienced individuals, indicating habituation. It has therefore been suggested that behavioural and physiological stress in naive lumpfish should be taken account for when lumpfish are introduced in commercial sea cages to improve welfare for the species. A habituation period could be applicable during the rearing phase to moderate the transition from a simple tank environment with conspecifics only to interspecies interaction with Atlantic salmon in sea cages (Staven *et al.* 2019).

Technology Readiness Level: 6-8; Technical risk: Low

Collection of cleaning waste: The effect of cleaning waste on fish health represents a big gap. Experts commented that it is a known issue throughout the industry but there is little

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[1] Net Cleaner 3: https://www.youtube.com/watch?v=HDG_-z8-McE

quantifying research in Europe proving that the cleaning material once removed flows into the cage and can irritate gills, gill health and skin. Similar problems are known from New Zealand where they have problems with skin health due to cnidarians sitting on the net as part of the biofouling material, which is released during cleaning. The cleaning material can easily drift to the next farm and potentially spread disease etc.

One of the Australian Mic cleaning systems uses suction to collect the cleaning material but the system never managed to become established in Norway (World Fishing & Aquaculture 2015). It didn't work well with the Norwegian net systems as they are not rigid enough to provide the tension needed to handle the climbing Mic cleaning system with its high pressure water one direction and the collection system working in the other direction. There is a potential for someone to make a system that collects the waste and utilise this for e.g. fertiliser or fish feed. Current commercial systems 'semi-collect' the cleaning material into a pipe and the material is released away from the pen so it doesn't enter the net. Another example is the Norwegian company MPI[1] which makes net groomers that are popular on the Norwegian and Scottish market.

Technology Readiness Level: 9; Technical risk: Moderate

Innovations with a potential for incremental performance improvement

Cleaning regime management: A reduction in cleaning frequency would increase the life expectancy of anti-biofouling coatings. Some of the biofouling concerns with regards to cleaner fish are becoming controversial and there is scope for changing the current cleaning regime. Recent studies have shown that the presence of organisms associated with biofouling has a moderate, but positive, influence on the prevalence of sea lice in the lumpfish diet indicating that net cleaning might have a negative influence on lumpfish grazing (Eliasen *et al.* 2018). Based on these findings, the salmon producer HiddenFjord on the Faroe Islands reduced the frequency of net cleaning to allow biofouling to accumulate for the benefit of cleaner fish, reporting positive results (personal communication). One of the key benefits to

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[1] MPI: https://www.mpi-norway.com/products/jetmaster

less frequent cleaning is the reduction in loss rate of the antibiofouling copper coating. In Norway and Scotland, however, regular net cleaning remains the norm.

Technology Readiness Level: 9; Technical risk: Moderate

Biocidal Coatings: Alternatives to copper coatings is a research focus, especially since it was documented that around 25% of the copper coating is lost during the first cleaning and it is estimated that around 1000 tons of copper is released into the coastal waters of Norway every year. Alternatives to copper coatings include booster biocides (Druvari 2016). However, they still have a negative impact on environment e.g. copper pyrithione, zinc pyrithione, and tralopyril (‘Econea’ (Druvari 2016). There is a limited number of materials that are allowed in the Biocidal Products Directive 98/8/E and it was highlighted by an interviewed expert that it is very expensive to register a new chemical for this use (personal communication).

Technology Readiness Level: 9; Technical risk: High

Non-biocidal coatings: The Aquaculture Stewardship Council, to which 70% of Norway’s farms have pledged to join by 2020, dictates that no high-pressure cleaning of nets is allowed if anti-fouling nets are used (personal communication). If farmers use anti-fouling coated nets, they have to change the nets three times in a production cycle and if no anti-fouling coating is used, they are recommended to clean with high pressure once or twice a week (depending on location). Also, since the new chemical directive from EU was passed, forcing all coating developers to apply for new licences for biocides and to adhere to set efficacy tests, it has become difficult to find chemicals that can be used within the EU. There is therefore an increasing interest in non-biocidal coatings. Most non-biocidal alternatives seal net surfaces under wax- or resin-based coatings and simply protect the fibres of the nets making them last longer.

Technology Readiness Level: 9; Technical risk: Low

Different netting material: The market standard for most marine finfish farms is to use nylon netting. There is limited research into novel net materials and interwoven nets where e.g. biocidal material becomes part of the netting material. This was identified as a gap with potential for innovative developments. Novel netting materials are potentially needed as pens are moved further out to sea, where cleaning regimes will have to be more automated (personal communication).

Technology Readiness Level: 3-5; Technical risk: Moderate

Natural compounds: Natural compounds that inhibit larval metamorphosis may be useful antifoulants in shellfish aquaculture (Bannister *et al.* 2019). These products typically have a contact active mode of action, whereby they are effective while remaining bound within a stable matrix, so effects are limited to coated surfaces. Although these compounds are suggested to have little environmental impact, be applicable to both farm infrastructure and shellfish, and reduce biofouling, experts in the field of biofouling were at the time of writing not aware of any commercial scale trials to test the effectiveness or feasibility of this method.

Other natural compounds, such as extracts from shellfish periostracum, exhibit strong anti-fouling properties and can be designed for commercial use. For example, periostracum dichloromethane extracts containing oleamide reduce algal spore settlement and crude periostracum extracts inhibit the attachment of barnacles, diatoms and marine bacteria (as reviewed by Bannister *et al.* 2019).

Technology Readiness Level: 3-5; Technical risk: Moderate

Antibiofouling on seaweed: Prevention, inhibition and treatment of biofouling on commercially cultivated seaweed species includes understanding and harnessing the natural anti-fouling defences of seaweeds, and strategic farm management and husbandry practices. Although seaweed aquaculture technologies have developed significantly over the last decades, simple, economically viable biofouling management solutions have not yet been realised (personal communication). Further research in this area is required, including trials of promising methods at commercial scales to facilitate future implementation by the industry.

Technology Readiness Level: 3-5; Technical risk: Low

Biological control: A range of invertebrate and fish species feed on specific biofouling organisms and these can theoretically be co-cultured in cages or on nets. Since the publication of Fitridge *et al.*, no significant advances in the use of biological controls have been made and therefore their use in finfish aquaculture remains at the experimental stage (Fitridge *et al.* 2012).

Technology Readiness Level: 3-5; Technical risk: Moderate

Air exposure: The system was used Norway 20 years ago, having a double net structure so the nets could interchangeably be taken out of the water and exposed to air and sunlight causing the biofouling to die. It was only used in small cages as considered too difficult on larger pens. However, Marine Harvest in Scotland adopted the method to circular pens of 120m (personal communication).

Technology Readiness Level: 6-8; Technical risk: Low

Biofouling as a reservoir for pathogens: It is known that biofouling can harbour pathogens but there is very little research in the area (personal communication). There is anecdotal evidence that there can be gill disease causing amoebae in the biofouling material, which therefore has the potential to spread between farms if cleaning material is not collected.

Technology Readiness Level: 1-3; Technical risk: Low

6.4 Introduction of non-fish alien species

Examples of unwanted organisms that can be transported between locations with the farmed fish in water (besides pathogenic viruses and microorganisms) include larvae of invertebrates such as *Didemnum vexillum*, jellyfish and seaweed. The potential of these organisms for establishment depends on several conditions related to the receiving location, physical conditions such as temperature, current conditions, etc. and whether or not the introductions happens repeatedly (Tricarico 2016; Taranger *et al.* 2015). The more introductions, the greater the chance that a new species can establish itself.

Innovations with a potential for incremental performance improvement

Reducing transfer of alien non-fish species: There are numerous developments in detecting and identifying invasive species through e.g. genetic typing using gene chips for automated monitoring (Chen 2016) but very little research on how to minimise the transfer of alien non-fish species.

Technology Readiness Level: 3-5; Technical risk: Low

6.5 Pests and diseases

Just as sea lice represents one of the major challenges for the salmonid aquaculture industry in terms of the impact on farmed fish, it represents one of the major challenges with respect to impact on the wild salmon population. Other pathogens of concern in terms of spreading from aquaculture to the surrounding environment includes viruses, such as salmonid alphavirus and infectious salmonid anaemia virus (ILAV) and skin lesion causing bacteria including Tenacibaculum spp., Aliivibrio wodanis,Moritella viscosa and Flavobacterium psychrophilum.

There is also the risk of introducing non-endogenous pathogens with the use of e.g. cleaner fish caught at one location and used at another.

Innovation with a potential for disruptive performance improvement

Closed pens: Improved physical containment at marine fish farming sites, through research and development of fish-farming technology, is a central recommendation of many international workshops and forums on the reduction of disease transfer from farmed to wild fish – and the other way round (personal communication) (please also refer to chapter 10 ‘Production and handling’).

Innovation with a potential for transformative performance improvement

Modelling of pathogen transmission: Research is limited and focused on agent-based modelling to simulate pathogen transmission especially between farms (Alaliyat, Osen, and Kvile 2013). There is little focus on innovations addressing direct prevention of transmission, other than through reducing escapes. Such modelling is used in Norway, and to some extent in Scotland, whereas there is little evidence of use elsewhere, potentially due to lack of data collection on movement of wild fish.

Technology Readiness Level: 6-8; Technical risk: Low

6.6 Organic material

The impact of regional effect on marine ecosystems due to emissions of nutrients and organic emissions from human activity is well known from the international literature. At present, there is insufficient monitoring data from areas with marine aquaculture to make a complete risk assessment of the effect of nutrients and organic compounds emission (Dauda *et al.* 2019). The risk of regional impact will be lowest in areas with good water exchange, while more confined areas and shallow waters (<100 metres deep) with high production intensity can be at risk. One suggested solution for managing the organic material related environmental impacts of aquaculture is to manage feed (Martins *et al.*, 2010; Turcios & Papenbrock, 2014).

Innovations with a potential for disruptive performance improvement

Biofloc technology: Biofloc technology is an emerging technology in fish culture systems that is progressing towards ensuring sustainable aquaculture, by ensuring maintenance of water quality through uptake of ammonia to produce microbial proteins and making food for the cultured fish through utilisation of the microbial protein produced. Please refer to chapter 10 ‘Production and handling’ for further information.

Technology Readiness Level: 9, Technical risk: Moderate

Innovations with a potential for transformational performance improvement

Advanced waste collecting systems: Advanced waste collection systems for collecting sunken waste from aquaculture cages are being developed and implemented in Norwegian salmon farms (Hyperthermics 2019; Skaugen 2016; ØPD Norge n.d.). *“The collected waste can be used as a resource for production of biogas, fertiliser, feed for polychaetes etc. instead of sending it out into an ecosystem where we worry about where it goes… The big concrete pens will allow us to collect the material”* (personal communication)*.*

Technology Readiness Level: 6-8, Technical risk: Moderate

Innovations with a potential for incremental performance improvement

Indicator species and their behaviour: Indicator species and life history traits for monitoring of both marine and freshwater aquaculture is the most common way to estimate impacts on the environment and surrounding ecosystem e.g. number or fluctuations in indicator fish species (Rennie *et al.* 2019), bacterial communities (Olsen *et al.* 2017), analysing the characteristics of valve movement pattern of the scallops in relation to environmental changes (Sakurai 2016) or monitoring the benthic fauna throughout rearing cycles, which is still seen as the best indicator (Mestres, Chaperón, and Sierra 2016 and personal communication). There is a wide range of indicator species and innovation is primarily in identifying new species and in methods that allow for increased efficiency in how these species (fauna and flora) are collected and counted or assessed.

Technology Readiness Level: 9, Technical risk: Low

Benthic Flux Sampling Device: Benthic Flux Sampling Device (BFSD), an instrument adapted from benthic flux chamber technology developed for oceanographic studies of the cycles of major elements and nutrients on the seafloor, to directly quantify the mobility and bioavailability of trace metals contaminants in marine sediments. The BFSD is an autonomous instrument for in situ measurement of flux rates of sediment contaminants like heavy metals (e.g., lead, mercury, chromium, zinc, and copper), polychlorinated biphenyls (PCBs), dioxins, and petroleum products. A flux out of, or into, sediment is measured by isolating a volume of water above the sediment, drawing off samples from this volume over time, and analysing the samples for increase or decrease in toxicant concentration.

Technology Readiness Level: 6-8, Technical Risk: Low

eDNA: A cost-benefit analysis shows that evaluating marine and freshwater macroinvertebrates from eDNA metabarcoding is more expensive than conventional techniques for determining macroinvertebrate communities but that it requires significantly fewer sampling and identification efforts. However, the molecular technique has proven to be more sensitive than the visual one and once the technique is more widely used, the cost will be reduced (Fernández *et al.* 2018).

Technology Readiness Level: 6-8; Technical risk: Low

Dual Frequency Identification: Dual Frequency Identification Sonar (DIDSON) technology has been developed in order to analyse the impact of freshwater aquaculture on wild fish population behaviour, in relation to aquaculture feeding times (Enders 2017).

Technology Readiness Level: 6-8, Technical Risk: Low

Dispersion modelling software: NewDEPOMOD is a software tool for modelling the dispersion of waste organic material (faeces and waste feed) from aquaculture sites (Black *et al.* 2016). The model inputs include bathymetry data, tides and currents, biomass and growth rates of the farmed fish, feed inputs etc. Developed by the Scottish Association for Marine Science, the New DEPOMOD software has become the defacto tool for assessing ecosystem impacts as part of the marine aquaculture planning and approval process in Scotland, with further uptake of the tool internationally. The model continues to be developed, notably in the modelling of exposed sites.

Technology Readiness Level: 9, Technical Risk: Low

6.7 Residual foreign matter

Much of the ongoing research addressing environment and ecosystem monitoring and impact is focused on measuring the direct impact on the local environment and ecosystem that foreign matter might have (Korostynska *et al.* 2016). Foreign matter in this context refers to environmental toxins from the fish feed, Veterinary Medicinal Products (VMPs) or compounds used as anti-fouling agents, for example copper (Cu). Environmental toxins in the feed can be released from a fish farms as excess feed or through faeces and the dispersion of it follows the organic material, which degrades in the sediment where it is known to affects e.g. lobsters and polychaetes (SERDP, 2019; personal communication).

Substance groups include halogenated organic compounds such as PCBs, dioxins, furans, chlorinated pesticides, brominated flame retardants and heavy metal compounds such as methyl mercury (MeHg) and cadmium (Cd). The halogenated compounds and methylmercury are persistent environmental toxins with a high ability to bioaccumulate and accumulate through the food chain because of their high-fat solubility, low degradability and because the organisms have little ability to metabolise and excrete drugs.

Prevention is sought through controlled feeding regimes (please refer to chapter 8 ‘Nutrition and feeding’) and reduction in use of medicines such as bath treatment with hydrogen peroxide in treating sea lice infestations. For antimicrobial usage a number of proximate factors are identified, including vulnerability to bacterial disease, antimicrobial access, disease diagnostic capacity, antimicrobial resistance, target markets and food safety regulations, and certification. Globally, governments especially in developing nations, need to act to reduce antimicrobial use through e.g. farmer training, spatial planning, assistance with disease identification, and stricter regulations. Rigid monitoring of the quantity and quality of antimicrobials used by farmers and the antimicrobial residues in the farmed species and in the environment needs to be implemented to promote measures to reduce potential human health risks associated with antimicrobial resistance (personal communication).

It has previously been suggested in the literature that national or regional authorities in charge of coastal zone management should carry out spatial planning defining optimal sites for aquaculture to promote development of sustainable marine aquaculture and avoid conflict with other users, following a participatory approach and adhering to the principles of ecosystem-based management (Sanchez-Jerez *et al.* 2016 Lithgow, de la Lanza, and Silva 2019).

Research and innovation are around modelling of spread and dilution, measuring quantities and removing or breaking down the foreign material. The use of ecological models for assessing the effects and risks of VMPs is almost absent (Rico *et al.* 2019).

Innovations with a potential for transformative performance improvement

Photodegradation: Application of solar photodegradation has been developed for the removal of Oxytracycline (OTC) from marine aquaculture waters (Leal, Esteves, and Santos 2016).

Technology Readiness Level: 6-8, Technical risk: Moderate

Electromagnetic wave sensing: Electromagnetic wave sensing has been developed as a method for real-time in situ monitoring of residual antibiotic concentrations in water samples. Antibiotics solutions were tested in contact with planar sensor with interdigitated electrode pattern on a number of substrates, including Rogers®, FR4 and flexible polyimide substrates. By using bespoke microwave planar type sensors the presence of Quinolones, in particular Enrofloxacin (ENR) and Norfloxacin (NOR) antibiotic concentrations can be determined (Korostynska *et al.* 2016).

Technology Readiness Level: 6-8, Technical risk: Moderate

Innovations with a potential for incremental performance improvement

Modelling dispersion: Where VMPs e.g. sea lice treatment has a long half-life (several days), the dilution effect will be the most important factor in reducing the concentration to below harmful level. Current speed, wind and depth will affect spread and dilution rate, parameters which will vary at the same location and between sites. The discharge is most likely to remain in the upper water layer whereas vertical transport of water to deeper water layers in e.g. a fjord are rare, but hydrogen peroxide can sink to the bottom when the water column is well mixed, which is more common in winter (Refseth 2017). Again, such models are used in Norway and Scotland with little evidence of uptake elsewhere.

Academics, industry experts and NGOs have mentioned that there is a need for research and collaborations to generate a common modelling strategy for Environmental Risk Assessment, which would benefit from a set of ready-to-use realistic (worst-case) environmental scenarios, that represent the main physicochemical conditions, geographic regions and management practices within Europe, similarly to the approach adopted within the regulatory Environmental

Risk Assessment of plant protection products (FOCUS, Forum for the Coordination of Pesticide Fate Models and Their Use 2001). The development of such a task for aquaculture would require that the major aquaculture zones in Europe are classified according to their environmental characteristics, and that main aquaculture production practices are identified for at least the key species produced (personal communications). In this way, the toolbox should also be complemented with a set of specific protection goals that consider the temporal and spatial frame of allowable chemical effects, and ecological modelling tools that allow the prediction of population and community-level effects under such relevant spatial-temporal frames.

Technology Readiness Level: 6-8, Technical risk: Moderate

Standardised methodology - estimation of hydrophobic contaminants: The desorption and bioavailability of bioaccumulated hydrophobic contaminants e.g. polychlorinated biphenyls has been estimated by applying the Tenax method. This has been suggested as a tool to manage contaminated sediments but application is limited due to the absence of a standard set of conditions to perform the extractions, as well as standard methods for using field sediments (Lydy 2014).

Technology Readiness Level: 3-5, Technical risk: Moderate

Constructed wetlands: Constructed wetlands for removal of antibiotics (enrofloxacin and oxytetracycline) and antibiotic resistant bacteria from saline aquaculture wastewaters (Boto, Almeida, and Mucha 2016; Cheng *et al.* 2017). This approach has been used in e.g. the oil industry in the Middle East but there is a potential for further disrupting the environment as such constructed wetlands need to be of a certain size in order to capture contaminants (personal communication).

Technology Readiness Level: 6-8, Technical risk: Moderate

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7 Farmed animal health and welfare

Contents

From the SIF Executive Board

The method applied in this review has generated numerous examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently happening. It is recognised that there are existing innovations and research areas that are not included here, and new areas where future innovations may occur. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

7.1 Overview: farmed animal health and welfare

What is the challenge in the UK?

The main challenges with regards to fish welfare are around the intensive farming of most fish species. Crowding is a key challenge as this has implication on health, makes the fish more sensitive to pest and diseases and has an impact on overall welfare.

Also, welfare can be improved with regards to stunning and slaughter for all species of farmed fish, which presents more of a technical problem.

Fast growth causes abnormalities and e.g. cardiovascular diseases in salmon are common and related to fast growth. Current farmed salmon will not be well equipped to cope with future challenges such as heat spells.

What are the most promising innovation categories?

- Improved welfare during farming through systems design and strategy
- Increased smoltification period on land
- Processing vessels for killing and slaughtering on site
- Novel pharmaceuticals against sea liceRegulations for slaughtering methods
- Regulations regarding stocking density (rather than licence for tonnes of meat)
- Effective electrical stunning methods
- Anaesthetics in relation to transport, although likely not approved for use during transport to slaughter

Where are the important knowledge gaps?

- Stress in hatcheries
- Large-scale stunning methods for gilthead sea bream
- Behavioural cues in relation to stress
- Behavioural cues in relation to unconsciousness

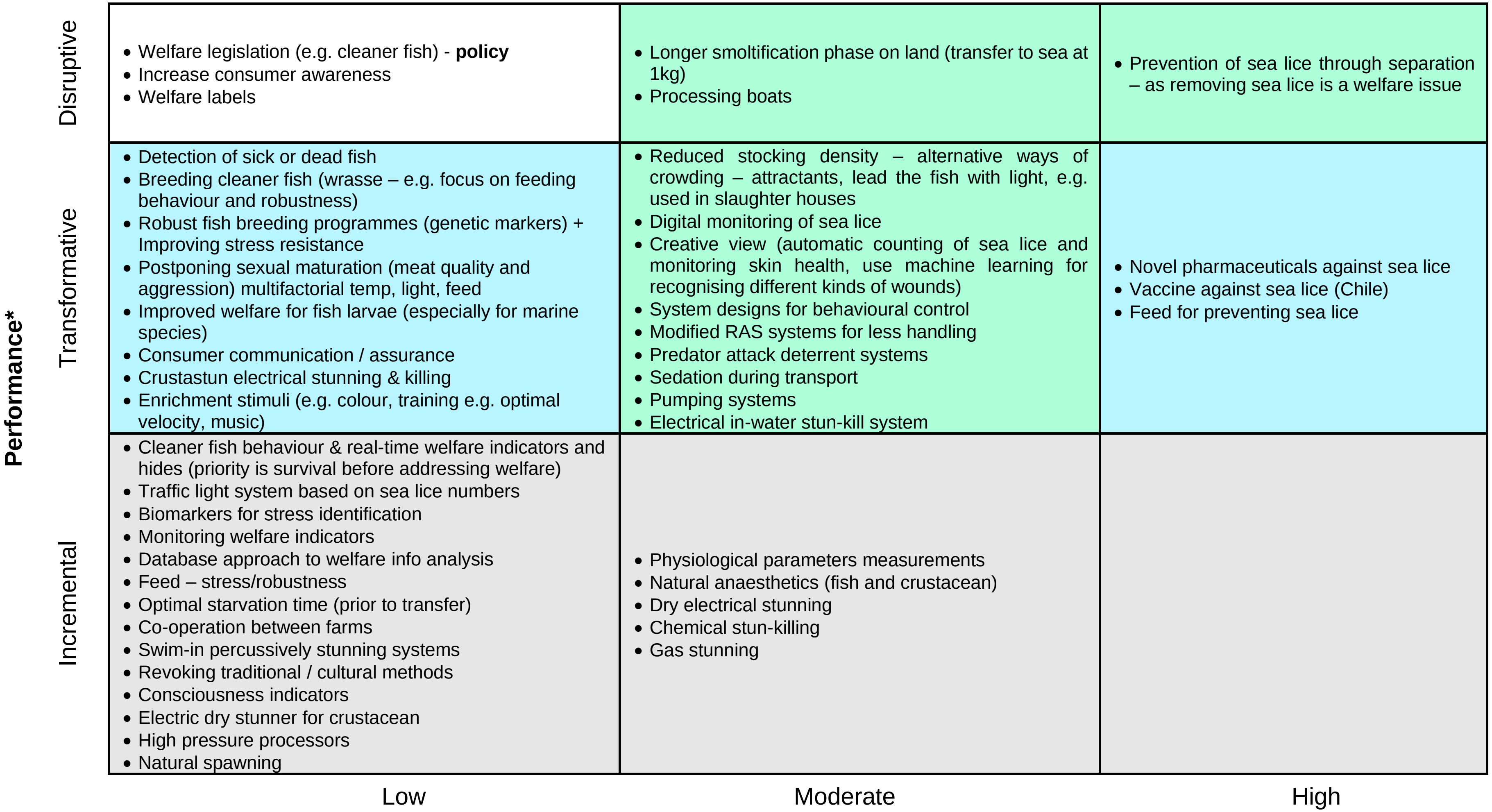
Animal welfare is an issue of growing interest, especially in western societies. In Europe, over the last ten years, animal welfare research is growing twice the rate of animal health research. Thus, during the last decade, fish welfare has attracted more attention (Browman *et al.* 2019), and this has led to the aquaculture industry incorporating a number of husbandry practices and technologies specifically developed to improve fish welfare of farmed fish (Espinal and Matulić 2019).

The importance of welfare in aquaculture increasingly comes from ethical considerations as well as from the perspective of improving standards and quality of seafood production technologies and aquaculture products. Ethical or scientific, a suggested approach is that even where a given taxon or species is convincingly shown to be devoid of the ability to feel pain or devoid of consciousness, that fact must not diminish the importance of welfare considerations (Browman *et al.* 2019). Previously, the focus was more on the quality of the flesh, which is higher if the fish welfare is high (Roth *et al.* 2012; 2010). The welfare status of the fish has direct implications for their production and for the sustainability of the industry as a whole. Fish kept under good welfare conditions are less stressed and less susceptible to diseases and therefore they require less medication and treatment, show better growth and food conversion rates and ultimately provide a better-quality product. Thus, the economic benefits are obvious (Kankainen *et al.* 2012; Noble *et al.* 2012). In addition, consumers care about welfare issues potentially associated with intensive production practices, and they expect from the fish farmers that the welfare of farmed fish is addressed (FAO 2019c).

Experts have pointed out that the interest in welfare of fish emerged at a much later stage compared to that of terrestrial livestock species. Traditionally, the view was that fish cannot suffer, nor experience pain. This perception came about as the neocortex in humans is an important part of the neural mechanism that generates the subjective experience of suffering and as fish and other non-mammalian animals lack the neocortex. It was therefore argued that its absence in fish implied that fish cannot suffer.

This has in recent years been somewhat “disproven” by research suggesting that complex animals with sophisticated behaviours, such as fish, have the capacity to feel suffering, though this may be different in degree and kind from the human experience of this state (Huntingford *et al.* 2006). In line with this view, it is known that fish respond to environmental challenges with a series of adaptive neuro-endocrine adjustments that are collectively termed the stress response. Prolonged activation of the stress response is typically damaging to the fish and leads to immuno-suppression, reduced growth and reproductive dysfunction (Cao, Tveten, and Stene 2017; Sneddon 2019; Schreck *et al.* 2016).

An overview of the potential performance improvement rating of recent (2015-2019) innovations in aquaculture health and welfare are outlined in Figure 6-1.



Performance*	Low	Moderate	High
Disruptive	• Welfare legislation (e.g. cleaner fish) - **policy** • Increase consumer awareness • Welfare labels	• Longer smoltification phase on land (transfer to sea at 1kg) • Processing boats	• Prevention of sea lice through separation – as removing sea lice is a welfare issue
Transformative	• Detection of sick or dead fish • Breeding cleaner fish (wrasse – e.g. focus on feeding behaviour and robustness) • Robust fish breeding programmes (genetic markers) + Improving stress resistance • Postponing sexual maturation (meat quality and aggression) multifactorial temp, light, feed • Improved welfare for fish larvae (especially for marine species) • Consumer communication / assurance • Crustastun electrical stunning & killing • Enrichment stimuli (e.g. colour, training e.g. optimal velocity, music)	• Reduced stocking density – alternative ways of crowding – attractants, lead the fish with light, e.g. used in slaughter houses • Digital monitoring of sea lice • Creative view (automatic counting of sea lice and monitoring skin health, use machine learning for recognising different kinds of wounds) • System designs for behavioural control • Modified RAS systems for less handling • Predator attack deterrent systems • Sedation during transport • Pumping systems • Electrical in-water stun-kill system	• Novel pharmaceuticals against sea lice • Vaccine against sea lice (Chile) • Feed for preventing sea lice
Incremental	• Cleaner fish behaviour & real-time welfare indicators and hides (priority is survival before addressing welfare) • Traffic light system based on sea lice numbers • Biomarkers for stress identification • Monitoring welfare indicators • Database approach to welfare info analysis • Feed – stress/robustness • Optimal starvation time (prior to transfer) • Co-operation between farms • Swim-in percussively stunning systems • Revoking traditional / cultural methods • Consciousness indicators • Electric dry stunner for crustacean • High pressure processors • Natural spawning	• Physiological parameters measurements • Natural anaesthetics (fish and crustacean) • Dry electrical stunning • Chemical stun-killing • Gas stunning	
	Technical Risk*		

Figure 7-1: Performance and technical risk rating of innovations in aquaculture health and welfare.

**See section 4.4 for definitions of performance and technical risk rating scales.*

7.2 Health

The physical health of an animal is fundamental for good welfare (Ashley 2007). Thus, one of the key aspects of farmed fish welfare is to keep the fish in good health (Assefa and Abunna 2018a). However, it can be argued that the fact that an animal is healthy does not necessarily mean that its welfare status is adequate. Welfare is a broader and more overarching concept than the concept of health. Physiological and behavioural measures are intrinsically linked and are dependent on one another for a correct interpretation with regrades to welfare (Huntingford *et al.* 2006).

One of most important steps to reduce or prevent losses due to diseases in aquaculture are breeding for more robust fish as a preventative measure, adapting the farming systems and monitoring as regularly as possible and appropriate action at the first sign(s) of suspicious behaviour, lesions, or mortalities (Ananda Raja and Jithendran 2015).

The focus is on fish welfare in this chapter. Please refer to chapter 9 ‘Pests and disease management’ for further information with regards to overall health in relation to fish parasites and diseases.

Innovation with a potential for disruptive performance improvement

With many individuals at each locality and many localities close together, pests and disease had been a major challenge for aquaculture. The main challenge is sea lice infestations and although vaccinations have helped, certain diseases, especially for salmon farming, such as pancreas disease (PD), cardiomyopathy syndrome (CMS) and heart and skeletal muscle inflammation (HSMI) are prevalent.

Longer smoltification phase on land: Current sea lice treatments cause crowding, stress, physical injuries and increased risk of disease infection. It is well known that there is an increased spread of e.g. pancreas disease during de-lousing as equipment cannot be fully sterilised (personal communication). Also, treatments such as hydrogen peroxide baths remove the epidermal mucus of the salmon, which is part of their innate immune system (Dash *et al.* 2018), and thus the treatment in itself, when performed on otherwise healthy fish, will typically cause around a 2ppt mortality. Furthermore, the pumping, brushing, heat shock treatments etc. cause secondary stress induced by the multiple treatments, which reduce appetite and inhibits growth.

An increasingly popular preventative strategy, currently attracting a lot of R&D funding in Norway, is to increase the length of the smoltification phase on land in salmon farming (RAS Tech Magazine 2019). According to experts and projects at Nofima and SINTEF, an independent research organisation), this involves the first sea water phase on land, and there is therefore overall increased welfare as there is no need for transport, reduced stress and higher survival and overall fitness as fish are in a controlled environment – which is furthermore free of sea lice. There are currently trials in Norway, where salmon are kept on land until they are 300-400g up to 1kg before they are transferred to pens at sea. This also means that there are less farmed animals in the sea at any one point and that there is less interaction between farmed fish and wild populations. Control in Aquaculture Production (CtrlAQUA), a centre for research-based innovation that was established in 2015 by the Research Council of Norway is focused on the first seawater phase, or so-called post-smolt stage, as this is the most sensitive phase for salmon in the production cycle.

Technology Readiness Level: 6-8; Technical risk: Moderate

Innovation with a potential for transformative performance improvement

Prevention of sea lice through separation: As removing sea lice pose a welfare issue attempts to separate salmon from sea lice exposure is a prevention strategy. Separation includes e.g. keeping salmon on land for longer (up till 1 kg), transfer salmon to closed pens for the growing stage at sea or rearing salmon in underwater pens (e.g. lice skirt, snorkel design etc.). Also, ‘Bubble Curtains’ deterring sea lice from entering the pen, deep light / deep feeding regimes and vertical light movement, controlling where the salmons are in the water column, are being further developed (Global Salmon Initiative 2019; Wright *et al.* 2015). Please refer to chapter on Production and handling for more information on pen designs.

However, light based attractants commonly used in open net pen aquaculture to control farmed fish behaviour (e.g. feeding, crowding or sexual maturation control) may increase the abundance of some fish and other marine species around the pens, thereby increasing the probability that farmed fish and wild marine species directly and indirectly interact in coastal marine environments (McConnell, Routledge, and Connors 2010).

Technology Readiness Level: 6-8 Technical risk: High

Digital monitoring: Majority of latest innovation in Europe related to sea lice evolve around smart monitoring and constant relay of live data (Kyst.no 2019). One example, specifically developed for sea lice detection, is the Falcon® Sea Lice Detection System[1], which is the latest development from MSD Animal Health. It is a system that delivers an intelligent and actionable snapshot of the sea lice data for the salmon stock. Reporting and insights as well as accurate and continuous monitoring 24/7, are delivered directly from the pen to the farmers desktop. Another system is the Creative view system, which is used in Norwegian salmon farms for counting of sea lice and monitoring skin health, using machine learning for recognising different kinds of wounds (Espmark 2020).

Technology Readiness Level: 6-8; Technical risk: Moderate

Novel pharmaceuticals: In e.g. Chile, novel pharmaceuticals to treat sea lice infestations are already in use (Elanco 2016). New drugs are not approved for use in Europe where there are stricter regulatory requirements, and therefore environmental impact, half-life in different environments, interactions with other species, etc. will have to be further tested. There are also developments in new strategies for treatment of sea lice, as the use of one pharmaceutical only will result in resistance, and thus alternating or cocktail treatments are in development (personal communication). Furthermore, the sea lice species in Chile is sufficiently different from the one in Norway and Scotland and hence, treatment that works in Chile is not always effective in Europe (personal communication).

Technology Readiness Level: 3-5; Technical risk: High

Vaccine against sea lice: Every option for vaccines against sea lice are being considered and this is a significant area of research. Recently, a vaccine was developed in Chile (Jensen 2018b), however, so far it has been found not very effective in Norway on commercial scale (personal communication).

Innovation with a potential for incremental performance improvement

Traffic light for regulating Norwegian salmon production based on sea lice numbers: The Norwegian Department of Fisheries and Aquaculture divided the Norwegian west coast into 13 zones based on regular inspections on sea lice numbers, in an effort to improve health

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[1] Falcon Sea Lice Detection System: https://www.aquafalcon.com/

of farmed fish and reduce the impact of lice on wild salmon (Saue 2017). For further detail, please refer to chapter 9 ‘Pests and disease management’.

Technology Readiness Level:9; Technical risk: Low

Detection of sick or dead fish: GO Smart® Mortality Counter[1] is currently the only existing system of its kind, designated for counting and separating the dead fish out of the cage. It claims that there is no need for an expensive pumping machine, piping system or energy wastage. Data is transmitted in situ and the farmer is made aware of the mortality numbers at all times.

Technology Readiness Level: 6-8; Technical risk: Low

7.3 Cleaner fish

In order to decrease reliance on, and use of, chemical louse treatments, the aquaculture industry increasingly relies on cleaner fish to control salmon lice. Cleaner fish are hailed as an environmentally friendly approach to delousing and are used as part of a parasite control approach at e.g. half of all Norwegian localities and at many of the Scottish farms. Some species of cleaner fish are still captured in the wild putting pressure on wild stock (e.g. different species of wrasse) and stress, diseases and malnutrition currently cause mortality rates of around 100% (personal communications). Concerns are being raised regarding the high mortality and cleaner fish welfare is hard to address when mortality rates are so high. Cleaner fish are generally used as a disposable tool in salmon production with an estimated 50 million cleaner fish dying every year in Norwegian fish farms alone (Stranden 2020). There is therefore debate within the Norwegian government whether or not the use of cleaner fish should continue to be legal in intensive fish farming, and there are talks that the use of cleaner fish will be phased out until a more sustainable practice (e.g. farmed, more robust cleaner fish) can be implemented (personal communications).

The key challenges evolve around the fact that the needs for cleaner fish and salmon are very different, and research is focused on addressing whether or not the species can co-exist in aquaculture and how to improve cleaner fish survival and welfare in the salmon farming environment. The current use of cleaner fish is not sustainable and there is a growing body of research to address the different aspects of cleaner fish use and their welfare (Brooker *et al.*

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[1] Go Smart Mortality Counter: https://www.gosmartfarming.com/

2018; Open Seas 2017; Powell *et al.* 2018; Eliasen *et al.* 2018; Whittaker, Consuegra, and Garcia de Leaniz 2018a; The Fish Site 2018d; Leclercq *et al.* 2018).

Cleaner fish research is progressing rapidly, although much of the basic knowledge regarding the species' biology remains unknown (Brooker *et al.* 2018). Researcher find that salmon farmers are moving fast, constantly trialling new methods and failing, often working independently, making a systematic approach difficult (personal communication). The simultaneous domestication of two new marine aquaculture species (wrasses and lumpfish) is a significant challenge, demanding sustained effort and funding over a prolonged period of time. Breeding schemes take generations and hence time, but most likely the best way to make the use of cleaner fish sustainable. Researchers emphasise that focus on enhancing the robustness of farmed stocks and increasing hatchery outputs, to meet the urgent demands, is the best way to increase cleaner fish survival rates and protect wild stocks from over-fishing (Brooker *et al.* 2018).

The "reuse of cleaner fish" pose an issue due to biosecurity as it is understood that cleaner fish represent a potential reservoir for diseases which can be transferred to salmon and potentially also transform in the cleaner fish host (personal communication).

Innovation with a potential for transformative performance improvement

Breeding cleaner fish: It is expected that by 2020, 10 million cleaner fish will be used in Scotland (OneKind 2018). In 2016, three hatcheries in Scotland produced 118,000 wrasse, and seven hatcheries produced 262,000 lumpsuckers. The remaining cleaner fish used by the industry are still wild-caught, and due to the high demand and limited regulations for fisheries targeting cleaner fish species, there is an impact on wild populations as well as questions around welfare issues relating to how they are caught, handled, and transported, and how well suited they are to captivity.

Breeding developments for wrasse have provided a proven, repeatable procedure for breeding and rearing, leading to a reduced reliance on wild stock (Aquaculture North America 2018; Powell *et al.* 2015).

Technology Readiness Level: 6-8; Technical risk: Moderate

Innovation with a potential for incremental performance improvement

Cleaner fish behaviour: An acoustic tracking system has been shown to be an effective tool for visualising cleaner fish behaviour under challenging farm conditions. The study highlighted the critical role of hides in cleaner fish husbandry (Leclercq *et al.* 2018).

Technology Readiness Level: 6-8; Technical risk: Moderate

Cleaner fish welfare indicators: The provision of suitable habitat and acclimation to net pen conditions may encourage natural behaviours, including delousing, and the use of operational welfare indicators can highlight potential welfare issues (Brooker *et al.* 2018). Also, for lumpfish, *Cyclopterus lumpus*, extensive research and reports have been generated to provide an overview of welfare indicators (Noble *et al.* 2019).

Technology Readiness Level: 3-5; Technical risk: Low

Hides: Continued research into hide types, colours and locations in the net pen may yield further enhancements (Brooker *et al.* 2018).

Technology Readiness Level: 6-8; Technical risk: Low

7.4 Welfare at different stages of farming

Fish culture involves a large number of species globally, with each species and its respective life stages having different welfare requirements. Ideally, welfare measures are based on the understanding of the needs of the various species, but the understanding of their welfare-relevant biology is indeed very limited. As a consequence of the limited knowledge of and the diversity of cultured species, relatively few operational welfare indicators for farmed fish have been validated to date (FAO 2019c).

Appreciating that the actual development and the risk of a disease outbreak is the result of a complex interaction between the host, the environment and the pathogens, has put stress in the context of fish welfare in focus in recent years. Effectively reducing the risk of disease outbreak requires stress reduction in an integrated, multidisciplinary approach at all levels of the production cycle as, during production, fish are subjected to a range of different husbandry practices that may cause chronic stress to the animals. Chronic stress can result in increased glucocorticoid levels, which render the fish more susceptible to disease. Stressors include, but are not limited to, stocking density, water quality, system design and handling processes such as grading, sampling and transportation. Not being able to escape aggressive individuals or poor environmental conditions can also cause stress for farmed fish. Long-term stress can inhibit normal behaviour and normal physiological processes.

There is typically a distinction between stress caused by different factors:

- Chemical stressors (e.g. pollution, low water quality e.g. low oxygen)
- Physical stressors (e.g. capture, handling)
- Perceived stressors (e.g. stimuli evoking a startle response such as sound or predators)

These lead to responses including:

- Primary response (e.g. increase in stress hormone levels)
- Secondary responses (e.g. metabolic changes, increase in glucose or lactate)
- Tertiary responses (e.g. changes in whole animal health, growth, reproduction, disease resistance, behavioural changes, feeding, aggression)

7.4.1 Breeding

Breeding should focus on healthy fish, and welfare has become increasingly important in breeding goals. Intensive breeding of salmon has led to salmon growing to full size twice as fast as they did in the 1970s (Alleyne 2012). Deformities due to breeding and fast growth leads to a proportion of farmed salmon experiencing severely compromised health and welfare.

With regards to diseases, the basis for controlling progression from infection to disease in farmed aquatic animals would benefit from a better understanding of fundamental mechanisms for pathogen tolerance in wild hosts where host background genetic diversity is higher (van Houte *et al.* 2016) and where exposure to pathogens may have left an inherited legacy of natural resistance (Verbruggen *et al.* 2015).

In this way, hatchery supply of specific-pathogen-free larvae (produced with confirmed freedom from certain pathogens, though not necessarily “tolerant” to the microbiome or pathobiome of the receiving farm) should be augmented by provision of more diverse and broadly resilient lines, produced via well-managed selective breeding programmes, and potentially augmented using emerging genetic technologies (such as SNP arrays (Hsin Y. Tsai *et al.* 2016)).

For further details of breeding please refer to chapter 7 ‘Genetic Improvements’.

Innovation with a potential for transformative performance improvement

Improving stress resistance: Genetic selection and breeding to specifically improve stress resistance in broodstock was recently highlighted as an area that need further research as well as research into hormonal induction of spawning (Manfrin 2018).

Technology Readiness Level: 6-8; Technical risk: Moderate

Natural spawning: Where wild-caught fish are used for broodstock e.g. sea bream and sea bass, the fish are highly stressed as they are removed from their natural habitat. However, wild broodstock is preferred in order to maintain the genetic diversity.

There are often significant welfare concerns for broodstock as these fish are typically kept captive for longer periods, handled for hormone treatment and light manipulations, and exposed to stripping at most fish farms. For the sturgeon, as the anatomy of the female fish does not make stripping possible, the fish is anaesthetised, eggs are then surgically removed, after which the fish will typically be euthanised.

A few farms let the fish spawn naturally, although most use light manipulation to somewhat control timing of the spawning (AquaSearch 2018). Letting the fish spawn naturally significantly reduces the handling and hence the stress levels of the broodstock, increasing overall fish welfare. However, some experts mentioned that natural spawning may negatively impact welfare (personal communication). Please also refer to ‘Postponing or regulating sexual maturation’ below.

Technology Readiness Level: 9; Technical risk: Moderate

Postponing or regulating sexual maturation: With regards to natural spawning, it was mentioned by experts that natural spawning for e.g. farmed salmon is unlikely to contribute to increased welfare, but potentially negatively impacting welfare, as fish will show more aggressive behaviour (personal communication). It was argued that rather than looking at natural spawning, regulating and / or postponing sexual maturation would lead to welfare improvement, as sexual maturation in finfish is often linked with increased levels of aggression amongst male fish. For salmonids sexual maturation is further linked with a negative impact on growth rate and meat quality and is known to increase mortality (Gjerde 1984). Postponing sexual maturation is not a novel field of research, but as early sexual maturation is detrimental to fish health and quality, when viewed from an aquaculture viewpoint, research is ongoing and there are several approaches to try to postpone or at least control sexual maturation including 1) traditional selection methods, 2) manipulation of external factors affecting puberty (e.g. light and temperature), 3) novel biotechnological methods improving breeding methods, 4) induction of polyploidy, and 5) genetic modification controlling maturation (Iversen, Myhr, and Wargelius 2016). Please refer to chapter 7 ‘Genetic improvements’ for further details.

Technology Readiness Level: 9; Technical risk: Moderate

Improved welfare for fish larvae: A research need on identification of indicators of stress in larvae and juveniles fish has been highlighted in recent research (Manfrin 2018; Rehman *et al.* 2017).

7.4.2 Growing on systems

The main welfare concerns in the growing phase include poor water quality, diseases and parasite load, high stocking densities, handling for grading or vaccinations, moving the fish e.g. for grading, which often involved crowding the fish to very high densities and exposure to predators. One development in the salmon industry addressing this, is the increased length of the smoltification phase on land as described above in the section on Health.

Welfare issues specifically relating to cage based growing systems include concerns about keeping fish captive in a much smaller space than their typical territory or range in the wild and restrictions on the behaviour of bottom dwelling fish, such as turbot, which are unable to engage in their normal behaviour when in cage systems (Eurogroup for Animals 2018).

Innovation with a potential for disruptive performance improvement

Welfare legislation: Interviewed experts commented that tighter regulations should be imposed on the aquaculture industry (Eurogroup for Animals 2018). If, for instance, dead fish meant that fish farmers might not get new concessions to farm, the problems that threaten fish welfare would likely be solved faster (personal communication). Also, rather than having a licence for the standing biomass a farm produces, farms should get licenses for the number of fish they set out, much like the poultry industry where chicken densities are licensed as number of animals and not in tonnes of meat (Andreassen 2019). *“This would likely be challenging to implement and audit and a consumer demand rather than just a regulatory demand is possibly required for implementation to be acceptable to farmers”* (personal communication).

Technology Readiness Level: 3-5; Technical risk: Low

Increase consumer awareness: Increasing consumer awareness of farmed fish welfare would likely contribute to the industry having to take action at a faster rate than currently seen (personal communication). While there is literature on animal welfare and willingness to pay (WTP) for it (Nocella, Hubbard, and Scarpa 2009), only a few studies have specifically considered consumers' perception of fish welfare and their willingness to pay for welfare fish. An older study undertaken in Denmark in 2011 found that 48% were on average willing to pay 25% extra for welfare rainbow trout (Solgaard and Yang 2011).

In a more recent study across Europe (Zander and Feucht 2018), on average of all countries, additional WTP was highest for organic production (+14.8%), followed by sustainably produced (+14%), produced with higher animal welfare (+14%), locally produced (+12.6%), by coastal fisheries (+11.7%), without discards (+10.3%), and produced in Europe (+9.4%). Thus, organic and sustainable production as well as higher animal welfare standards appear to be the most promising attributes, from a consumer perspective, with respect to product differentiation in European fish markets (Zander and Feucht 2018).

In line with the EU strategy for blue growth, sustainable production is promoted as a strategy for growth of the European seafood sector. Seafood which is produced sustainably presumably will be more expensive and will have to be located in higher priced market segments. A recent public survey conducted by Savanta ComRes shows that the majority of EU citizens believe that finfish should be better protected. The dramatic headline findings include 79% of EU citizens thinking that the welfare of fish (salmon) should be protected to the same extent as the welfare of other animals we eat and that it should be better protected than it is now (Savanta ComRes 2018). The findings also clearly show that consumers want welfare guarantees on their fish products (79%) and that welfare guarantees are an indicator of the product characteristics that are less visible but most important to them (quality and sustainability) as well as assuring them that the fish was well treated.

However, there is a huge gap between the consensus in science, citizens' expectations, and the reality for fish. At the end of 2017, the European Commission published a study into the welfare of fish during transport and at slaughter in European Aquaculture and followed this with a report to Parliament and Council (Eurogroup for Animals 2019). The Commission recommended that the European Union take no further regulatory action, stating that voluntary efforts would be enough to achieve the same outcome (European Parliament 2019.).

The farmed seafood industry has in the past responded to requirements from large buyers such as Tesco, which have the means to drive the market through asking about e.g. how the animals sold in Tesco are being killed in order to ensure it is in a humane manner. E.g. Seachill are reported to have a big emphasis on welfare in order to secure their position as main supplier (Hilton Food Group 2018).

Technology Readiness Level: 6-8; Technical risk: Low

Welfare labels: Experience with other food labels suggests that fish producers should ensure that welfare related labelling (including logos or husbandry related terminology) clearly reflects the standards achieved and allows both identification of standards and comparisons between products. In that way demand can drive up standards in the whole industry (Opinion on the welfare of farmed fish, 2014).

Technology Readiness Level: 3-5; Technical risk: Low

Innovation with a potential for transformative performance improvement

System designs for behavioural control: Novel designs of closed pens highlights fish welfare as a separate point, but primary focus is still on water quality and disease control (Floating and submersible closed-contained aquaculture farming invention 2017). It should be stressed however, that stress as a result of confinement is somewhat species dependent. For instance, sea bass (*Dicentrarchus labrax*) has been shown to exhibit higher stress levels at high densities, as indicated by cortisol, innate immune response and expression of stress-related genes (Vazzana *et al.* 2002; Gornati *et al.* 2004). In contrast, as an example, the Arctic charr (*Salvelinus alpinus*) feed and grow well when stocked at high densities while showing a depressed food intake and growth rates at low densities (Jørgensen, Christiansen, and Jobling 1993).

Behaviour control is key to improved welfare. There is a need for better understanding of fish behaviour in general in order to gain insights into how to better maintain schooling behaviour. This is a research area that has often been neglected, but as closed and semi-closed aquaculture farming systems become more popular e.g. in Norway, with the potential to become the new standard, new designs that are engineered to cater for behavioural control will be promising in improving welfare. In such systems the total environment can be control and currents, counter currents and lighting can be engineered so that fish are encouraged to align themselves to their neighbour and swim in the same direction. This will keep the fish calm, significantly reduce stress and reduce the likelihood of the fish obtaining physical injuries from swimming into each other or into the nets.

Technology Readiness Level: 6-8; Technical risk: Moderate

Modified RAS systems for less handling: The Danish company Kruger has developed a specialised ASC certified system with reduced handling, based on the RAS model (State of Green). The whole system is designed to reduce handling, consisting of two circular tanks, divided into sections. Fish can be aggregated in the sections by moving the separation grids in the circular tanks, and that way fish can be transferred from one tank to another without handling. There are currently four of these in operation for farming kingfish and salmon. Rainbow trout has also successfully been farmed in their systems. Growth and survival of the fish is the focus, welfare as such is not the focus. The main advantage of the system is the low footprint (land use), the high water quality and that the water velocity can be adapted to the fish. It requires a velocity of 0.2 litres per second and so not suitable for bottom dwelling species such as e.g. turbot. Please also refer to chapter 10 ‘Production and handling’ for further examples.

Technology Readiness Level: 9; Technical risk: Moderate

Reduced stocking density: The high stocking densities for conventionally produced salmon cause stress. Lower stocking densities is a possible improvement (personal communications), however too low densities can cause territoriality and aggression. Lower stocking densities would reduce the number of available hosts for parasites and disease, thus alleviating some of the severe problems that the industry is facing today (The Fish Site 2018). Practical approaches as alternative ways of crowding includes attractants e.g. leading the fish with light (Føre *et al.* 2014).

Technology Readiness Level: 6-8; Technical risk: Moderate

Feed for improved welfare: Feeding regimes are linked to welfare, especially in relation to starvation periods. It is common practice to starve fish prior to transfer and slaughter but research is still needed to determine optimal starvation periods. Currently, there is debate that fish are starved for periods longer than needed for gut emptying with the potential of leading to decreased welfare (Waagbø *et al.* 2017). The use of different additives in fish diets to mitigate stress responses has been deeply studied (Herrera, Mancera, and Costas 2019). Also, feed to discourage sea lice from feeding on the fish are being developed (Global Salmon Initiative 2019). Such feed both strengthens the fishes external barriers by thickening protective mucus layers on the skin and boosting fish immune and inflammatory responses, as well as affecting the sea lice by altering their development/growth, decreasing their ability to attach to the fish and reducing the immune suppression caused by sea lice. Please refer to chapter 8 for further details on nutrition and feed.

Technology Readiness Level: 9; Technical risk: Moderate

Environmental enrichment: In 2016 at the Loch Duart salmon company in Scotland the welfare benefits of environmental enrichment for tank-based juveniles was tested by introducing a string of coloured balls and some tarpaulin in the tank. Animal welfare is a primary concern for Loch Duart, whose production has long been Royal Society for the Prevention of Cruelty to Animals (RSPCA) Assured[1]. This standard covers all aspects of the fishes' lives, including health, diet, water quality, husbandry, handling and slaughter. However, they noticed that the juveniles were nipping each other's fins, a practice that needed to be controlled to prevent damage to the health and quality of the fish. Fin nipping is similar to tail biting in farmed pigs and feather pecking in farmed hens, but less understood. After a short trial with environmental enrichment, dorsal fin quality appeared to be improved (Global Aquaculture Alliance 2016). The use of tarpaulin has been trialled at other farms in Scotland.

Environmental enrichment providing the fish with something to play with is in line with findings made by Gordon Burghardt and team at the University of Tennessee, the first to document play with objects in a cichlid fish species, which includes tilapia (Burghardt, Dinets, and Murphy 2015). Burghardt, a professor in the departments of psychology, ecology and evolutionary biology, is known for defining play in a way that allows it to be identified in species not previously thought capable of doing so, such as wasps, reptiles and invertebrates. He defines play as “a repeated behaviour that is incompletely functional in the context or at the age in which it is performed and is initiated voluntarily when the animal or person is in a relaxed or low-stress setting. Play is an integral part of life and may make a life worth living” (Burghardt, Dinets, and Murphy 2015).

Technology Readiness Level: 6-8; Technical risk: Low

Non-physical enrichment stimuli: Physical installations are not feasible as these will interfere with e.g. cleaning regimes and so environmental enrichment focus is on stimuli / installations that cause minimum disruption to the farm environment e.g. sound stimulation. Sound levels and frequencies measured within intensive aquaculture systems, and especially during transport, are within the range of fish hearing, but species-specific effects of aquaculture production noise are not well defined (Davidson, Bebak, and Mazik 2009).

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[1] RSPCA Assured: https://www.rspcaassured.org.uk/about-us

It has been observed that noise levels can negatively impact behaviour, growth, feed conversion, smoltification rates and survival of fish (Terhune *et al.* 1990; Davidson, Bebak, and Mazik 2009; Cox *et al.* 2016). Hence, chronic exposure to aquaculture production noise is likely to impact stress levels, reduced growth rates and feed conversion efficiency (Aquaculture North America 2018). Musical stimuli could be considered as a growth promoting factor ensuring fish welfare in intensive aquaculture facilities (Kusku *et al.* 2019).

Technology Readiness Level: 3-5; Technical risk: Low

Predator attack deterrent systems: Attacks by predators lead to holes in the nets, large enough for fish to escape, as well as increasing stress levels in the farmed fish. Using e.g. ultrasonic transmission developed by OTAQ, SealFence creates an acoustic “fence” of protection around cages as a deterrent against seal and sea lion attacks. See also chapter 5 on Aquaculture environment and ecosystem monitoring and impacts.

Technology Readiness Level: 6-8; Technical risk: Moderate

Innovation with a potential for incremental performance improvement

Biomarkers for stress identification: Various biomarkers and methods to measure those have been developed for different life cycle stages of farmed fish (Kroon, Streten, and Harries 2017). Examples include e.g. glucocorticoid profiling in whole body of a single fish larva, in tank water or in scales as biomarker for chronic stress (Aerts and Saeger 2016).

Technology Readiness Level: 6-8; Technical risk: Low

Monitoring of behavioural welfare indicators: Behavioural welfare indicators have the advantage of being fast and easy to observe and therefore are good candidates for use in aquaculture (Goddek *et al.* 2019). According to FAO (2018), more than 350 finfish species are cultivated in aquaculture. Many of these species evolved in a variety of entirely different habitats and adapted to different environmental conditions and thus developed highly diverse biological traits. However, common for all species is that changes in foraging behaviour, ventilatory activity, aggression, individual and group swimming behaviour, stereotypic and abnormal behaviour have been linked with acute and chronic stressors in aquaculture and can therefore be regarded as likely indicators of poor welfare (Martins *et al.* 2012).

On the contrary, measurements of exploratory behaviour, feed anticipatory activity and reward-related operant behaviour are beginning to be considered as indicators of positive emotions and welfare in fish. Despite the lack of scientific agreement about the existence of sentience in fish, the possibility that they are capable of both positive and negative emotions may contribute to the development of new strategies (e.g. environmental enrichment, see below).

The need to develop on-farm, operational behavioural welfare indicators that can be easily used to assess not only the individual welfare but also the welfare of the whole group (e.g. spatial distribution) was already mentioned around 10 years ago (personal communication). With technology progress and ongoing development of video technology and image processing, on-farm surveillance of behaviour at a relatively low-cost is now a non-invasive tool that can be used to assess the welfare of farmed fish. In recent years, a Qualitative Behavioural Assessment (QBA) method has been developed.

Monitoring of fish behaviour (as outlined above) and live data feeds from pens is an area with much development. This includes vision systems with deep learning, which can localise and analyse unusual patterns of behaviour to identify aggressive or stressed behaviour (personal communication). Artificial intelligence is starting to be incorporated, an example is the CreateView sensor, which combines sensors, cameras and machine learning (The Explorer 2016).

Technology Readiness Level: 6-8; Technical risk: Moderate

Database approach: As an example, the database FishEthoBase aims to provide information on the welfare of all fish species currently farmed worldwide (Saraiva *et al.* 2019). Presently with 41 species, this database is directed to all stakeholders in the field and targets not only to bridge the gaps between them but also to provide scientific information to improve the welfare of fish. Such frameworks are proposed as fundamental to the design of strategies that improve the welfare of farmed fish.

Technology Readiness Level: 6-8; Technical risk: Low

Physiological measures: Using data loggers in the form of implants for measuring physiological parameters such as heartrate, body temperature, gut blood flow etc. This is useful as a research tool but are too invasive and too stressful for the fish to use on a commercial scale (personal communication). Bio-loggers for remote monitoring of physiological and behavioural variables have provided unique insights into ‘real-life’ responses of fish, which can largely differ from the responses observed in confined laboratory settings. This has been made possible by the rapid development and miniaturisation of bio-loggers and biotelemetry systems presents a solution, as it allows the remote recording of physiological data in free-living organisms over long uninterrupted periods (Brijs *et al.* 2019).

Technology Readiness Level: 3-5; Technical risk: Moderate

7.5 Transportation

All handling of fish is likely to cause increased stress levels. Handling occurs during transportation, sorting, vaccination and non-feed based medical treatment (e.g. chemical treatment for salmon lice as outlined above and in the chapter on Pests and Disease Management). Transportation typically includes juveniles being brought to a growing on facility, mature fish being moved to a new growing on facility or fish ready for slaughter being moved from the farm to the processing facility.

Transport includes overland transport and sea transport. Overland transport is normally by truck with closed system tanks, where sensors measure temperature and oxygen levels in the water. Sea transport is by well-boats or ships with build-in tanks and the system may be open or closed depending on biosecurity measures, regulations or risk of fish pathogen contamination on route (Bergevoet *et al.* 2017).

The tolerance to stress varies between the species. Good handling by well-trained staff is essential to minimising stress and achieving good welfare practices, especially during loading and unloading of the transport vehicles. The main welfare concerns include changes in stocking density, crowding, handling and loading and unloading, water movements, noise and vibrations and poor water quality (Farrell *et al.* 2010). Close monitoring of the fish and the water is needed throughout the journey (Eurogroup for Animals 2018).

Short distance transport e.g. between ponds, from pond to grading or processing plant or for loading and unloading well-boats can be done using fish pumping systems e.g. Euskan systems[1]. Vacuum-based, smaller scale pumps can lead to exhaustion of fish because they may resist travelling with the flow of water. It has been observed that after vacuum pumping, salmon may struggle to swim into an automated percussive stunner and some may be incapable of remaining upright for effective stunning. Roth, Birkeland and Oyarzun found that

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[1] Euskan: http://euskan.com/

stunning Atlantic salmon at the rearing cage produced fillets with better quality attributes (e.g. higher pH, later onset of rigor mortis, best colour and less gaping), whilst pre-rigor filleted fillets became lighter in colour with increasing pumping distance (up to 120 metres) from the cage. The authors concluded that, for flesh quality, pumping of conscious fish should be minimised (Roth, Birkeland, and Oyarzun 2009).

Innovation with a potential for transformative performance improvement

Sedation during transport: Studies have suggested that stress during transportation can be reduced by adding a sedative to the water. However, one should be aware that this can cause increased oxygen consumption and that oxygen levels must be closely monitored and extra oxygen added to water if necessary.

More recently it has been shown that sedation affects the fish stress response and to some extent their osmoregulation (Espmark 2017). The study, however, does not include data suggesting that the effect persists long after the sedation has ceased or that sedation has a long-term negative effect on performance, but they also have no data showing the opposite. In situations where it is expected that the fish provide great resistance, sedation can prevent the fish from getting injuries due to collisions and hard swimming activity. It is therefore advisable to cautiously sedate, and only when needed, i.e. in situations where the fish is handled a lot and where it is expected that the fish must work a lot, and to avoid repetitive and long-lasting sedation (Espmark 2017).

Technology Readiness Level: 9; Technical risk: Moderate

Improved pumping systems: Increased capacity impeller pumps are better for fish welfare than smaller pumps used in aquaculture. These newer impeller pumps are typically bigger with e.g. 400mm in and outlet, taking in more water and with a much higher capacity of e.g. 1000 tons/hour. The speed, large water volume and hence the pressure allows for the fish to keep a distance to one another and therefore fish experience less stress and less physical damage. The pump designs are made so that the pressure does not result in high G force experience. Tests in the past showed that fish were exposed to up to 14G in standard impeller pumps, which caused fish to haemorrhage especially around the heart (personal communication).

Another example is the AquaLife Biostream BP60 fish pump[1] from AquaLife. By using Computational Fluid Dynamics (CFD) and simulating the flow of water and fish in single vane snail pumps already on the market, several problems have been addressed in the new design of the Biostream. Using data generated from the CFD software, the design of the BioStream was developed to generate maximum discharge heads while still allowing operation at very low speeds.

Another pump with a focus on improved welfare is from the Irish company SeaQuest[2], which has a high capacity and high lifting performance without too much pressure in the pump. A 400mm inlet & outlet allows the pumping of larger species without the risk of any harm. Recent vet testing in Norway has proven this pump to have 300% less stress on the fish during the process compared to the more traditional pumping processes. The fish go through the system much faster than in the older vacuum pump systems.

Technology Readiness Level: 9; Technical risk: Moderate

Innovation with a potential for incremental performance improvement

Natural anaesthetics: The challenge is to discover environmentally friendly natural anaesthetics with strong effect, low costs, and no negative effects on stunned fish. From a higher quality perspective, there is an increased interest in anaesthetising fish, which can then be transported in larger quantities without being stressed during transfer. Some studies have demonstrated that the bioactivities of aquatic “products” are better than terrestrial products and thus, derivatives from seaweeds represent a potential source for exploration when identifying natural anaesthetics (Purbosari *et al.* 2019).

Technology Readiness Level: 6-8; Technical risk: Moderate

Co-operation between farms: The effect of adhering to improved animal welfare practices on the cost price for the average fish farm in Europe is quite limited in most cases (Bergevoet *et al.* 2017). Nevertheless, low or negative income, which can be common on carp and sea bass/sea bream farms, might prevent enterprises from investing €150,000-200,000 in improved animal welfare practices. On relatively small-scale farms, such as the average carp

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[1] Aqualife Biostream fish pump: https://www.sterner.co.uk/docs/Biostream.pdf

[2] SeaQuest live fish pump: https://seaquest.ie/fps16-01-live-fish-pump/

farm in Germany and Romania, and the average trout farm in France, the effect on cost price can be substantial. In these cases, co-operation between farms, for the use of specialist transporters and slaughterhouses, will increase the throughput of fish and thus reduce costs. For trout in Germany, for example, the use of specialised abattoirs is already common practice.

In situations where investments in improved animal welfare practices can be combined with labour saving, such as in salmon and portion-sized trout operations, a cost reduction might even occur, as is the case on relatively large-scale salmon farms in Norway and trout farms in Italy (Bergevoet *et al.* 2017; FAO n.d.).

7.6 Slaughter

An important farmed fish welfare challenge is in relation to the slaughter activity. The farming capacity has increased drastically over the past 10 years, and the killing and slaughtering methods have not scaled as fast.

The fasting prior to slaughter is believed to cause enhanced levels of stress, as well as the crowding during transportation and processing / harvesting the fish. Research is mainly focused on the actual method of killing the fish.

European legislation requires farmed fish to be stunned prior to slaughter. So far, scientists have identified humane stunning parameters for 17 species of farmed finfish (Humane Slaughter Association. 2018). Today, the two main methods used for stunning in Europe are electric stunning and percussive stunning. Interviewed experts highlighted that the key challenge with regards to farmed fish welfare in Europe is around stunning and slaughtering, followed by crowding (appreciating that these factors are not even being discussed yet in other parts of the world), *“as methods currently used have not been updated and that goes for all farmed species”* (personal communication). It is e.g. known that visual indicators of subconsciousness are not sufficient as it is not possible to tell if the fish are unconscious or just paralysed, yet, most methods rely on visual indicators only.

Previously, CO_2 was used for stunning, however this method was banned in 2012 following pressure from the Norwegian Animal Protection Alliance as CO_2 is believed to cause a feeling of suffocation in fish.

The impact of improved animal welfare practices on product quality is complex, because the effects may vary between welfare practices and between the fish species under consideration. Improved welfare practices such as percussion and electrical stunning can lead to carcass damage, but this can be avoided or minimised by drawing up specifications to ensure little or no detriment to product quality. As fish welfare becomes more widely acknowledged as a factor in product quality, it can be expected that more attention will be given to identifying practices that improve both welfare and product quality (Bergevoet *et al.* 2017).

Currently common carp are stunned and killed by a manual blow to the head, with a period of prior exposure to air. Exposure to air for 10 minutes, as is common practice, is stressful. Electrical stunning in water is also used. For rainbow trout, electrical stunning and asphyxia in ice are the most common methods, although manual percussion, CO_2 stunning, and chilling in ice slurry followed by electrical stunning are also used to a limited extent in France. Asphyxia in ice is still the most common slaughter method for European sea bass and gilthead sea bream; electrical stunning is still in an experimental stage in Greece for these species.

Innovation with a potential for disruptive performance improvement

Processing boats: Processing boat in e.g. the salmon industry enables the salmon to be slaughtered in a large, converted well-boats on site. Hence, there is no need for crowding, starvation, loading and unloading in order to transport the fish to a slaughtering facility. Processing boats are furthermore more economic, as they are more efficient and with a smaller carbon footprint and better for disease control. The use of processing vessels shorten the down the time and with a capacity of 1000 ton it takes seven to eight hours for empty a standard cage with pumping, stunning, killing and gutting. There are very few mortalities in this process, which means that all harvested fish are fit for human consumption (personal communication).

Transporting fish often involves mortalities due to e.g. cardiac arrest as many of the fish harbour viral heart infections and so it is often the biggest and fattest ones that end up dying during transport. In the salmon industry up to 20-40% of the fish can die of heart burst and so there is a great welfare and economic risk aspect to transport (personal communication). With the average capacity of 200 tons of salmon per day, the standard of a typical slaughtering facility in Norway (Jensen 2018a), it takes around five days to empty one cage and an additional one to two extra days of waiting if bad weather conditions. During this time the fish are starved and often crowded and becoming increasingly stressed.

Technology Readiness Level: 9; Technical risk: Moderate

Innovation with a potential for transformative performance improvement

Consumer communication / assurance schemes to improve fish welfare at slaughter: There is a need for scientific research and development to keep-up with the requirements of aquaculture standards and to identify humane stunning methods and parameters for fish species covered by the different schemes. Assurance schemes might wish to be involved in funding such research and assisting finfish producers in adopting humane slaughter technology. Communication of the scientific research investigating the capabilities of finfish to experience fear and pain, is necessary to enable the global general public to identify fish as animals that can suffer. Making consumers aware of the existence of technology for more humane slaughter of fish may encourage consumers to choose products with fish welfare in mind (e.g. by selecting assured products/brands). To this end e.g. the Humane Slaughter Association is producing a short video for the public, describing fish welfare and humane slaughter (Humane Slaughter Association 2018).

Technology Readiness Level: 9; Technical risk: Low

Vision technology: Also in slaughtering, developments in vision technology for automation and increased precision are being made. An example include Tordivel's Scorpion 3D Stinger for Robot Vision (IMV Europe 2018). The Scorpion 3D Stinger for Robot Vision camera captures a 3D stereovision image of the salmon using structured light. It can locate five to ten fish simultaneously and guides the robot by first finding the fin and then calculating where to insert the needle. This has to be done in 3D, as the system needs to know the height profile of the fish to correct for perspective errors. The capacity is around 4,800 fish per hour, which are said to be killed quickly and accurately. The robot has a 90 percent hit rate and removes what is otherwise a tough and laborious job for a worker. The system is estimated to pay for itself in 6 to 12 months in Norwegian slaughter houses.

Electrical in-water stun-kill system: Electrical methods can be divided into two types: stunning only (electronarcosis), where the stun is quickly followed by a method of killing; and stun/kill (electrocution), where fish are rendered permanently insensible by an electrical current, so there is no need, for welfare reasons, to follow up with any other procedure.

Historically, only 5% of UK Atlantic salmon were electrically stunned between 2009-2013; the rest were percussively stunned (Bergevoet *et al.* 2017). Similarly, electrical stunning of rainbow trout was previously trialled in Poland but abandoned due to carcass damage (Bergevoet *et al.* 2017). Members of the Atlantic salmon industry would like to use in-water electrical stunning because of the benefits for the fish (e.g. reduced stress because fish are not immersed before stunning) but it has been difficult to find equipment (or parameters perhaps) that are suitable. Previously, a disadvantage of whole-body electrical stunning for all vertebrates, was the risk of damage to the flesh. Haemorrhaging, gill flaring and distorted or broken spines are some reasons given as to why conventional electrical stunning did not become widely used within the Atlantic salmon and European sea bass industries.

Humane Fish Harvester (HFH)[1] is a system which is described as an inline, in-water, stun-kill system, which can be used to either stun or stun and kill fish. It is made by a small manufacturing company with the manufacturing facility based in Northern Ireland. Fish are pumped from pens or tanks through a pipeline which is approximately 100 metres long. The pipeline is typically mounted on a suitable frame and occupies a footprint of 11. G m x 2.6 m x 2 m. On entry, the fish are rendered senseless in less than 1 second. The fish continue their passage through the pipeline which takes about 90 seconds, during which time the electric stun is maintained, and the fish die from asphyxia. The system is already in operation in Scotland and in the US ('Humane Fish Harvester - Smith-Root' n.d.). They have systems that work with fresh or sea water and can be operated in-line with a fish pump or a batch system. UK and global adoption is limited due to the following (main) reasons:

- Capital cost - €20k for a batch system or €60-90k for inline system. Most farmers have limited access to capital
- Bad reputation of electrical stun/kill systems – people are concerned about electrical safety and have also seen previous generation of systems that have caused damage to the fish. Systems now produced by Fish Management Systems address all these problems
- Existing investments – Many large factories have invested in other systems and are unwilling to change at this time

Another example is the "Humane Stunner Universal" from the UK-based company Ace Aquatec, which is said to reduce fish stress and handling by fully stunning any species while still in the water. The system comes with a unique flexible electronics system to protect against damage and has a capacity of up to 200 tonnes per hour ('Electric Stunning' n.d.).

Technology Readiness Level: 9; Technical risk: Moderate

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[1] Humane Fish Harvester: https://www.smith-root.com/aquaculture/humane-fish-harvester

Innovation with a potential for incremental performance improvement

Swim-in percussively stunning systems: The most common methods for slaughtering Atlantic salmon are percussion, and electrical stunning followed by a killing method. In most cases Atlantic salmon are removed from water before electrical stunning, which may, however, be more stressful than electrical stunning in water, as the fish are exposed to air. Live chilling with CO_2 is used to a limited extent in Norway. In Ireland, CO_2 stunning is still used to a limited extent, although its use is declining (Bergevoet *et al.* 2017). Swim-in stunning systems, such as the BAADER 101 automated Swim-In System[1] provide a higher welfare system in that they remove the need for pre-slaughter handling of fish as the automated harvest system takes advantage of the fish's natural behaviour where they swim into the stun/bleed machines.

Technology Readiness Level: 9; Technical risk: Low

Dry electrical stunning: A dry electrical stunning method has been proposed on research scale for turbot and common sole (Daskalova *et al.* 2016). This enabled fish to be humanely stunned irrespective of their orientation (i.e. even if the fish enter tail-first). However, the voltage requirements can be 40% greater. There are currently no large-scale stunning methods available for gilthead sea bream as electrical stunning parameters have not yet been identified/scientifically validated for percussive stunning is not suitable for the scale of a typical harvest (Humane Slaughter Association 2018).

Technology Readiness Level: 3-5; Technical risk: Moderate

Chemical stun-killing: Chemical stun-killing or rested-harvest methods may offer advantages for fish welfare if the fish are, thereafter, deemed safe for human consumption. Research has investigated AQUI-S® as a pre-slaughter sedative because it appears to reduce distress during emersion for application of the chosen method of stunning (e.g. percussive).

In the past trials with rested-harvest looking at physiological responses and fillet quality of channel catfish, *Ictalurus punctatus* have been undertaking with positive results (Bosworth *et al.* 2007). However, as AQUI-S® (isoeugenol) is currently the only approved in certain countries as an aquatic anaesthetic for use during harvesting of fish for human consumption

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[1] BAADER 101 Swin-in System:
https://www.baader.com/en/news/product_news/BAADER_101_Stunning_Bleeding.html?requested_lang=de&substitute_lang=en

(namely Australia, Chile, Costa Rica, Faroe Islands, Honduras, Korea, New Zealand and Vietnam), rested-harvest methods are still of limited-use globally because not all governments approve them from a food safety perspective.

In addition, consideration must be given as to whether isoeugenol may negatively affect other fish species' welfare. Ideally, for the farmers' ease and for fish welfare, chemical methods will stun-kill fish to enable a one-step slaughter process. However, it is likely to be a significant challenge to identify stun-kill doses of suitable chemicals which do not compromise consumer (i.e. human) health and safety.

Technology Readiness Level: 9; Technical risk: Moderate

Gas stunning has been proposed, where fish are exposed to a mixture of gases (e.g. argon and nitrogen) that produce unconsciousness or death through hypoxia or asphyxia Experiments were undertaken to investigate the effects of CO^{2}-Argon (Ar)-N^{2} mixtures which are reported to appear to cause less discomfort than CO2 alone, which is not considered humane (Roque 2016).

Technology Readiness Level: 3-5; Technical risk: Moderate

Revoking traditional methods: Ikejime is a killing method that was refined around 200 years ago in Japan. There are three variations on ikejime, submerging fish in ice water (a method known as no-jime), stunning the fish by immediately spiking them in the brain and leave them to bleed out in water through an incision in their gills (standard ikejime) or feeding a wire along the fish's spinal cord in between spiking and bleeding (shinkei-jime). All three methods are said to delay the process of putrefaction. Shinkei-jime is the most effective because it destroys nerves that would otherwise encourage the build-up of lactic acid (Waters 2019). It is however, advised that the fish is properly stunned first for any of these methods to be regarded as humane killing.

In Britain ikejime has so far been restricted to fishermen on smaller boats using lines, as opposed to nets. In Japan, where demand for ikejime fish is much higher, commercial fishermen have streamlined the process and tuna caught by Australian and New Zealand fleets bound for Japanese markets is often killed using the method. Ikejime fish can command a higher price than fish killed in other ways: in Britain the mark-up is about 150%. As a recent editorial in Fishes, a scientific journal, put it: *"when the welfare of animals is improved, both the quality of the product and its value increase – a rare case when the interest of the industry and the ethical standards underlying its activity walk hand in hand."*

Technology Readiness Level: 6-8; Technical risk: Moderate

Development of more accurate indicators of consciousness: Although some degree of generalisation is possible, there is no single set of behaviours that can be used for all species of finfish, to determine the effectiveness of stunning. It is therefore necessary to assess each type (e.g. order, family or genus), or even species, of fish. Visual indicators of subconsciousness are not sufficient to tell if the fish are unconscious or just paralysed and thus continuously scoring welfare outcomes should be used as part of a proactive programme of measurement and continuous improvement, including target setting (Humane slaughter Atlantic salmon 2018).

Technology Readiness Level: 3-5; Technical risk: Low

7.7 Welfare of farmed marine invertebrates

There is very little protection of farmed marine invertebrates such as shellfish and crustaceans. Historically, these species have been considered unable to perceive pain, and although this view has been challenged, changes with regards to welfare measures in the industry are slow (R. W. Elwood 2012; Diggles 2019).

Pain in crustaceans is an important area of animal welfare research because substantial numbers of them used in the food industry and the extreme treatments to which they are exposed should indicate the potential for improved welfare if evidence of pain is found (R. W. Elwood 2012). According to a preliminary investigation in the UK in 2017, looking at 325 lobsters (potentially wild-caught) housed in tanks outside restaurants, where housing was scored according to restraints, stocking density, lighting and shelter, it was concluded that basic requirements for these lobsters were not being met, thereby compromising their welfare (Carder 2017).

There is an increasing focus on welfare of crabs with the increasing industry of Red King Crab (Paralithodes camtchaticus) and Snow Crab (Chionoecetes opilio) in Norway (Lorentzen *et al.* 2018).

In January 2018 the government in Switzerland passed a ruling that entered into force March 2018 that lobsters and other crustaceans will have to be stunned before they are put to death. In the UK the boiling of live lobsters is still permitted.

7.7.1 Stunning and killing crustaceans

There is very limited research on overall welfare of farmed seafood other than fish. It is for most species common practice to transport them live under cold conditions, which lowers their metabolism and induce a sort of hibernation state (personal communication). For the Red King Crab and the Snow Crab, this poses an industry challenge, as these animals are active at low temperatures and do not survive at over 4° C degrees.

The main focus with regards to welfare of crustaceans is on welfare of crustaceans at slaughter (Yue 2008). Splitting, spiking, chilling, boiling, gassing and "drowning" does not produce an immediate loss of consciousness. As crustaceans do not have a centralised nervous system, unlike vertebrates, they do not die immediately upon destruction of one discrete area, such as the brain. Thus, only method of stunning/killing crabs and lobsters that can produce an immediate loss of consciousness (within 1 second) is electrical stunning, enabling them to be killed without pain.

Innovation with a potential for transformative performance improvement

Crustastun electrical stunning and killing system: Technologies, including the Crustastun electrical stunning and killing system, developed in the UK may improve the welfare of crustaceans during slaughter, which is critically important as most if not all current techniques are inhumane.
Technology Readiness Level: 9; Technical risk: Low

Innovation with a potential for incremental performance improvement

Electric dry stunner: In a separate development, scientists in Norway have adapted the commercial dry stunner for fish (Stansas, from the equipment manufacturer Seaside) for the humane electrical stunning of edible crabs in bulk (Mood 2014). Crabs must be killed immediately after stunning (e.g. by boiling) to prevent recovery of consciousness.

Technology Readiness Level: 9; Technical risk: Low

Anaesthetic: Research suggests that humane killing of crustaceans may also be achieved using the fish anaesthetic AQUI-S which, though the process takes several minutes, appears not to cause distress (Yue 2008). The methods of spiking (crabs) and splitting (lobsters) are analogous to the spiking method of killing fish but take several seconds to perform.

Technology Readiness Level: 9; Technical risk: Moderate

High pressure processing: Lobsters, clams, crabs and oysters are also killed by high pressure in hydrostatic pressure processors[1]. The lobsters are crushed to death quickly in big batches, at the same time separating their meat from the shells without having to cook it. It is claimed that they are killed within 6 seconds, though it is unclear if there is any evidence to support this. The High Pressure Processing (HPP) method is more efficient in terms of separating 100% of meat from the shells. The same goes for oysters, clams and any seafood with shell attached to it. A welfare advantage of this method is that, by enabling the killing of bacteria without cooking, it could reduce the transport of live lobsters to restaurants and supermarkets. The method could presumably be made humane if the lobsters were electrically stunned before high pressure treatment.

Technology Readiness Level: 6-8; Technical risk: Low

Monitoring of behavioural welfare indicators: Stress behaviour is not well understood in crustaceans. Stress behaviour observed in crabs and lobsters includes trying to escape, thrashing and autotomy. Autotomy is a behavioural response in which limbs or other body parts are shed by the animal in response to damage or capture, or to stop the spread of potentially harmful stimuli to the rest of the body (Mood 2014). As, crustacean stress responses are typically preceded by escape behaviour it has been proposed that the physiological change might be attributed to the behaviour rather than a pain experience (Robert W. Elwood and Adams 2015). However, findings measuring lactate levels in relation to electric shock showed that behavioural responses to a variety of aversive stimuli, provide evidence of both short- and long-term changes similar to those changes found in cephalopods and vertebrates. That is, the criteria suggested to indicate pain in animals and thus it was concluded that crustaceans can perceive pain (Robert W. Elwood and Adams 2015).

Technology Readiness Level: 6-8; Technical risk: Low

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[1] Avure HPP: https://www.avure-hpp-foods.com/hpp-foods/seafood/

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8 Genetic improvement

Contents

From the SIF Executive Board

The method applied in this review has generated numerous examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently happening. It is recognised that there are existing innovations and research areas that are not included here, and new areas where future innovations may occur. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

8.1 Overview: genetic improvement

What is the challenge in the UK?

To date, the primary focus of R&D in genetic improvement of aquaculture in the UK has been salmon, with ground-breaking discoveries translating to significant improvements in animal health and welfare and profitability. Despite these successes, the genetic improvement of shellfish and other species has been limited. Numerous centres of excellence advance knowledge in their respective areas of expertise, but UK-grown commercial enterprises remain rare

What are the most promising innovation categories?

- **Improvement of important traits –** Disease resistance, robustness, etc.
- **Genomic selection –** Faster/greater gains than traditional selective breeding, projected to become industry standard
- **Genome editing –** Potential for rapid and widespread dissemination of improvements, with focus on CRISPR/Cas9 system
- **Epigenetics –** Identification of environmental-induced markers for more favourable breeding conditions with increased economical revenue

Where are important knowledge gaps?

- Genetic improvement of non-salmonid species
- Improvement of traits underpinned by polygenic genetic architecture

For millennia, humans have been genetically improving plants and animals through selective breeding. Since the 1970s, advancements in genetic research led to the modification of DNA, creating cisgenic (intraspecific recombinant DNA) and transgenic (interspecific recombinant DNA) species. Today, numerous technologies are available to improve aquatic genetic resources (The Fish Site 2015b).

By definition, aquatic genetic resources for food and agriculture include DNA, genes, chromosomes, tissues, gametes, embryos and other early life history stages, individuals, strains, stocks and communities of organisms of actual or potential value for food and agriculture (FAO 2019).

According to the recently released FAO report, “The State of the World’s Aquatic Genetic Resources for Food and Agriculture,” the first-ever global report of its kind is based on information provided by 92 countries representing 96% of global aquaculture production, the FAO argues that “wider, appropriate and long-term application of genetic improvement in aquaculture, with a focus on selective breeding, will help boost food production to meet a projected increase in demand for fish and fish products with relatively little extra feed, land, water and other inputs” (FAO 2019).

Currently however, aquaculture lags far behind terrestrial agriculture (crops and livestock) in terms of the characterisation, domestication and improvement of its genetic resources for food production. Most farmed aquatic species are either still sourced from the wild or in the early stages of domestication, suggesting that there is substantial standing genetic variation for traits of economic importance. The reproductive biology of aquatic species can be amenable to the application of genetics and breeding technologies, enabling high selection intensity and, therefore, genetic gain (Gratacap, Wargelius, and Houston 2019). Genetic resources were found to be managed at some level in about 60% of aquaculture species, with the remaining 40% cultured as wild types. Gratacap *et. al.* conclude that there is opportunity to significantly enhance sustainable aquaculture production through the strategic management and development of some of the more than 550 species currently farmed worldwide. Aquaculture geneticists in the report have stated that if all farmed aquatic species were in traditional selective breeding programmes alone, improvements in aquaculture production efficiency could produce a doubling in aquaculture production by 2050.

Biotechnologies are now increasingly used, albeit in a more limited range of species and geographies, to characterise genetic resources and further increase performance under farming conditions. One area of growing R&D interest since the 1990s is genomics, which applies the techniques of genetics and molecular biology to better understand genome structure, organisation, expression and functions, thus heralding the transition from hypothesis-driven research to data-driven research. Applications of genomic technologies have made large strides with plants and livestock animal species; however, similar applications in their aquaculture counterparts have been limited, with the exception of Atlantic salmon and perhaps rainbow trout, where private corporations run major breeding programmes. This limited application is largely attributed to the uncoupling of genome research with breeding programmes and a general lack of major breeding companies (FAO 2017).

In the public domain, genetically modified organisms for use in the food industry is a highly controversial topic. On the one hand, there are concerns surrounding their potential impacts on human, animal and environmental health and welfare. On the other hand, there are those who argue that the use of GMOs in aquaculture has exciting potential to contribute to the improved quantity, quality and sustainability of seafood production globally (The Fish Site 2015b; Gratacap *et al.* 2019a).

The FAO stresses the importance of resource allocation from the government and other sources to support the breeding programmes of aquaculture species, stating that “great progress will be made only when genomics research is well coupled with breeding programmes (FAO 2017)”. This is not only a matter of aquaculture production, but also of environment, animal welfare and sustainability because more efficient use of aquatic resources will have a positive impact on aquaculture and natural fisheries (personal communication).

8.1.1 State of research and development in the UK

To date, the primary focus of R&D in genetic improvement of aquaculture in the UK has been salmon, the predominant commercial species. Ground-breaking research includes the discovery ten years ago by researchers at the University of Edinburgh of a major quantitative trait locus (QTL) affecting resistance to Infectious Pancreatic Necrosis (IPN) in salmon, which enabled selection of lines with improved IPN resistance now used in numerous countries. This breakthrough was estimated to have produced an additional £26 million in gross value added to the UK economy annually. Since then, numerous projects have built on these outcomes, directly or indirectly, by using different tools and techniques to understand and improve production traits in various aquaculture species (University of Edinburgh 2016a).

And perhaps most importantly, this was a watershed moment serving as a bridge between academia and the aquaculture industry, convincing the latter that molecular genetic data was a powerful tool in improving aquaculture breeding (University of Edinburgh 2019).

Despite these successes, the genetic improvement of shellfish and other species in the UK has been limited, and lags behind, for instance, oyster breeding programmes in France (personal communication). China was highlighted as another leader in aquaculture genetics, however, much work remains unpublished in the English language, and thus inaccessible (personal communication).

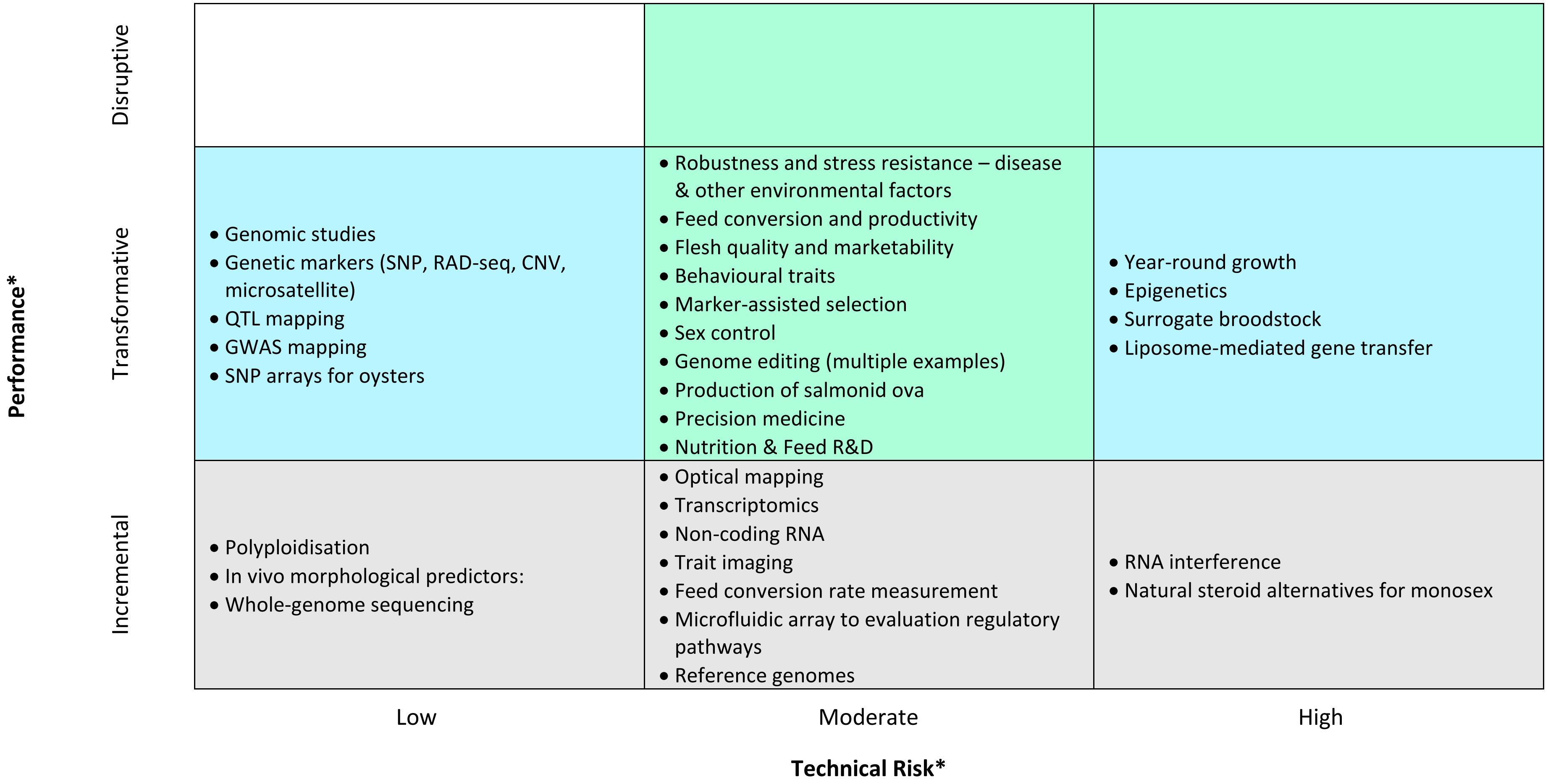
While regulation is indeed a factor for genome editing and transgenic modification, in general, it is not considered a barrier to advancing overall genetic improvement in aquaculture.

In terms of the approach in the UK, policy-makers and fish farmers may need to make decisions in the future on whether to try to farm more species to meet consumer and production demands, or to continue to diversify existing species into more productive strains, as has occurred in terrestrial agriculture.

Aquaculture genetics and breeding is an area where the UK has considerable strengths. While there is international competition (especially from USA, Scandinavia and emerging expertise in East and SE Asia), there is no reason why the UK should not be globally competitive - providing genetic services, and production of high performing fish to the table market (Seafish 2016). Doing so, however, will require cross-sectoral partnerships for greater efficiency as well as research funding to underpin technical advances and maintain skills at the leading edge.

NOTE: The focus of this chapter is to identify innovations in genetic improvement in aquaculture and research topics related to such innovation, and thus, excludes topics pertaining to fisheries and conservation.

An overview of the potential performance improvement rating of recent (2015-2019) innovations in genetic improvement in aquaculture are outlined in Figure 7-1.



Performance*	Technical Risk*		
	Low	Moderate	High
Disruptive			
Transformative	• Genomic studies • Genetic markers (SNP, RAD-seq, CNV, microsatellite) • QTL mapping • GWAS mapping • SNP arrays for oysters	• Robustness and stress resistance – disease & other environmental factors • Feed conversion and productivity • Flesh quality and marketability • Behavioural traits • Marker-assisted selection • Sex control • Genome editing (multiple examples) • Production of salmonid ova • Precision medicine • Nutrition & Feed R&D	• Year-round growth • Epigenetics • Surrogate broodstock • Liposome-mediated gene transfer
Incremental	• Polyploidisation • In vivo morphological predictors: • Whole-genome sequencing	• Optical mapping • Transcriptomics • Non-coding RNA • Trait imaging • Feed conversion rate measurement • Microfluidic array to evaluation regulatory pathways • Reference genomes	• RNA interference • Natural steroid alternatives for monosex

Figure 8-1: Performance and technical risk rating of innovations in genetic improvement in aquaculture.

**See section 4.4 for definitions of performance and technical risk rating scales.*

8.2 Genetic improvement of traits in aquaculture species

In this first section, examples of R&D efforts relating to specific desirable traits will be presented, primarily using species of particular economic importance to the UK.

8.2.1 Selective breeding

Selective breeding is a traditional genetic technology that has the longest history of use in aquaculture and is the most common form of genetic technology application reported globally. Selective breeding permits the accumulation of genetic gain in each generation, typically achieved within a well-managed, commercial programme of family and pedigree tracking, combined with extensive trait measurements on selection candidates or their relatives (Gutierrez and Houston 2017). Selective breeding programmes exist for various aquaculture species, such as Atlantic salmon, rainbow trout, tilapia, common carp, sea bream, channel catfish, European seabass, turbot, Pacific and eastern oyster, shrimps, scallops and pearl oysters, among 60 some species (Gjedrem and Baranski 2009).

The FAO states that well-designed, long-term selective breeding programmes, which can increase productivity of aquatic species by 10% per generation, is a good and often highly cost-effective strategy for strain improvement and domestication (FAO 2019a). Furthermore, aquaculture geneticists project that selective breeding alone could meet future demand for fish and fish products with few extra inputs such as feed and land (FAO 2019).

Genomic selection although still in the experimental stage or in the early phase of adoption, is projected to become the industry standard in aquaculture breeding programmes. Genomic selection uses the DNA profile (aided by genetic markers) of an individual to predict its potential to transmit genes of preferred traits to the next generation. Implementation is pioneered by the Atlantic Salmon industry. For any genomic breeding programme, a major obstacle is to reduce genotyping costs and to create cost-effective phenotyping of thousands of individuals under commercial conditions for traits such as fillet pigmentation, disease resistance and feed efficiency. However, genetic progress in selective breeding is limited by the heritability of the target traits (Gratacap, Wargelius, and Houston 2019). Optimisation work and power calculations can be used to find economically feasible production plans and experimental designs for both industry and research use (European Aquaculture Society 2019).

For rainbow trout aquaculture, genomic selection models were able to double the accuracy of predicted breeding values for bacterial cold water disease (BCWD) resistance, compared to a traditional pedigree-based model. Overall, it was found that in using a much smaller training sample size than similar studies in livestock, genomic selection could substantially improve the selection accuracy and genetic gains for BCWD (Vallejo *et al.* 2017).

The economic impact of genomic selection in Atlantic salmon aquaculture was conducted by the University of Wageningen, with results suggesting a growth rate up an additional 4%, feed conversion down 8%, sea lice resistance up an extra 9% and fillet yield up 4% - compared to family selection. This translated to a €291/tonne benefit for the farmer per generation (compared to €275/tonne for family selection) (The Fish Site 2018b). The following section presents a number of examples where genomic selection is employed.

Innovations with a potential for transformative performance improvement

Robustness and stress resistance - disease and parasites: As with all forms of intensive farming, disease has been a long-running issue in aquaculture, and one that is largely tackled with vaccines and antibiotics. But significant costs to aquaculturalists, and public concern relating to the potential overuse of antibiotics in some geographies are major issues. Research into disease-resistant fish may offer a way to reduce antibiotic and vaccination loads for the benefit of the economy as well as animal welfare.

Acceptance of the use of genetics as a solution to disease is increasing, resulting in more research and development efforts in the last five to ten years within academia, coupled with greater interest from companies in applying selective breeding for disease resistance (University of Edinburgh 2019).

However, despite several quantitative trait locus (QTL) studies in aquaculture species and ample evidence for the heritability of disease resistance traits, only a handful of large-effect QTL have been detected (e.g. infectious pancreatic necrosis), and most disease resistance and other production-relevant traits are underpinned by a polygenic (multiple genes) genetic architecture. As such, genetic improvement of disease resistance relies on family-based selective breeding programmes, augmented by the use of genomic selection (Gratacap, Wargelius, and Houston 2019).

Below are examples of topics currently being explored in this area. Research and innovation is focused around understanding the underlying genetic mechanisms of resistance, thereby enabling researchers to identify targets for improved or novel treatment strategies including the identification of novel traits for genomic selection.

Sea lice – Sea lice is the costliest disease-related problem in all major salmon-producing countries. Previous studies have shown the existence of genetic variation in resistance to sea lice (heritability of 0.22-0.33) and body weight (heritability of 0.5-0.6), and both traits were found to have a polygenic genetic architecture, hence lend themselves to genomic selection (European Aquaculture Society 2019). AquaBounty is currently exploring the underlying genetic mechanisms underpinning lice resistance in coho salmon skin for potential exploitation in Atlantic salmon, possibly via gene editing (Fish Farming Expert 2018c). In a Chilean/British study, a comparison between the skin transcriptome of sea lice-resistant and susceptible Atlantic salmon highlighted expression differences in several immune response and pattern recognition genes, and also in myogenic and iron availability factors. Components of the pathways may be targets for improved or novel treatment strategies, or for genomic selection (Robledo, Gutiérrez, *et al.* 2018).

Amoebic gill disease - Amoebic gill disease (AGD) is one of the largest threats to salmon aquaculture, causing serious economic and animal welfare burden. A group at the University of Edinburgh have discovered that indicator traits for AGD are indeed heritable and associated with two chromosome regions. Using a cross-validation approach, genomic prediction accuracy was up to 18% higher than that obtained using pedigree, and a reduction in marker density to ~2,000 single nucleotide polymorphisms (SNP) was sufficient to obtain accuracies similar to those obtained using the whole dataset, suggesting that AGD resistance is a suitable trait for genomic selection (Robledo, Matika, *et al.* 2018).

Winter ulcer disease (Moritella viscosa) - Wound-related mortality is a relatively serious issue in the salmon farming industry today, and the situation is worsened by frequent treatments against sea lice and AGD (Fish Farming Expert 2018b). Findings from an ongoing collaboration between AquaGen, Skretting ARC, Vaxxinova Norway and the Norwegian Veterinary Institute suggest that there is a genetic component to robust salmon skin, showing that healing of mechanical wounds and infection by the bacterium *Moritella viscosa* can be improved by breeding. Preliminary results are promising and will be supplemented with genomic selection, fine mapping and transcriptome studies, and studies of the combined effects of genetic selection, optimal diets and optimal vaccines on improved salmon skin robustness (European Aquaculture Society 2019).

Cardiomyopathic syndrome (CMS) - In a recent study conducted as part of the “SalmoResist” research project funded by the Research Council of Norway, Nofima and industry partners Marine Harvest (now Mowi) and SalmoBreed have uncovered two QTL markers for this disease that explained about 50% of the genetic variation of CMS resistance (Nofima 2018).

Bacterial cold water disease - Bacterial cold water disease (BCWD), caused by *Flavobacterium psychrophilum*, is an endemic and problematic disease in rainbow trout (*Oncorhynchus mykiss*) aquaculture. The National Center for Cool and Cold Water Aquaculture (USA) validated 37 single nucleotide polymorphisms (SNPs) and 3 QTLs associated with BCWD resistance and demonstrated that marker-assisted selection (MAS) for BCWD resistance is feasible in commercial rainbow trout breeding populations (S. Liu *et al.* 2018).

Oyster diseases (various) - Significant response to selection to improve disease resistance was observed after two to four generations of selection for *Haplosporidium nelsoni* and *Roseovarius crassostrea* in *Crassostrea virginica*, oyster herpes virus-1 in *Crassostrea gigas*, and *Martelia sydneyi* in *Saccostrea glomerata*. Generally, it seems breeding for higher resistance to one disease does not confer higher resistance or susceptibility to another disease (Dégremont, Garcia, and Allen 2015).

European sea bass - Akvaforsk Genetics is employing MAS on selective breeding of sea bass to increase resistance to viral nervous necrosis (VNN) also known as viral encephalopathy and retinopathy (VER). Their study was performed during two consecutive years in a commercial European sea bass programme and compared with traditional methods to prevent this disease (European Aquaculture Society 2019).

Technology Readiness Level: 3-5; Technical risk: Moderate

Marker-Assisted Selection (MAS): Also called marker-aided selection, MAS is a process whereby a selection decision is made based on the genotypes of DNA markers. MAS is especially useful for traits that are difficult to measure, lethal to measure, exhibit low heritability, and/or are expressed late in development. MAS has been applied mostly with plants and livestock animal species, but less so with aquaculture species (FAO 2017).

The best example of MAS in aquaculture species is perhaps the Japanese flounder, whereby MAS lymphocystis disease-resistant flounder had a market penetration rate of 35% in Japan in 2012 (Ozaki *et al.* 2012). Elsewhere, Akvaforsk Genetics is employing MAS on selective breeding of sea bass to increase resistance to viral nervous necrosis (VNN) also known as viral encephalopathy and retinopathy (VER). Their study was performed during two consecutive years in a commercial European sea bass programme and compared with traditional methods to prevent this disease (European Aquaculture Society 2019).

Technology Readiness Level: 6-8; Technical risk: Moderate

Robustness and stress resistance – other environmental factors: Reducing disease risk is not the only way in which farmed species are being bolstered. R&D activities are underway to increase resistance to stress and thermal tolerance, such as producing warm-water fish that can be farmed in colder waters. Below are examples of topics currently being explored in this area. Research and innovation is focused around understanding the underlying genetic mechanisms of tolerance or adaptation to relevant environmental factors, thereby enabling researchers to identify targets for genomic selection, generating more robust aquatic organisms.

Alkalinity stress - Researchers in China performed RNA sequencing (RNA-Seq) to survey the gill transcriptome of the Nile Tilapia and identify genes of potential importance to alkalinity tolerance. Differential expression analysis revealed 302 up-regulated and 193 down-regulated genes between differentially exposed fish, which may contribute to greater understanding of the molecular mechanisms of adaptation (Y. Zhao *et al.* 2015).

Salinity stress - Using RNA-seq technology, transcriptomic responses to salinity stress were studied in the Pacific oyster *Crassostrea gigas* exposed to low and optimal salinity seawater. Results highlighted genes related to osmoregulation, signalling and interactions of osmotic stress response, anti-apoptotic reactions as well as immune response, cell adhesion and communication, cytoskeleton and cell cycle (Xuelin Zhao *et al.* 2012).

Thermal stress - Heat tolerance is a complex and economically important trait for aquaculture breeding programmes. With global climate change, its importance is further mounting. A genome-wide association study (GWAS) was carried out on channel catfish using a SNP array. Three significant associated SNPs were detected and could be promising candidates for selecting heat-tolerant catfish lines after validating their effects on larger and various catfish populations (Jin *et al.* 2017). A team of researchers from the Netherlands and France conducted the first study to calculate the economic value of growth rate in different temperature conditions in the Mediterranean for sea bass, revealing the importance of variation in ambient temperatures for breeding programmes (Besson *et al.* 2016).

Overcrowding - A study on rainbow trout suggested that elevation of stocking densities and crowding resulted in the increase in stress-related *HSP70* gene expression and down-regulation of immune gene expression (Yarahmadi *et al.* 2016).

Technology Readiness Level: 3-5; Technical risk: Moderate

Please also refer to chapter 6 ‘Farmed animal health and welfare’.

Feed conversion and productivity: To further expand production, the aquaculture industry must continuously strive to overcome the high cost of feeds, which may account for 50 to 70% of production costs (and as much as 80% for smaller operations), depending on the species (Price 2014). Advances in genetic selection for growth, food conversion and flesh quality traits may also increase competitiveness in both production and marketing.

Below are examples of topics currently being explored in this area. Of all traits, genetic improvement of parameters relating to growth are the most advanced, largely due to their high priority and easier assessment (personal communication). Improvements in growth and yield in aquaculture is mainly the product of long-term selective breeding programmes and shorter-term crossbreeding, sterility, polyploidy and gene transfer methods. Genetic gain from selective breeding alone in Atlantic salmon has been greater than 12% per generation for growth rate and disease resistance, when challenge tests are applied (Gjedrem and Robinson 2014).

Cod - Norwegian venture Norcod[1], together with support from Nofima are set to revive large-scale cod aquaculture, thanks to a long-term breeding programme that has produced fish developed for faster growth, higher harvest yield and higher resistance. This farmed cod now grows up to 35 to 40% faster than fish in the wild, and a growth increase of approximately 3% annually, similar to farmed salmon (The Fish Site 2019f).

Tilapia - The Colombian government has recently granted permission to Spring Genetics[2] (Benchmark Holdings) to import a new high-performance tilapia strain with rapid growth, survivability and yield. More recently the company has also used advanced genomic selection to help it develop tilapia with improved resistance to *Streptococcus iniae* and *S. agalactiae* (The Fish Site 2019d).

Atlantic salmon - Results from a study identifying QTL affecting economically important complex traits in a commercial Atlantic salmon population, suggest that the traits are relatively polygenic and that QTL tend to be pleiotropic and relatively population-specific. Therefore, the application of marker or genomic selection for improvement in these traits is likely to be most effective when the discovery population is closely related to the selection candidates (e.g. within-family genomic selection) (Hsin Yuan Tsai *et al.* 2015). Follow-up work on a major locus

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[1] Norcod: https://www.norcod.no/

[2] Spring Genetics: http://spring-genetics.com/

harbouring the *vgll3* gene, explaining approximately one-third of individual variation in the maturation age of salmon, provide insights into the mechanisms by which *vgll3* is operating in reproductive systems and evidence for distinct regulation between sexes (Kjærner-Semb *et al.* 2018).

Technology Readiness Level: 9; Technical risk: Moderate

Please also refer to sections on: Genome editing and Gene transfer

Breeding for flesh quality and marketability: Flesh quality traits such as body composition and texture directly influence yield of final product and consumer preferences and thus, have long been considered in breeding goals. In the case of salmonids, however, to date there has been little information on the response to selection for carcass quality traits (Lhorente *et al.* 2019). Below are examples of topics currently being explored in this area. Genetic improvement of parameters relating to flesh quality are advanced due to their high priority and industry focus and represents an area of constant research and further improvements.

Flesh fat content - A group of Chinese researchers have located major QTL in the common carp for flesh fat content, an important trait in flesh quality of fish. These findings may pave the way for marker-assisted selection (MAS) programmes (Kuang *et al.* 2015).

Texture - In a Spanish study on gilthead sea bream, flesh quality traits such us body composition and texture were analysed, the latter for the first time. Heritabilities were medium for muscular fat, moisture and hardness, with relevance in breeding programmes (García-Celdrán *et al.* 2015).

Colour - A correlated response breeding study of coho salmon found a positive genetic trend for both harvest weight and flesh colour after eight generations of selection for the former, showing that selection for harvest weight can increase flesh colour (Dufflocq *et al.* 2017). Body colour, together with growth and survival, are traits of commercial importance in Pacific whiteleg shrimp (*Litopenaeus vannamei*). A first attempt to elucidate the genetic architecture of body colour discovered heritability dependent on environmental factors. Other findings were that the genetic improvement for body colour can be achieved through direct selection and increased redness colour is also expected to have favourable impacts on growth traits (Giang *et al.* 2019).

Technology Readiness Level: 5-8; Technical risk: Moderate

Breeding for behavioural traits: Genetic improvement of behavioural traits has the potential to improve the health and welfare of species, and reduce incidence of aggressive behaviour, cannibalism and farm escape. Research and innovation is focused around understanding the underlying genetic mechanisms of calm, non-aggressive behaviour, including lack of desire to escape, for researchers to identify targets for genomic selection. Breeding for behavioural traits is also an important part of addressing animal health and welfare. An example include Norcod's cod strain, which now show significant domestication, in the form of calm behaviour in the sea phase and little desire to escape (The Fish Site 2019f).

Technology Readiness Level: 6-8; Technical risk: Low

Please also refer to chapter 6 'Farmed animal health and welfare'.

Breeding for sex control: Several broad goals in aquaculture can be reached through a better understanding of sex control. These include: (i) prevention of precocious maturation and uncontrolled reproduction (e.g., in tilapia); (ii) the desire to farm monosex populations due to differences in growth rate and economic value of the sexes (e.g., tilapia, shrimp); (iii) reducing the impact of phenotypic sex on product quality (e.g., Atlantic salmon, oysters); (iv) increasing stability of mating systems (e.g., sex change in groupers) and (v)) environmental and/or intellectual property protection (e.g., non-indigenous species, or genetically improved strains) (Budd *et al.* 2015).). Below are examples of topics currently being explored in this area.

Crustaceans - Crustacean aquaculture production has developed rapidly in recent years due to increasing market demand in different regions of the world. Monosex crustacean aquaculture (all-male or all female) is being employed to achieve higher yields and reduce the risk of cannibalism. Sexual differentiation for crustaceans will continue to increase in the next few years, either for basic research or in aquaculture (Harlıoğlu and Farhadi 2017).

RNA interference - RNA interference (RNAi) based biotechnology using gene silencing was employed for the large-scale production of all-male freshwater prawn *Macrobrachium rosenbergii*. In addition to the aquaculture yield advantage, the use of RNAi in crustacean aquaculture seems to be safe due to its temporary nature (Lezer *et al.* 2015).

Natural steroid alternatives - The utilisation of steroid hormones to produce monosex tilapia populations is well-documented but due to the potential ecological and health-related hazards of such synthetic steroids, the use of plant materials, namely *Asparagus racemosus* root extract was explored as a potential alternative for the production of an all-male tilapia population (Mukherjee, Ghosal, and Chakraborty 2015). Please note that the Technology Readiness Level of this specific example is: 1-2; Technical risk: High

Technology Readiness Level: 5-8; Technical risk: Moderate

Modification of epigenetics: The transcriptional impact of epigenetic modifications, triggered by environmental stimuli, has been shown to influence the organism's phenotype. Therefore, understanding the environmental-induced epigenetic markers related to disease resistance or other economically important traits will allow the establishment of favourable breeding conditions with increased economical revenue (Granada *et al.* 2018). Although very challenging to study in aquaculture, epigenetics was identified as a particular area of promise in one interview (personal communication). An example includes the EU-funded programme ARRAINA[1] (2012-2016) which demonstrated that feed with fishmeal and fish oil inclusion rates as low as 3-5% still achieved excellent performance in commercially valuable species (Feed Navigator 2017).

Technology Readiness Level: 3-5, Technical risk: High

Innovations with a potential for incremental performance improvement

Polyploidisation: Genome polyploidy has been revealed to result in evolutionary advantages and novelties, and therefore, polyploid aquatic animals may possess excellent traits of economic interest including rapid growth, extensive adaptability and disease resistance (Zhou and Gui 2017). Furthermore, as the long-term impacts of farm escapes to wild populations remain unclear, one precautionary approach to minimise the risk of interbreeding with wild species can be to ensure that their farmed counterparts are sterile (e.g. triploid) (The Fish Site 2015b). Genetic technologies such as polyploidisation can produce significant one-time gains in the short-term. An example includes the commercial production of triploids, and the creation of tetraploid broodstock to support it, as an important technique in aquaculture of the eastern oyster, *Crassostrea virginica*. Tetraploids are produced by cytogenetic manipulation of embryos and have been shown to undergo chromosome loss with unknown consequences for breeding. In a study investigating the extent of aneuploidy, it was concluded that somatic chromosome loss may be a regular feature of early development in triploids, and perhaps polyploid oysters in general (de Sousa *et al.* 2016).

Technology Readiness Level: 9; Technical risk: Low

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[1] Project ARRAINA: http://www.arraina.eu/

8.2.2 Trait measurement

In order to accurately select the right animal as a breeding parent, geneticists need to track key characteristics, including body weight and morphometrics (size and shape). However, in aquaculture, data collection on individual animals offers significant challenges. The following are examples of innovations striving to circumvent these.

Innovations with a potential for incremental performance improvement

Trait imaging: Plant & Food Research has developed new image-based processes to measure a range of traits in fish automatically. The high-throughput system uses species-specific distinguishing features, such as visual patterning akin to a fingerprint, to identify individuals and track their growth over time. This information can be used to identify individuals with the right characteristics to offer potential as parents in aquaculture breeding programmes. The development project will assess the viability of this technology in a commercial environment by performing a number of test cases in trout (The Fish Site 2019a).

Technology Readiness Level: 6-8, Technical risk: Low

Feed conversion rate measurement: GenetiRate, a US-based start-up, has developed a technology that can predict feed conversion based on metabolic rates measured on fish larvae or muscle tissue of rainbow trout (Undercurrent News 2019b). This patent pending technology allows for "quantitative high-throughput measurement of metabolic rate to select individual aquatic animals with improved feed efficiency and growth rate."

Technology Readiness Level: 3-5, Technical risk: Moderate

***In vivo* morphological predictors:** A European consortium has discovered that there is a solid potential for genetic improvement of slaughter yields in common carp by selecting for predictor traits recorded on live breeding candidates, using external (phenotypes, 2D digitization) and internal measurements (ultrasound imagery) (Prchal *et al.* 2018).

Technology Readiness Level: 3-5, Technical risk: Low

Microfluidic array to evaluation regulatory pathways: US researchers have developed a targeted multi-tissue microfluidic array for the rapid evaluation of regulatory pathways in response to alternative feeding strategies, dietary formulations, and supplementation, as well as environmental and management effects as indicators of catfish appetite, growth, metabolism and intestinal health of channel catfish culture. This cost-effective platform can be transferred to other cultured fishes (Schroeter, Peterson, and Small 2016).

Technology Readiness Level: 6-8, Technical risk: Moderate

8.3 Non breeding-based technologies for genetic improvement

There is perhaps a greater range of genetic technologies that can be applied to aquatic genetic resources than is generally possible for terrestrial genetic diversity. Traditional approaches of selection, hybridization and crossbreeding are applied, but there are also means of readily manipulating ploidy and sex. Notably, the first transgenic animals produced for commercial food production were fish (FAO 2019).

As discussed in the previous section, genetic technologies can be applied in aquaculture for better disease and parasite resistance, increased production, control of reproduction, improved marketability, more efficient utilisation of resources, and better identification and characterisation of genetic resources.

Some technologies can be used for immediate short-term gain, whereas others are for longer-term gain, with genetic improvements accumulating each generation. While selective breeding has long been, and continues to be, the method of choice for genetic improvement in aquaculture species globally, others are attracting scientific and commercial interest. New developments in established and emerging technologies are outlined below.

8.3.1 Transgenesis

Gene transfer is a process of transferring one or a few foreign gene(s) into an organism. However, the foreign gene can be from other organisms (transgenic) or from the organism (cisgenic) itself. If the functions of a gene are well known, then the gene can be transferred into the organism to deliver the functions.

Public acceptance of transgenic fish has been relatively low because of two lines of concerns: (i) food safety concerns; and (ii) ecological safety concerns. The question on whether it is safe to consume transgenic fish has been one major question of consumers. As aquaculture species have aquatic living environments, tracking of transgenic aquatic animals is more difficult, and therefore the concerns over ecological safety have been serious (FAO 2017).

Since the first successful gene transfer in goldfish was demonstrated in 1985, transgenic fish have been produced with various aquaculture species, including rainbow trout, channel catfish, Nile tilapia and northern pike. According to one interviewee, any risks associated with the consumption of transgenic products was deemed “minimal” but ultimately, that potential risks will need to be weighed against benefits (personal communication).

Innovations with a potential for disruptive performance improvement

Year-round growth: Created by US biotech company Aqua Bounty Technologies, AquAdvantage® salmon contains a growth hormone from chinook salmon and a promoter from an antifreeze gene found in ocean pout, enabling it to grow year-round, not just seasonally. Growth time to marketable size is reduced from approximately three years to just 18 months, reducing the amount of feed required (Seafood Source 2019a). Having campaigned for two decades to obtain FDA approval to sell its fish, the company is now poised for an IPO and will launch their salmon in US stores soon (Forbes 2019). Although the salmon is now available in Canada, there is still considerable public and industry opposition (Seafood Source 2019c). A 2017 review of aquaculture in Europe advised the European Commission to await the market effects of GM salmon in North America before allowing it in Europe, stating that short-term development is unrealistic, not to mention lacking in demand (Salmon Business 2018).

Technology Readiness Level: 9; Technical risk: Moderate

Innovations with a potential for transformative performance improvement

Liposome-mediated gene transfer: The delivery of exogenous biomolecules into teleost eggs is currently mostly relying on the manual microinjection methods, which, due to their high costs and low throughput, are not economically feasible for large-scale aquaculture applications. Norwegian researchers have successfully demonstrated the use of liposomes as a system of delivery in Atlantic salmon eggs, opening an avenue for large-scale aquaculture therapeutic applications (Kumari *et al.* 2017).

Technology Readiness Level: 1-2; Technical risk: High

8.3.2 Genome editing

In contrast to transgenesis, which involves the transfer of a gene from one organism to another, genome editing allows specific, targeted and often minor changes to the genome of the species of interest and offer new solutions and opportunities in genetic improvement (Gratacap, Wargelius, and Houston 2019). The three main categories are (i) detecting, promoting, removing, or fixing targeted functional alleles at single or multiple QTL(s) segregating within current broodstock populations of a selective breeding program; (ii) targeted introgression-by-editing of favourable variants from different populations, strains, or species to introduce or improve novel traits in a population; and (iii) creating and *utilizing de novo* favourable alleles that are not known to exist elsewhere. Initial progress using other technologies has been largely superseded by the advent of the repurposed CRISPR/Cas9 system.

Target production traits for genome-editing studies in aquaculture species to date have included sterility, growth, and disease resistance. Should favourable alleles for a target trait (e.g., disease resistance) be created or discovered, then there is potential for widespread dissemination of the improved germplasm for rapid impact via selective breeding programmes.

According to one interviewed academic, genome editing is still in the experimental phase, and is more a research tool to better understand functionality and other parameters. However, recently the commercial application of genome editing for genetic improvement has particularly attracted the interest of the salmon industry and sparked industrial collaborations with academia.

Commercialisation of genome edited products is to date exceptionally rare, such as the recent approval of genome-edited tilapia in Argentina. Similar improvements to salmon would take “an additional several years,” excluding regulatory hurdles.

Genomic editing can provide numerous benefits to stakeholders across the sector including animal welfare, environmental impact and profitability.

Innovations with a potential for transformative performance improvement

Gene-edited tilapia: In 2018, transgenic salmon producer AquaBounty’s gene-edited line of tilapia was exempted from GM regulation in Argentina. According to AquaBounty, the developed tilapia demonstrates a significant improvement in fillet yield of 70%, a growth rate improvement of 16% and a feed conversion rate improvement of 14%, offering promise to producers to shorten the time to harvest (Fish Farming Expert 2018d).

Technology Readiness Level: 9; Technical risk: Moderate

CRISPR-Cas9 sterilisation: Following the successful sterilisation of Atlantic salmon using CRISPR-Cas9 technology, Norway's Institute of Marine Research conducted additional research to track the performance of the gene-edited salmon throughout their lifecycle. Although edited fish were smaller than controls at the beginning, differences later became insignificant. Growth rates were normal and smoltification capacity too, were on par with controls. Further research on stress response is required (The Fish Site 2019e).

Technology Readiness Level: 6-8; Technical risk: Moderate

Myostatin knockout: Japanese researchers have developed a strain of myostatin complete knockout red sea bream exhibiting a 16% increase in skeletal muscle within two years, a rate significantly faster than that of conventional breeding methods (Kishimoto *et al.* 2018).

Technology Readiness Level: 3-5; Technical risk: Moderate

Fixing alleles at existing QTL: Simulations have demonstrated that harnessing genome editing for favourable causative alleles at multiple QTLs as part of a breeding programme has the potential to expedite genetic gain compared with pedigree or genomic selection alone (Gratacap *et al.* 2019b).

Technology Readiness Level: 6-8; Technical risk: Moderate

Introgression-by-editing: If alleles responsible for desirable intra- or interspecific variation in phenotype can be identified, then CRISPR technology potentially allows editing of the unfavourable allele in the target strain and/or species to correspond to the sequence of the favourable allele found in the related strain or species. This offers new opportunities to bypass traditional introgression, thereby avoiding the downsides associated with linkage drag and allows access to genetic variation in other strains and species that would not be possible using conventional selective breeding methods (Gratacap *et al.* 2019b).

Technology Readiness Level: 3-5; Technical risk: Moderate

Surrogate broodstock technology: Surrogate broodstock technology facilitates the production of donor-derived gametes in surrogates and comprises transplanting germ cells of a donor into recipients of a different strain or different species. Potential benefits in aquaculture include: (1) the efficient and reliable production of offspring carrying superior genetic traits; (2) the reduction of breeding times; (3) the long-term storage of valuable species or strains through cryopreservation; (4) the mass production of genetically sterile fish. It is expected that a combination of these techniques will greatly accelerate the breeding of aquaculture species (Yoshizaki and Yazawa 2019).

Technology Readiness Level: 3-5; Technical risk: High

8.4 Genetic improvement of feed raw materials

Please refer to chapter 8 ‘Nutrition and feeding’

8.5 Opportunities for multidisciplinary collaboration

The following examples represent potential opportunities in which advancements in genetic improvement and/or analysis in aquaculture may be commercially exploited, beyond food production.

Innovations with a potential for transformative performance improvement

Production of salmonid ova: A specialist activity supplying an international market. While this in itself would not make a huge economic impact, downstream impacts could be substantial as it also crosses over with the animal genetics and biotechnology sectors and would strengthen the UK as a leader in these areas of activity (Seafish 2016). However, tighter import controls may impact the success of international ova transfer.

Technology Readiness Level: 3-5; Technical risk: Moderate

Precision medicine: Work conducted by Pontifical Catholic University of Valparaíso in Chile showed that familiar variation explained reduced protection of commercial vaccines against bacterial pathogens such as piscirickettsiosis (*Piscirickettsia salmonis*) in Atlantic salmon. It was concluded that manufacture of vaccines for salmon should move towards a strategy of precision medicine, whereby the genetic variation of the host plays a key role in the development of effective vaccines (European Aquaculture Society 2019).

Technology Readiness Level: 3-5; Technical risk: Moderate

Nutrition and feed R&D: Evidence suggests that breeding programmes change fish traits in relation to growth, feed conversion ratio, lipid deposition and fillet percentage, but also specifically lipid metabolism, protein retention and adaptation to plant-based diets. Feeds hence need to be matched to the genetic characteristics of fish from breeding programmes.

Data from rainbow trout farms showed that breeding and feed development has had a strong favourable impact on economics and environmental footprint at farm-level (up to 70% reduction in nitrogen and phosphorus loading to water from 1980's onwards). Further improvements can be obtained by genomics (European Aquaculture Society 2019).

Technology Readiness Level: 3-5; Technical risk: Moderate

8.6 Genetic Research

The practical purpose of aquaculture genomics and genetics studies is to reveal the genetic basis of performance and production traits and use such information for genetic breeding programmes. With aquaculture species, domestication is a very recent event for many species. Genome-based technologies include DNA marker technologies, genome mapping technologies and sequencing technologies. To a certain extent, these technologies have been used in aquaculture species, and exhibit significant potential for their continued applications (FAO 2017).

With the second- and third-generation sequencing technologies, the cost of sequencing a genome with a size of one billion base pairs has reduced to manageable levels of approximately US$100,000. With such a major reduction in costs, the “sequencing rush” is on the way for many species. Genomes of at least two dozen aquaculture species have been sequenced or are now being sequenced. Of the six aquatic species groups included in the United States Animal Genome NRSP-8 Program, a whole genome has been sequenced for tilapia, rainbow trout, Atlantic salmon, catfish, striped bass, and oysters and shrimps (FAO 2017).

Innovations with a potential for transformative performance improvement

Reference genomes: The debate over whether brown trout (*Salmo trutta*) constitute a single species or several may soon be resolved, following the completion of the brown trout reference genome. This has been achieved by scientists at the Wellcome Sanger Institute and their collaborators and will enable researchers to identify any sub-species currently classified as brown trout (The Fish Site 2019h).

Technology Readiness Level: 9; Technical risk: Low

Species-specific development of Single Nucleotide Polymorphisms (SNP): Single nucleotide polymorphisms are single base-pair differences in DNA sequence at a specific region of the genome and considered one of the most obvious ways that genomics is benefitting the aquaculture industry. Today SNP markers are routinely applied and the preferred choice in several major finfish breeding programmes for both marker-assisted and genomic selection (FAO 2017). This is most evident in salmon, but the development of SNP arrays for sea bass and sea bream are enabling genomic selection in these smaller, but very important sectors for European aquaculture (European Aquaculture Society 2019).

Technology Readiness Level: 9; Technical risk: Low

SNP arrays for oysters (chips): A microarray platform that provides the genotype of an individual for many thousands of SNPs dispersed throughout the genome has become part of the state-of-the-art in several globally important aquaculture sectors, offering higher selection accuracies than selection based on phenotypic and pedigree records alone (Gratacap, Wargelius, and Houston 2019). In 2019, a consortium of 12 US universities and government agencies won a five-year, $4.4 million grant funded by NOAA Fisheries to accelerate and localise selective breeding of the eastern oyster *Crassostrea virginica*, including the development of a SNP chip as a reference (William & Mary 2019).

Technology Readiness Level: 6-8; Technical risk: Low

Restriction site-associated DNA sequencing (RAD-seq) markers: RAD sequencing (RAD-seq), refers to a method called restriction site-associated DNA sequencing that can identify and score thousands of genetic markers randomly distributed across the target genome from a group of individuals using next-generation sequencing technology. RAD-seq has been broadly used in aquaculture species. Future prospects are good, given the power of RAD-seq markers. However, for many applications involving over 100 individuals, analysis of a common set of RAD-seq markers is required (FAO 2017).

Technology Readiness Level: 9; Technical risk: Low

Application of 2b-restriction site-associated DNA sequencing method: The recently developed 2b-restriction site-associated DNA (2b-RAD) sequencing method was found to be a cost-effective and flexible genotyping platform for aquaculture species lacking sufficient genomic resources, when tested for the genomic selection of Yesso scallop (*Patinopecten yessoensis*), through simulation and real data analyses (Dou *et al.* 2016).

Technology Readiness Level: 9; Technical risk: Low

Copy number variation (CNV): Copy number variation (CNV) owing to insertions, deletions and duplication or multiplication of a DNA segment is widespread, and this type of genomic variation has recently caught the attention of genome researchers (FAO 2017).

When genes are involved, the duplicated or multiplied genes can affect genome expression activities. The significance of CNV is gaining interest, with suggestion they could potentially be used for whole genome selection programmes, upon identification of correlation or causation of certain genome segments with performance traits. The importance of CNV in teleost fish is further signified by the fact that teleost fish have an additional round of genome duplication followed by random gene loss, thereby resulting in various CNV situations involving various genes.

Technology Readiness Level: 6-8; Technical risk: Low

Microsatellite markers: Microsatellites are simple sequence repeats of 1-6 base pairs. They are highly abundant in various eukaryotic genomes, including all aquaculture species. Microsatellite markers are currently one of the most important to characterise and monitor aquatic genetic resources, namely for the construction of genetic linkage and quantitative trait locus (QTL) maps. Over the past decade, microsatellite markers have been used extensively in fisheries and aquaculture research, including studies of genome mapping, parentage, kinships and genetic structure of stocks, and the technology is constantly improved and refined (FAO 2017).

Technology Readiness Level: 9; Technical risk: Low

8.6.1 Genome mapping, sequencing and transcriptomics technologies

The genomes of aquaculture fish vary from several hundreds of millions of base pairs to several billion base pairs. Their study requires first “breaking” them into smaller pieces and then sorting out their relationships, which is the task of genome mapping. There are two distinctive types of mapping methods: genetic linkage mapping and physical mapping, which produce genetic linkage maps and physical maps, respectively. While both maps are a collection of genetic markers and gene loci, distances in genetic maps are based on the genetic linkage information and recombination rate between markers, while physical maps use actual physical distances of DNA, usually measured in the number of base pairs (FAO 2017).

Innovations with a potential for transformative performance improvement

Quantitative trait locus mapping: The fundamental goal of aquaculture genomics in the practical sense is to understand the genomic basis for performance and production traits. Because most aquaculture traits are complex traits that are likely controlled by multiple genes, quantitative trait locus (QTL) mapping is the core of applied aquaculture genomics. In recent years, notable progress has been made with QTL analyses conducted in several dozen aquaculture species. The studied traits include growth rate, disease resistance, sex maturation time, body conformation, fat content, response to stress, swimming abilities, salinity tolerance, muscle traits, osmoregulation capacities and smoltification, among others. Of these, the largest amount of efforts has been devoted to QTL mapping of growth traits and disease resistance.

Most disease resistance QTLs have a relatively small effect, suggesting many genes are involved in the resistance. In addition, it may also suggest that the phenotypic evaluation is difficult and the environment effect may be large such that the percentage of phenotypic variation explained by the QTL is small (FAO 2017).

Technology Readiness Level: 9; Technical risk: Low

Genome-wide association studies: Genome-wide association studies (GWAS) are another method for mapping genes involved in performance traits and has been extensively used for genetic analysis of genetic diseases in humans. It has been also used for aquaculture species, but is still in its infancy. Recently, GWAS was used to identify associated markers with fillet yield in rainbow trout (Gonzalez-Pena *et al.* 2016) and to identify genes associated with disease resistance against columnaris disease in catfish (Geng *et al.* 2015).

Technology Readiness Level: 9; Technical risk: Low

Innovations with a potential for incremental performance improvement

Optical mapping: Optical mapping is a physical mapping method for constructing high-resolution restriction maps of a whole genome from single, fluorescently stained molecules of DNA. Although the principles of optical mapping have been established for more than two decades, it has not been widely used until recently. This is largely due to recent technological advances in nanotechnology and the ability to optically capture the fluorescence from a single molecule of DNA. Optical mapping is now mostly used to validate the whole genome reference sequence but is not known to be used in aquaculture species (FAO 2017).

Technology Readiness Level: 6-8; Technical risk: Moderate

Innovations with a potential for incremental performance improvement

Whole genome sequencing: Third-generation sequencing technologies are marked by single molecule sequencing (SMS) and real-time sequencing. Some areas of applications include the following: (i) *de novo* genome sequencing, whole-genome resequencing; (ii) marker development for the identification of microsatellites or SNP markers; (iii) transcriptome sequencing for the analysis of genome level expression profiling and identification of differentially expressed genes or co-induced genes; (iv) large-scale analysis of epigenetic regulation, such as DNA methylation, by deep sequencing of bisulfite-treated DNA; and (v) genome-wide mapping of DNA-protein interactions by deep sequencing of DNA fragments pulled down by chromatin immunoprecipitation.

With the advances of the sequencing technologies, rapid progress continues to be made with whole genome sequencing of aquaculture species (FAO 2017).

Technology Readiness Level: 9; Technical risk: Low

Non-coding RNAs: The functions of non-coding RNAs are being unravelled and the discoveries are continuing. Abundant and functionally important types of non-coding RNAs include transfer RNAs (tRNAs) and ribosomal RNAs (rRNAs), as well as small RNAs such as microRNAs, siRNAs, piRNAs, and thus, are important for key pathways relevant to e.g. epigenetics and hence nutritional programming to achieve more efficient utilisation of sustainable feeds (please refer to section 8.9). A few studies are being conducted in rainbow trout and catfish but the studies are still in the stage of infancy (Paneru *et al.* 2016).

Technology Readiness Level: 1-2; Technical risk: Moderate

Transcriptomics: The application of other genomic tools to the industry, such as transcriptomics or metagenomics, appears to be further away, but holds potential. The transcriptome refers to the complete composition of RNAs of an organism. Recently, RNA sequencing using next-generation sequencing has allowed the most rapid progress (FAO 2017).

Technology Readiness Level: 1-2; Technical risk: Moderate

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9 Nutrition and feeding

Contents

From the SIF Executive Board

The method applied in this review has generated numerous examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently happening. It is recognised that there are existing innovations and research areas that are not included here, and new areas where future innovations may occur. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

9.1 Overview: nutrition and feeding

What is the challenge in the UK?

To further expand production in aquaculture, the industry must continuously strive to overcome the high cost of feeds, which accounts for at least 50% of production costs. The primary limiting factor is finite supplies of fishmeal and fish oil, leading to R&D in a slew of new raw materials. However, for best use of limited R&D resources, there is suggestion that greater dividends may be achieved by identifying essential or beneficial attributes of aquafeeds and developing complementary raw materials accordingly.

What are the most promising innovation categories?

- **Sustainable fish meal and fish oil alternatives** - Single cell and algal sources, and improvements to established plant-based raw materials
- **Enzymes** - Improving utilisation of plant-based fish meal alternatives
- **Tailor-made nutrition** - Species-specific nutrition research, improving nutrient utilisation for greater growth and ingredient sparing
- **Functional feeds** - Improving health and disease/stress resistance
- **Hatchery feeding** - Live feed, early weaning and microdiet alternatives

Where are important knowledge gaps?

- **Species-specific nutritional requirements** - Across all life stages, especially broodstock and larval stages
- **Ingredient/nutrient complementation** - Increasingly complex interactions among non-marine feed ingredients, with implications for functionality

Fish feed should satisfy every nutritional need of farmed fish. Developing feed thus requires a holistic understanding of the dynamic nutritional needs of a species, how best to deliver them in their production system, and the sustainability of the ingredients. From strengthening immune systems and the search for sustainable sources of omega-3 fatty acids, to reducing nutrient leaching through better utilisation, nutrition and feeding in aquaculture require the co-operation of numerous stakeholders to meet the needs of farmed fish, the aquaculture industry and the environment.

To further expand production the aquaculture industry must continuously strive to overcome the high cost of feeds, which globally, account for 50 to 70% of production costs (and as much as 80% for smaller operations) (Price 2014; Hassan 2017). This leads to the primary limiting factor - namely finite supplies of fishmeal and fish oil. The sector has grown over three decades to become the planet's main consumer of fishmeal, accounting for 73% of total consumption as of 2016 (Undercurrent News 2019a). However, it can no longer be the default choice with super prime fishmeal averaging $1,600 (£1,325) per tonne in June 2019 (IntraFish 2019a).

Given the limitations of wild catches and agricultural land, growth in the industry is predicted to come out of scalable, alternative feed ingredients. A slew of such raw materials is currently under development, from insect meal to single-cell proteins and a range of fermentation-based products, as well as oils such as algal oil or genetically modified canola oil. However, most of these ingredients are still in the early development phases.

Feed companies are following suit – according to the Marine Ingredients Organisation (IFFO), the global Fish in – Fish out (FIFO) ratio has declined from 0.63 in 2000 to 0.33 in 2010, and 0.22 in 2015 (IFFO 2015). Retailers too, spurred on by consumers, are demanding greater sustainability in the products they sell. Whole Foods Market and Tesco have set a precedent by reviewing feed standards and promoting sustainable ingredients alternatives (Undercurrent News 2019d; IntraFish 2019c).

Within the UK, aquafeed production, especially with regards to Atlantic salmon, is almost exclusively dominated by four (non-British) global companies: Skretting (Nutreco), BioMar, Ewos (Cargill) and Mowi.

Greater public awareness of issues pertaining to sustainability, the environment, food safety and animal welfare means that consumer interests are gradually spreading further up the supply chain to include aquaculture feed, health and welfare. Cost, however, appears to remain a major driver for British consumers, as in a recent study it was found that they were generally supportive of using avian-based processed animal protein (PAP) if it meant savings passed onto them. This was in stark contrast to retailers, who remained firmly against PAP (Fish Farming Expert 2018a). However, the line of consumer acceptability appears to be drawn at genetically modified feed ingredients, which are still met with resistance in the UK and Europe (BBC 2018).

Acceptance must also come from retailers, who are increasingly aware of the sustainability and ethical credentials of their products – following in the footsteps of leading edge British retailers M&S and Waitrose, Tesco will support key salmon suppliers in ramping up the use of omega-3 enriched algal oil in a bid to reduce the use of wild-caught fish in salmon feed, (IntraFish 2019c). However, the use of PAP in aquafeed is still met with reluctance (Fish Farming Expert 2018a).

According to Turchini, Trushenski and Glencross (2019), the staggering diversity of species, rearing systems, and culture conditions in aquaculture will always strain the resources available for R&D and will force researchers to thinly spread investments and effort across a broad array of data gaps. Instead of “doubling down” on the search for alternative raw materials, the authors argue that limited R&D resources may yield greater dividends by identifying essential or beneficial attributes of aquafeeds and developing complementary raw materials accordingly. In short, shifting our focus from one single raw material to nutrients and the way ingredients can complement each other as a strategy will likely open numerous and as-yet untapped possibilities for improving the next generation of aquafeeds (Turchini, Trushenski, and Glencross 2019).

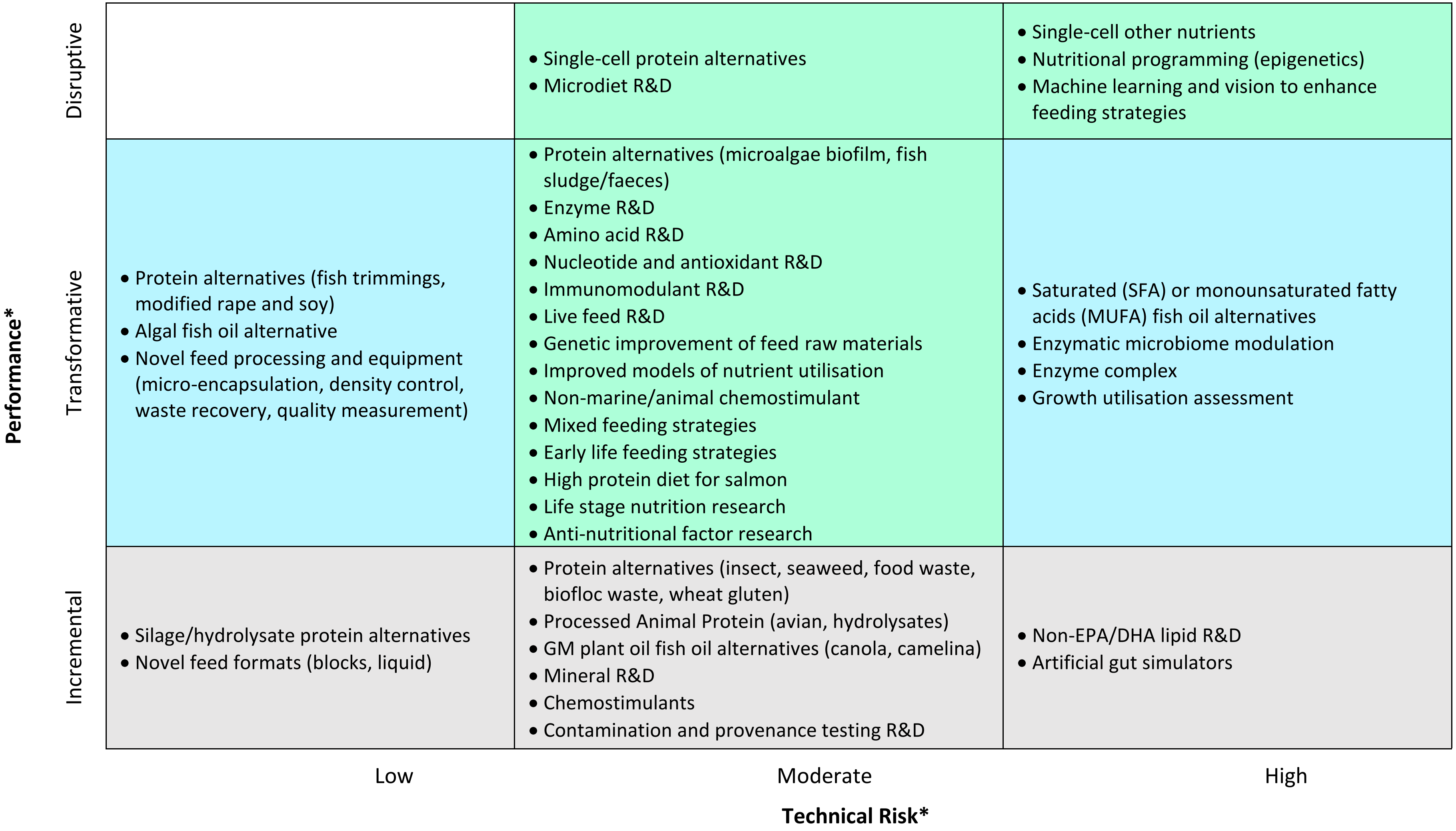
The continued expansion of intensive fish farming and changes in the composition of feeds will necessitate the determination of the amino acid, fatty acid, vitamin and mineral requirements for a wider range of fish species and life history stages (Jobling 2016).

Interviews with industry confirmed that despite five decades of progress, aquaculture nutrition R&D is still considered to be in its infancy, with scope for discovery even in established species such as salmon and halibut.

One aquafeed industry player advised that R&D in nutrition and feeding requires the full collaboration of all stakeholders including academia, which will need to pursue more “commercially viable” research interests to remain competitive. They also suggested that attention should be diverted from competing with soy or omega-3 fatty acids to other value-added products with health benefits (personal communication).

Another expert advised that in order to compete with the aquafeed giants of Japan and Scandinavia, to pursue value-added feeds catering to emerging aquaculture species such as cleaner fish, rather than established ones such as salmon. Success in the feed industry for small and medium players is possible by keeping abreast of new research developments and adjusting formulations quickly and flexibly, a challenge for larger companies (personal communication).

An overview of the potential performance improvement rating of recent (2015-2020) innovations in nutrition and feeding in aquaculture are outlined in Figure 8-1.



Performance*	Low	Moderate	High
Disruptive		• Single-cell protein alternatives • Microdiet R&D	• Single-cell other nutrients • Nutritional programming (epigenetics) • Machine learning and vision to enhance feeding strategies
Transformative	• Protein alternatives (fish trimmings, modified rape and soy) • Algal fish oil alternative • Novel feed processing and equipment (micro-encapsulation, density control, waste recovery, quality measurement)	• Protein alternatives (microalgae biofilm, fish sludge/faeces) • Enzyme R&D • Amino acid R&D • Nucleotide and antioxidant R&D • Immunomodulant R&D • Live feed R&D • Genetic improvement of feed raw materials • Improved models of nutrient utilisation • Non-marine/animal chemostimulant • Mixed feeding strategies • Early life feeding strategies • High protein diet for salmon • Life stage nutrition research • Anti-nutritional factor research	• Saturated (SFA) or monounsaturated fatty acids (MUFA) fish oil alternatives • Enzymatic microbiome modulation • Enzyme complex • Growth utilisation assessment
Incremental	• Silage/hydrolysate protein alternatives • Novel feed formats (blocks, liquid)	• Protein alternatives (insect, seaweed, food waste, biofloc waste, wheat gluten) • Processed Animal Protein (avian, hydrolysates) • GM plant oil fish oil alternatives (canola, camelina) • Mineral R&D • Chemostimulants • Contamination and provenance testing R&D	• Non-EPA/DHA lipid R&D • Artificial gut simulators

Technical Risk*

Figure 8-1: Performance and technical risk rating of innovations in nutrition and feeding in aquaculture.
** See section 4.4 for definitions of performance and technical risk rating scales.*

9.2 Fishmeal alternatives

In the past two decades, aquaculture nutrition research has made major strides in identifying alternatives to traditional marine-origin resources, with feed manufacturers worldwide replacing increasing amounts of fish meal and fish oil in aquafeeds (Turchini, Trushenski, and Glencross 2019). No longer seen as the "be-all, end-all" of raw materials, there is considerable economic incentive to reduce dependency on fishmeal and fish oil, and the combination of this and other incentives relating to sustainability, marketing, and consumer expectations is a powerful one. In recent news, aquafeed producer Salmofood has announced plans to achieve a fish-free diet in 2020 (Aquafeed 2020; personal communication).

Today, there is a limited amount of the alternate feed ingredients available: most of these are still in the early development phases (IntraFish 2019a). Despite promising milestones, the reality is that feeds containing little or no marine inputs routinely do not yield the same growth performance as traditional feeds in carnivorous species.

Furthermore, of high-performing FM/FO-free formulations, not all are considered economically viable, due to limited quantities, weak economies of scale and costly production, in addition to relying on expensive supplements to replace nutrients (e.g. taurine and other amino acids, cholesterol) found in marine-origin resources and to ensure feed attractability/palatability. Indeed, Aquafeed giant BioMar still deems fishmeal and fish oil as important raw materials because they contain many of the essential nutrients these novel ingredients do not have (IntraFish 2019a).

Another consideration is the overall environmental impact of these materials, not just on the sea but also agricultural land. In a recent study, it was found that the complete substitution of 20–30% fishmeal totals could lead to substantial increases in demand for fresh water (up to 63%), land (up to 81%), and phosphorus (up to 83%) (Malcorps *et al.* 2019).

There is suggestion that most of the "low-hanging fruit" in fishmeal and fish oil sparing has already been picked and that this approach has reached (or will soon reach) the point of diminishing returns. Still, as the sector develops, cost differences could be offset by the resulting performance or quality. However, expectations of high supply in the market should be reduced, and any scale-up will be incremental.

9.2.1 Single-cell technologies

Via gaseous fermentation, some companies can now produce proteins using the biological conversion of other compounds. Single-cell technologies are gaining interest for being both sustainable (easy growth, on substrates such as cellulose from forestry by-products) and space-saving. There is suggestion from industry that this technology shows great promise and more so than for instance, insect meal (Undercurrent News 2019e).

Innovations with a potential for disruptive performance improvement

Single-cell organism-derived protein: Below are examples of single-cell technologies currently being explored as a source of protein.

Methanotrophic bacteria - FeedKind®[1] protein is a sustainable fish feed ingredient made of naturally occurring methanotrophic microbes via fermentation. A trial showed shrimp fed a diet including FeedKind had equivalent or higher survival and growth compared to a standard fishmeal-based diet (Undercurrent News 2017a). In 2019, Norwegian research institute Nofima was said to launch large-scale feeding trials using FeedKind with salmon (Feed Navigator 2018a).

Methylobacteria - KnipBio[2], a US-based biotechnology company developing sustainable single-cell protein alternatives, has developed methylobacteria strains capable of providing taurine missing from many commercial fish feeds. Additional strains in their portfolio contain prebiotics and carotenoids (Undercurrent News 2017b)

Fungus - Prarie AquaTech[3], a US feed ingredients maker has developed MEPro, which is microbially enhanced (*Aureobasidium pullulans*) non-GMO soy protein, resulting in 70% (as fed) digestible protein (Undercurrent News 2019c).

Yeast - French animal health company Phileo[4] has recently launched ProSaf, a yeast extract containing a source of small size bioavailable peptides, free amino acids and nucleotides

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[1] FeedKind: http://www.feedkind.com/

[2] KnipBio: https://www.knipbio.com/

[3] Prarie AquaTech: https://www.prairieaquatech.com/

[4] Phileo: https://phileo-lesaffre.com/en/products/premium-yeast-protein-prosaf/

obtained from a proprietary *Saccharomyces cerevisiae* baker's yeast strain (Aquafeed 2018). A collaboration between Swedish and Vietnamese researchers found that spent brewer's yeast represents a possible high-volume substitute for fishmeal in tilapia diets, especially when reared in a biofloc environment (Nhi *et al.* 2018).

Technology Readiness Level: 9; Technical risk: Moderate

9.2.2 Microalgae

Marine microalgae may be able to supply some essential nutrients in aquaculture, with evidence suggesting microalgae-fed live food organisms often gives increased survival of fish larvae in greenwater rearing techniques such as seabream and as feed for live feed (Jobling 2016).

Innovations with a potential for transformative performance improvement

Microalgae biofilms: Inalve[1] is a French, industrial biotechnology start-up specialising in the scalable production of microalgae using a proprietary biofilm technology that uses 70% less water and 50% less energy than existing techniques. A species of high protein concentration and amino acids composition equivalent to fishmeal was selected, which can be reared alongside aquaculture and delivered in the form of a highly-concentrated living paste. Chemical company JNC Corp Korea has filed a patent for a "method for red sea cucumber aquaculture using adhesive microalgae isolated from jeju lava sea water" using adhesive diatomaceous microalgae (Ko 2017).

Technology Readiness Level: 9; Technical risk: Moderate

Biofilter systems: Please also refer to algae used in biofiltration systems covered in chapter 12 'Aquaculture waste management and valorisation'.

Algal oil: Please refer to section 9.3.

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[1] Inalve: https://www.inalve.com/en

9.2.3 Macroalgae (Seaweed)

In the last decade, a variety of genera including *Porphyra*, *Ulva* and *Gracilaria* have been explored for protein and lipid replacement in aquafeeds. According to SINTEF, 5-15% inclusion of seaweed meal provides beneficial effects to rainbow trout, Nile tilapia, seabream and sea bass, whilst higher inclusion may have anti-nutrient effects caused by polyphenols, heavy metals, etc. (SINTEF *et al.* 2014).

Innovations with a potential for incremental performance improvement

Sea Lettuce: In Israel, trials have been conducted in which the sea lettuce (*Ulva lactuca)* grown as part of the biofiltration process is then dried, ground and fed to the primary species as a partial protein replacement for fishmeal in the production of gilthead seabream, *Sparus aurata* (Ben-Ari *et al.* 2014).

Technology Readiness Level: 6-8; Technical risk: Moderate

9.2.4 Food waste

Initiatives are underway to promote a circular economy by reutilising (human) food waste in the development of aquaculture feeds. However, European regulatory restrictions and costs remain a barrier.

Innovations with a potential for incremental performance improvement

Food waste: In a public-private partnership in France, efforts are underway to develop aquafeed pellets using old bread. The next steps will be an experimental phase in a local fish farm (species undisclosed) and an industry study to estimate volumes and existing value chains (European Union 2015).

Technology Readiness Level: 6-8; Technical risk: Moderate

9.2.5 Processed animal protein

In Europe, the use of Processed Animal Protein (PAP) in aquaculture was restricted until 2013. Since then, non-ruminant PAP has been permitted reflecting scientific consensus on the safety of feeding land-animal proteins to fish. Rendered animal fat and oil have been available to use in aquafeed for many years without any restrictions (EFPRA n.d.).

Innovations with a potential for incremental performance improvement

Avian protein: Research revealed that while feed manufacturers and UK consumers are generally supportive of the use of avian protein derived from e.g. feather meal in salmon production, British retailers are showing reluctance (Fish Farming Expert 2018a). Due to lack of commercial demand, future funding in innovation in this area has been stalled.

Technology Readiness Level: 6-8; Technical risk: Moderate

Animal protein hydrolysates: Compared to biogas and compost, by-products from animal processing industries have a potential for conversion into useful products of higher value, such as protein hydrolysates, in compliance with current legislation. Low levels of animal protein hydrolysates in aquafeeds may enhance growth rate and feed conversion of farmed fish and crustaceans and enhance the nonspecific immunity of fish (Martínez-Alvarez, Chamorro, and Brenes 2015).

Technology Readiness Level: 6-8; Technical risk: Moderate

9.2.6 Insect protein

Research and development into the use of protein derived from insects such as the black soldier fly and meal worm has been gaining traction, as seen with the EU-funded programme PROteInsect[1] and BioMar's recent validation trials (Feed Navigator 2019b). However, at present, the price of insect protein is not competitive, with feed producers likely to offer a price per tonne on par with soy protein concentrate. Regulatory hurdles in Europe and the USA restrict the use of catering waste and other wastes as larvae feed, while approved substrates such as brewery and distillery waste are already widely and directly used in poultry and salmon feed. Regardless of the substrate, formulators will struggle to produce the consistent quality and quantity required in precise, formulated aquafeed diets. Thus, production may be better suited in countries with more lenient legislation and access to cheaper substrates. Insect feeds are at present quite niche and will perhaps be produced for a premium (The Fish Site 2019i). Indeed, major aquafeed producer Skretting has introduced insect meal into their feeds (personal communication), but have commented, "…over time, we expect the volume of insect meal available to the market to increase from a select number of suppliers. However, we do

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[1] PROteInsect: http://www.proteinsect.eu/index.php?id=31

not expect that these volumes will ever compete at the scale of traditional high protein ingredients used" (Skretting 2018).

Innovation with a potential for incremental performance improvement

Fly larvae: South African feed firm AgriProtein[1] produces large-scale quantities of natural protein using fly larvae fed on organic waste and was named by TIME magazine as a "top 50 Genius Company" and a number of the largest insect protein companies cater solely for the aquaculture industry (Undercurrent News 2018a).

Technology Readiness Level: 9; Technical risk: Moderate

9.2.7 Fishery discard and waste

There has been industry-wide progress in improved utilisation if fishery discard and waste. In 2018, almost a third of ingredients in Cargill's salmon feed from marine sources came from trimmings and fishery waste (Undercurrent News 2019a). It should be noted however, that current EU regulations dictate that fish cannot be given feed made from their own species (IntraFish 2019f).

Please also refer to chapter 12 on 'Waste management and valorisation'.

Innovation with a potential for transformative performance improvement

Fish trimmings: Increased utilisation of fish trimmings reflect the fisheries industry's commitment to greater sustainability. SINTEF estimates that the value of trimmings has increased by as much as £90.5 million since 2018, with 72% going to feed ingredients. Norwegian fishermen alone produce approximately 954,000 metric tons of seafood trimmings destined for the aquaculture sector as a feed component (IntraFish 2019g). However, the reality remains that the aquaculture industry is not willing to pay for trimmings when they can buy cheap feed internationally. Any change would require greater impetus from the industry and government.

Technology Readiness Level: 9; Technical risk: Low

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[1] AgriProtein: https://agriprotein.com/

Fish faeces: Norwegian firm Hyperthermics has developed a fermentation method to recycle fish sludge, comprised of fish faeces and feed leftovers into protein powder that can be used again as a feed ingredient for shrimp and lumpfish (IntraFish 2019f). Provided fish sludge supply is sufficient, 40% of total volumes can be turned into protein. A recent study conducted by the Norwegian University of Science and Technology suggests that the great scallop, *Pecten maximus*, has the potential to utilise salmon feed and faecal waste and thus could be a candidate for IMTA (Bergvik *et al.* 2019).

Technology Readiness Level: 9; Technical risk: Moderate

Innovations with a potential for incremental performance improvement

Silage/Hydrolysate: The Nordnes Group[1] produces silage from the discards of whitefish, which is then used in salmon feed, resulting in nearly 99% utilisation of catches. Silage was chosen because it is unlimited, and it is the cheapest and easiest to sell, but remains “marginally profitable.” Several new fishing vessels have installed silage and hydrolysis plants. A Brazilian study has shown that tilapia waste silage could be an effective alternative to traditional feed in vannamei shrimp diets, with no effect on shrimp performance (da Rocha Soares Neto *et al.* 2019). Meanwhile, Australian researchers demonstrated that the replacement of 5 to 10% fishmeal with tuna hydrolysate improved growth, immune response, intestinal health and disease resistance in juvenile barramundi (Siddik *et al.* 2018).

Technology Readiness Level: 9, Technical risk: Low

Biofloc waste: A Korean patent filed by environmental assessment company NeoEnBiz[2] pertained to the production of a feed additive containing dried, organic compounds extracted from biofloc (Lee 2017).

Technology Readiness Level: 3-5, Technical risk: Moderate

9.2.8 New versions of established raw materials

Alternative aquafeed ingredients will have their markets in the future of aquaculture, but some argue that real, usable volumes are going to come from “new versions” of existing raw materials (Undercurrent News 2019e). A patent granted by the US Department of Agriculture

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[1] Nordnes Group: https://www.nordnesgruppen.no/about-us/

[2] NeoEnBiz: http://www.neoenbiz.com/index_eng.htm

as recently as 2018 involved processing small grains to provide four separate nutrient fractions in the preparation of aquaculture feed (K. Liu and Barrows 2018).

Please also refer to the section 8.3 on Fish oil alternatives.

Innovations with a potential for transformative performance improvement

Rape: German firm EuroProtein recently announced that rapeseed protein concentrate was capable of replacing its soy counterpart (Undercurrent News 2018b).

Technology Readiness Level: 9, Technical risk: Low

Soy: Prarie AquaTech[1], a US feed ingredients maker was recently recognised at the Aquafeed Horizons conference in Cologne, Germany for its new feed ingredient, MEPro, which is microbially enhanced non-GMO soy protein, resulting in 70% (as fed) digestible protein (Undercurrent News 2019c).

Technology Readiness Level: 9, Technical risk: Low

Wheat gluten: In a feeding study involving the Giant croaker, one-third of high-quality fish meal or 65% of soy protein concentrate could be safely replaced by a taurine-supplemented mixture of vital wheat gluten and wheat flour without causing any adverse effect on feed intake, growth rate, feed conversion, whole body compositions, and nitrogen and energy retention (Lu 2016). In one interview, gluten was lauded for both its high protein content and digestibility, but due to its high price, would only be suitable in high-value feeds (personal communication).

Technology Readiness Level: 3-5, Technical risk: Moderate

9.3 Fish oil alternatives

Novel oil products are the focus of considerable promising research, with much of the attention in fish oil replacement studies focused on essential (or conditionally essential) fatty acids, particularly the omega-3 fatty acids (n-3 LC-PUFAs, e.g. Docosahexaenoic acid (DHA) and Eicosapentaenoic acid (EPA)) and omega-6 fatty acids (n-6 LC-PUFAs, e.g. arachidonic acid) found almost exclusively in marine-origin ingredients. While these are crucial for the development of most if not all carnivorous fish, non-essential lipids also have nutritional

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[1] Prarie AquaTech: https://www.prairieaquatech.com/

importance (Turchini, Trushenski, and Glencross 2019). Optimal dietary fatty acid composition for a growing fish would be one that minimises in vivo bioconversion processes (to reduce unnecessary energetic costs), while simultaneously providing an efficient substrate for energy production. The very importance of these nutrients has made the sparing and replacement of fish oil significantly more challenging than those of fish meal (personal communication).

A range of novel non-marine oils containing n-3 LC-PUFAs has been developed, and they are at different levels of commercialisation and availability, of which omega-3 fatty acid-containing oils derived from microalgae/single-cell organisms and genetically modified oilseed crops are of particular interest.

Feed companies are taking notice - in October, 2019, BioMar and algal ingedients firm Corbion entered into a new feed partnership with the Salmon Group (Press Release 2019).

Innovation with a potential for transformative performance improvement

Algal oil: Veramaris of Norway has become a leader in scalable marine algal oil rich in omega-3 EPA & DHA and ARA thanks to early adoption by Norwegian salmon farmers. Mowi, Yuehai Feed Group and AlphaFeed have committed to using Veramaris' algal oil in new trial feeds (Veramaris 2019). The company has recently been awarded winner of Future of Fish Feed's Fish Oil Challenge (Future of Fish Feed 2019).

Technology Readiness Level: 9, Technical risk: Low

Hydrogenated soy oil (SFA and MUFA): A study conducted by Southern Illinois University recently discovered that California yellowtail fed diets containing fully-hydrogenated soybean oil was effective for growth and fatty acid profile (Feed Navigator 2018b). These findings appeared to confirm earlier research that diets containing predominately saturated fatty acids (SFA) or monounsaturated fatty acids (MUFA) appear to improve the metabolism of available LC-PUFA, leading to fish oil sparing, although tissue levels were lower. However, SFA soy diets yielded fillets richer in DHA than fish oil-fed diets. This research reveals that cheaper lipids may be possible to maximise profitability. Longer-term studies with larger fish required.

Technology Readiness Level: 3-5, Technical risk: High

Innovations with a potential for incremental performance improvement

Rapeseed (canola) oil: Cargill, through a collaboration with BASF has recently launched Latitude, a genetically modified variety of rapeseed rich in omega-3 fatty acids for use in salmon feed. Recent regulatory clearance by the US Department of Agriculture will see the commencement of growing for commercial use in Canada, Chile and likely USA by 2020 (Seafood Source 2019b). While the EU's GM Food and Feed Regulation currently states that products derived from an animal reared on feeds containing GM ingredients do not need to be labelled as such, consumer acceptance remains an issue, especially in Europe (Sprague, Betancor, and Tocher 2017).

Technology Readiness Level: 6-8, Technical risk: Moderate

Camelina oil: In a collaborative research project between the University of Stirling and Rothamsted Research, scientists developed GM camelina plants to produce high levels of essential omega-3 fish oils suitable for Atlantic salmon farming (University of Stirling 2015; BBC 2018). However, salmon fed GM feed is unlikely to be sold in the UK and Europe due to perceived resistance to GM products.

Technology Readiness Level: 6-8, Technical risk: Moderate

9.4 Individual nutrients

Shifting our focus from one single raw material to nutrients and the way ingredients can complement each other as a strategy will likely open numerous and as-yet untapped possibilities for improving the next generation of aquafeeds (Turchini, Trushenski, and Glencross 2019).

The following section covers individual nutrients that have been the focus of recent R&D activity since 2015.

9.4.1 Minerals

Minerals are inorganic elements necessary in the diet for normal body functions. Fish can absorb many minerals directly from the water through their gills and skin, allowing them to compensate to some extent for mineral deficiencies in their diet. These minerals regulate osmotic balance and aid in bone formation and integrity and are required in small amounts as components in enzyme and hormone systems (Craig *et al.* 2017).

Innovations with a potential for incremental performance improvement

Mineral R&D: Examples of research and development into minerals for inclusion in feed are presented below.

Selenium - Very limited information is available on the relationship between dietary selenium and plant protein sources in carnivorous marine aquaculture species. In one study it was found that lupin meal diets supplemented with organic selenium can enhance growth, physiological and histological performances of juvenile barramundi (Ilham, Fotedar, and Munilkumar 2016).

Zinc - Current EU legislation pertaining to aquaculture is often inherited from agriculture. Restrictions on the use of zinc in aquafeeds are in place to reduce pollution, however set levels fall below the optimum for salmon and other fish species (personal communication). Research on better zinc utilisation in salmon is underway at Nofima, with focus on its interaction with omega-3 fatty acids in maintaining skin, intestinal and gill barrier tissues (Nofima 2019).

Iodine - Lean fish such as pollack and Atlantic halibut is a major source of iodine for Norwegians (Nerhus *et al.* 2018). In an interview one aquafeed industry player suggested that tailor-made, market-driven enrichment with iodine and other desirable nutrients is an area of promising growth (personal communication).

Technology Readiness Level: 3-5, Technical risk: Moderate

9.4.2 Enzymes

Current research on enzymes mainly focuses on greater digestibility of alternative protein feeds and improving bioavailability of their nutritional components. These also have the added benefit of reducing environmental pollution and feed costs.

Innovations with a potential for transformative performance improvement

Enzyme R&D: Examples of research and development into enzymes for inclusion in feed are presented below.

Protease - Dietary proteases are being investigated to assist in the breakdown of difficult to digest macromolecular proteins, especially in smaller fish. One study found that a mixture of dietary protease, carbohydrase and micro-encapsulated organic acid salts into the diets of vannamei shrimp yielded a high level of growth and thus may serve as an alternative to using increased volumes of fishmeal (Yao *et al.* 2019). In another, the supplementation of 150–175mg/kg protease in pelleted diets could improve the growth performance, nutrient digestibility and nutrient retention of gibel carp (Shi *et al.* 2016).

Phytase - More than 50% of phosphorus reserves in seeds of most legumes are stored as phytate-bound phosphorous, which is not bioavailable for most fish species. Phytases have been used in poultry and pig productions for decades, mainly to reduce the environmental impact and phosphorous loads from farm effluents, as well as to reduce feeding costs through nutrient sparing. The use of phytases in aquafeeds is still in an initial stage, but it is presented as one of the most effective tools used by aquaculture to include alternative plant protein ingredients in diet formulas, improve fish growth and control the diet-related environment pollution from aquaculture operations (Morales *et al.* 2016).

Carbohydrase - Carbohydrases hydrolyse non-starch polysaccharides, which are anti-nutritional factors present in plant-based feeds (please also refer to the section: Anti-nutritional factors). Compared to phytase, the use of carbohydrase enzymes has not been nearly as common in aquatic species. Research supports the view that supplementation of exogenous carbohydrases to plant-based fish diets should improve nutrient digestibility and reduce nutrient excretion. However, gaps in the knowledge remain due to the difficulty in cross-study comparisons. Improvements may also be made in stability and performance for these enzymes to be more readily incorporated in fish diets (Castillo and Gatlin 2015).

Technology Readiness Level: 6-8, Technical risk: Moderate

Microbiome modulation: Folium Science[1] is a Cambridge, UK-based firm that has developed its first 'Guided Biotic,' which uses enzymatic activity to destroy target bacteria to stabilise the early life gut and act as a preventative measure in rearing systems. Founded in 2016, Folium has been working on proof-of-concept studies in poultry this year. Previously, the company has conducted successful *in vitro* studies and *in vivo* trials with Guided Biotics. Nutreco 2018 Feed Tech Challenge Finalist (Feed Navigator 2019c).

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[1] Folium Science: https://www.foliumscience.com/#home

Technology Readiness Level: 6-8, Technical risk: High

Enzyme complex*:* The mycelial fungus strain *Trichoderma reesei* is a producer of a endoglucanase, xylanase and pectinase complex, which is described in a patent for an enzyme preparation to destroy non-starch polysaccharides of cereal and legume raw materials for value-added aquafeed production (Синицын *et al.* 2019).

Technology Readiness Level: 3-5; Technical risk: High

9.4.3 Lipids

The primary focus of lipid research and development to date in aquaculture pertains to essential (or conditionally essential) fatty acids, particularly the omega-3 or n-3 LC-PUFAs (e.g. DHA and EPA) and the omega-6 or n-6 LC-PUFAs (e.g. arachidonic acid) found almost exclusively in marine-origin ingredients. While these are crucial for the development of most if not all carnivorous fish, non-essential lipids also have nutritional importance by triggering differential responses in regulation of gene transcription.

However, there is a dearth of research addressing these as well as individual fatty acid requirements. Optimal dietary fatty acid composition for growth would be one that minimises in vivo bioconversion processes (to reduce unnecessary energetic costs) while simultaneously providing an efficient substrate for energy production (Turchini, Trushenski, and Glencross 2019).

Please also refer to section 8.3 on Fish Oil Alternatives.

Innovations with a potential for incremental performance improvement

Non-EPA/DHA lipid R&D: Examples of research and development into the role of non-EPA/DHA lipid and potential sources for inclusion in feed are presented below.

Ballan wrasse: Efforts are now underway to elucidate essential fatty acid dietary requirements for this cleaner fish species. A recent study led by the University of Stirling demonstrated that the wrasse is incapable of arachidonic acid synthesis and thus requires exogenous nutrient supply but appears able to synthesize DHA from EPA (Kabeya *et al.* 2018).

Sterol - Cholesterol play important roles in fish growth and metabolism and it has been suggested that aquafeeds not providing sufficient quantities of cholesterol (e.g., plant-based formulations) should be fortified with additional cholesterol to improve overall fish performance

(Jobling 2016). A recent study on juvenile turbot found significant interaction between dietary cholesterol and phospholipids in terms of weight gain rate (Zhu *et al.* 2018). In another study it was found that campesterol and brassicasterol appeared to be the phytosterols with the highest intestinal absorption in Atlantic salmon (Sissener *et al.* 2018).

Technology Readiness Level: 3-5, Technical risk: High

9.4.4 Amino acids

All dietary amino acids, whether considered essential, non-essential or conditionally essential, have physiological importance, serving not only as building blocks for protein synthesis but also as precursors to various metabolites and as factors contributing to the regulation of gene expression, cell signalling, and overall metabolism (Turchini, Trushenski, and Glencross 2019). Continuing advances in amino acid nutrition technologies will play a defining role in shaping the viability and sustainability of aquafeed formulation and manufacturing.

Diets for aquatic animals must contain the proper balance of all amino acids to optimise growth, health, and reproduction. A more holistic approach of balancing dietary levels of amino acids can be achieved through specific amino acid fortification or careful blending of raw materials according to their complementary characteristics and composition.

Innovations with a potential for transformative performance improvement

Amino acid R&D: Examples of research and development into the role of amino acids are presented below.

Tryptophan - Feeds developed for broodstock usually contain more protein than grow-out feeds, and a good supply of the amino acid tryptophan seems to be particularly important for successful completion of reproduction. Tryptophan, the precursor of serotonin, may have influences on gonad maturation in both sexes (Jobling 2016) and plays a role in diminishing spinal deformities, stress and aggression in some species. Recent studies investigate tryptophan requirement in commercially valuable species such as Nile tilapia (L. Nguyen *et al.* 2019).

Taurine - Dietary supplementation with taurine also seems to be beneficial for improving broodstock performance of marine fish species. Taurine, a sulphur-containing amino acid-like compound, has several physiological roles, including osmoregulatory and antioxidant functions, and as a neuro-modulator (Salze and Davis 2015).

Technology Readiness Level: 9, Technical risk: Moderate

9.4.5 Other nutrients

Innovations with a potential for transformative performance improvement

Nucleotide and antioxidant R&D: Examples of research and development into the role of amino acids are presented below.

Nucleotides - These molecules play an important role in most biological processes, including encoding genetic information, mediating energy metabolism and signal transduction. A Chinese study found that in moderation, dietary nucleotides were helpful in improving growth, feed utilisation, antioxidative capacity and intestinal morphology of turbot fed with a low fish meal diet (Meng *et al.* 2017). Japanese and Bangladeshi researchers demonstrated that juvenile red sea bream diets supplemented with either inosine or inosine monophosphate promote growth, immune responses, stress resistance and intestinal health condition (Hossain *et al.* 2016).

Citric acid - A Chinese study found that dietary inclusion of 3% citric acid markedly improved the bioavailability of phosphorous, without compromising intestinal function and health of juvenile turbot. Furthermore, citric acid seemed to be a promising feed additive for aquafeeds to reduce phosphorous discharge, a major water pollutant, into the environment (Dai *et al.* 2018).

Antioxidants - Astaxanthin is a carotenoid widely used to boost pigmentation in a variety of farmed species, but the antioxidant is also linked to various improvements in survival, growth performance, reproductive capacity, stress tolerance, disease resistance and immune-related gene expression (Lim *et al.* 2018). Found in the natural diets of wild cleaner fish, in one interview astaxanthin was highlighted as key to maintaining their health (personal communication).

Technology Readiness Level: 3-5, Technical risk: Moderate

9.5 Functional Feeds

Functional feeds can be defined as feeds that result in physiological benefits beyond fulfilling the basic nutritional requirements of a species. For example, a functional feed could improve health status and reduce disease incidence, and it is known, or suspected, that several feed components have prophylactic properties or act as immuno-stimulants (Jobling 2016).

Natural plant products and extracts are being increasingly used as replacers for chemotherapeutics for disease control and management in aquaculture.

Although most studies associate the change in microbiota levels (increased *Lactobacillus* abundance) with improved health outcomes, the mechanism by which increases in Lactobacilli ameliorate fish health still needs to be demonstrated. Still, pre- and probiotic supplementation of fish feed is viewed as a promising alternative for antibiotic treatment in aquaculture. Further in-depth studies are required in different species (Brugman *et al.* 2018; personal communication).

In addition to some of the aforementioned nutrients, most of the recent innovation in this space such as probiotics and bacteriophage are covered in chapter 9 ‘Pests and disease management’.

Innovations with a potential for transformative performance improvement

Immunomodulant R&D: Examples of research and development into the role of immunomodulants are presented below.

Microbiome transplantation - Researchers from the Max Planck Institute for Biology in Ageing in Germany have demonstrated in killifish that older fish lived approximately 40% longer after they consumed microbes from the faeces of younger fish (Nature News 2017).

Inactivated microbes - Non-viable microbes are being explored for their beneficial effects as immunomodulants to increase inclusion rates of alternative protein meals in sensitive species. Once inactivated, they are considered both safe and highly tolerant to processing stresses such as temperature. Research on their application as a dietary supplement crustacean and fish species such as gilthead bream. One Japanese study found that oral administration of heat-killed *Lactobacillus plantarum* in amberjack diets appeared to improve soy bean meal utilisation, immune response, and stress resistance (Dawood *et al.* 2015).

β-glucans - These components found in the cell walls of yeast and other single-cell organisms are immunostimulants demonstrated to improve bacterial resistance and other growth parameters. There are numerous species-specific studies underway worldwide, and β-glucans were highlighted by one industry expert as an area of promise for Atlantic salmon (personal communication).

Technology Readiness Level: 6-8, Technical risk: Moderate

9.6 Live feeds and alternatives

Complete reliance upon live food organisms for larviculture is undesirable, but over four decades of research into developing microdiets for start-feeding marine fish larvae have not met with universal success. At present, the start-feeding phase of many farmed fish species depends on an artificial food chain comprising live food organisms, such as brine shrimp (*Artemia salina*), rotifers (*Brachionus* spp.), copepods and other zooplanktonic organisms. Rotifers and brine shrimp are not natural food for marine fish larvae, but they are relatively easy to produce at high densities, and their nutritional profile can be improved using enrichment procedures (Jobling 2016).

Sights have recently turned to other species of live feed as alternatives to *Artermia* and rotifers, which have fluctuating prices and are of non-marine origins, thus requiring enrichment to suit marine fish larvae nutrition.

9.6.1 Live feed species

Innovations with a potential for transformative performance improvement

Live feed R&D: Examples of research and development into sources of live feed are presented below.

Copepods - Copepods are regarded as the link between phytoplankton and larval fish, with the right size range, biochemical profile and swimming pattern to trigger the appropriate hunting behaviour in fish larvae (Hansen 2017). Copepod hatcheries such as C-Feed AS[1] in Norway, were singled out by one industry interviewee as an area showing significant promise

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[1] C-Feed AS: http://www.cfeed.no/

(personal communication). Prolonging the shelf life of live feed is also of interest, as seen with a recently granted Russian patent regarding the 6-month refrigerated storage of copepod eggs (Ханайченко 2018).

Barnacle nauplii - Norwegian company Planktonic AS[1] now offers live, wild-caught nauplii, a zooplankton that can be cryopreserved until needed. This product is claimed to have “optimal nutritional profile, unparalleled biosecurity and an unparalleled stability in product quality” (The Fish Site 2018a).

Biofloc - Bioflocs are macroaggregates of bacteria, fungi, algae, protozoans and meiofauna that can provide protein- and micronutrient-rich food for microphagous and filter feeding species (e.g. penaeid shrimp and tilapia), improve culture environments, reduce disease and treat wastewater from aquaculture. A US study investigating the effect of combining biofloc with conventional and fish-free feed for shrimp found that shrimp obtained some fatty acids from biofloc material and had significantly greater sweet aromatic aroma as well as significantly higher moisture release and texture. These results show scope to optimise product quality of biofloc-raised shrimp fed fish-free diets (Ray, Leffler, and Browdy 2019).

Technology Readiness Level: 9, Technical risk: Moderate

9.6.2 Live feed alternatives: microdiets

The potential benefits of microdiets are clear: reducing the time, effort and space required for the production of the live food organisms and ensuring that the fish larvae were being fed a diet of uniform nutritional composition (Jobling 2016). Progress has been considerable, with good weaning results being currently delivered by several commercial microdiets for major cultivated species, but there is significant room for improvement, especially for the earlier life stages (Conceição *et al.* 2018). However, while earlier weaning is achieved, complete elimination of live feeds is not anticipated in the short-term or ever, for some species (Duke 2019).

Currently, there are a numerous, species-specific studies underway for the development of microdiets to expedite weaning.

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[1] Planktonic AS: https://www.planktonic.no/

Innovations with a potential for disruptive performance improvement

Microdiet R&D: Examples of research and development into microdiet sources and delivery technologies are presented below.

Micro-encapsulation - Norwegian start-up Molofeed has developed larval feed for marine finfish and shrimp based on proprietary technology. This makes it possible to include pre-digested and other water-soluble components in a capsule, and slow-release nutrients after feeding. Molofeed claims to successfully substitute more live feed than current offerings, with a vision of one day replacing live feeds altogether (Molofeed 2019).

Artemia cyst extract - Bern Aqua NV[1] of Belgium has recently launched Vitellus, an enriched microdiet comprising artemia cysts, to be used in the same quantities of natural cysts. As a dry formulation, significant cost savings can be made.

Co-feeding: - Use of a small amount of live feeds augmented with manufactured feeds could potentially be quite successful as a strategy to minimise a hatchery's exposure to the risks of live feeds, while still keeping their presence for benefits (Duke 2019).

Technology Readiness Level: 9, Technical risk: Moderate (Species dependent)

9.7 Methodologies for improving nutrition and feeding

This section explores innovations in various strategies, as a means to improve nutrition and feeding in aquaculture.

9.7.1 Genetic improvement of feed raw materials

Even though there is resistance in some quarters to using plant genome and metabolic engineering in crop plants for feeds and food products, various forms are almost certain to continue, perhaps at an increasing rate (Jobling 2016). Knowledge about the metabolic pathways involved in fatty acid synthesis in marine unicellular organisms has opened a route for the transgenic modification of terrestrial plants to produce oils that resemble those extracted from marine fish species.

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[1] Bern Aqua NV: https://www.bernaqua.com/marine-larvae-weaning/

While the EU's GM Food and Feed Regulation currently states that products derived from an animal reared on feeds containing GM ingredients do not need to be labelled as such, consumer acceptance remains an issue, especially in Europe (Sprague, Betancor, and Tocher 2017). There is growing agreement within academia and the aquafeed industry, however, as to the use of these products with regards to their safety and viability to meet food security requirements (personal communication). This sentiment was confirmed in another interview with a researcher who felt that provided labelling is sufficient, consumers can make informed decisions on their purchases (personal communication).

Please also refer to chapter 7 'Genetic Improvement'.

Innovations with a potential for transformative performance improvement

Genetic improvement of feed raw materials: Examples of research and development into technologies for genetic improvement of feed raw materials are presented below.

Transgenic engineering - Cargill, through a collaboration with BASF has recently launched Latitude[1], a genetically modified variety of rapeseed rich in omega-3 fatty acids for use in salmon feed. Recent regulatory clearance by the US Department of Agriculture will see the commencement of growing for commercial use in Canada, Chile and likely USA by 2020 (Seafood Source 2019b).

Genome editing - Breaks are introduced into the genome at specific sites, and the repair of the break is used to introduce DNA sequence changes or deletions. Deletions or specific gene knockouts could lead to plants with for example, reduced concentrations of anti-nutritional factors or accumulation of desirable oils. Genome editing can be used to induce genetic variation without transgenic modification, and thus may be more socially acceptable than those generated by transgenic engineering (Jobling 2016).

Directed evolution - British algal biotechnology firm Algenuity has employed directed evolution, which uses successive rounds of conditional selection to isolate highly specialised variants without genetic recombination, to produce a temperature-tolerant strain of *Tisochrysis lutea* , a microalga used extensively in copepod production (Algenuity 2019).

Technology Readiness Level: 6-8, Technical risk: Moderate

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[1] Latitude: https://www.cargill.com/page/latitude

9.7.2 Genetic improvement of target aquaculture species

Please refer to chapter 7 ‘Genetic improvement’.

9.7.3 Improvement of utilization

Improvement of digestibility, retention and bioavailability of aquafeed nutrients contribute to the health and welfare of fish as well as the reduction of aquatic pollution, ultimately leading to better feed conversion and cost savings. There are currently numerous studies worldwide in this area focusing on specific species, primarily with a focus on the optimisation of fish meal alternatives. This was confirmed as an area of great interest in one interview (personal communication).

Innovations with a potential for transformative performance improvement

Omega-3 sparing: Please refer to Saturated fatty acids (SFA) and Monounsaturated fatty acids (MUFA) under the section 8.3 on Fish Oil Alternatives

Nucleotides: Please refer to the section on 8.4 Other Nutrients.

Phytase: Please refer to the section 8.4.2 Enzymes

Improved models of nutrient utilisation: WiseFeed[1] was an EU-funded project from 2016 to 2018 led by the University of Bergen addressing knowledge gaps on the impact of aquafeeds on digestive function to enhance nutrient utilisation, improve production yields while reducing feeding costs, and reducing the environmental impact of released nutrients. Key output included development of new and improved models for measuring the digestion, absorption and retention efficiency of selected macro nutrients in key cultured fish species, with a focus on methionine.

Technology Readiness Level: 3-5, Technical risk: Moderate

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[1] WiseFeed: https://cordis.europa.eu/project/rcn/199942/brief/en

9.7.4 Palatability and attractability

While the development of fish meal alternatives has brought benefits to the aquaculture industry, feeds based on these raw materials often require chemostimulants to increase palatability and attractability, or risk feed wastage, low feed conversion and decreased profitability.

Innovations with a potential for transformative performance improvement

Non-marine/animal chemostimulant: A group of researchers from Georgia State University have developed a “cost-effective feed attractant mixture composed of natural compounds found in the food of shrimp and without marine meal or other animal products (Derby, Bharadwaj, and Chamberlain 2018).

Technology Readiness Level: 3-5, Technical risk: Moderate

9.7.5 Formats and processing

Raw material processing and feed manufacturing can greatly influence the nutrient composition and digestibility of feeds as well as their physical properties and utilisation. The challenge is to produce feeds that can be effectively formed into pellets or other formats with the desired physical characteristics, water stability, durability, or buoyancy profile.

Please also refer to the section on Feeding Systems in chapter 12 ‘Waste management and valorisation’.

Innovations with a potential for transformative performance improvement

Micro-encapsulation: Norwegian start-up Molofeed has developed larval feed for marine finfish and shrimp based on proprietary technology. This makes it possible to include pre-digested and other water-soluble components in a capsule, and slow-release nutrients after feeding (Molofeed 2019).

Density control in extrusion: Product density is one of the most important product characteristics in aquafeed production. Computer-controlled devices take advantage of instantaneous in-line measuring for greater control and monitoring (Kearns 2017).

Waste Recovery System: Wenger Manufacturing has demonstrated that start-up and shutdown waste ingredients can be reintroduced in a controllable liquid stream back to the extruder. Up to US $2,000 (£1,550)-worth of ingredient can be recovered per day, at the site of waste development and turned into product. Significantly less expensive than other waste handling systems (Kearns 2017). Please also refer to chapter 12 ‘Management and valorisation of wastes’.

Product quality measurement: In-line devices placed, for example, before dryers can predict final product outcome based on measurement of characteristics prior to treatment. This leads to substantial energy and time savings (Kearns 2017).

Technology Readiness Level: 9, Technical risk: Low

Innovations with a potential for incremental performance improvement

Feeding blocks: Feeding blocks are said to maintain integrity and encourage natural grazing behaviour and reduce aggression during feeding. In 2019, UK fish food company World Feeds has recently launched blocks specifically designed for wrasse and lumpfish (IntraFish 2019d).

Technology Readiness Level: 9, Technical risk: Low

Liquid feeds: A Korean patent describes a process for manufacturing liquid type feed of squid and fish by-product using acid base cross-hydrolysis (Han *et al.* 2017).

Technology Readiness Level: 9, Technical risk: Low

9.8 Feed delivery systems

Please refer to chapter 10 ‘Production and handling technologies’ and chapter 12 ‘Waste management and valorisation’.

9.9 Feeding strategies

Given the high cost of aquafeeds, it is of utmost importance to design a feeding strategy that allows for optimised animal performance and minimal waste. Parameters to consider include animal age and density, environment (temperature, dissolved oxygen, etc.), feed composition, feed distribution and waste management.

Innovations with a potential for disruptive performance improvement

Nutritional programming (epigenetics): A strategy to better achieve more efficient utilisation of sustainable feeds, which involves exposing an animal to a dietary stimulus early in life to alter that individual metabolically and physiologically such that it becomes adapted and better able to respond to a similar nutritional challenge later in life. The EU-funded programme ARRAINA (2012-2016) demonstrated that both salmonids and non-salmonid fish are able to grow with plant-based diets without any or very limited supply (<7%) of marine feed ingredients from first life stages to completion of sexual maturation, producing ova and viable alevins (ARRAINA 2017).

Technology Readiness Level: 3-5, Technical risk: High

Machine learning and vision to enhance feeding strategies: US and Norway-based start-up Aquabyte is integrating machine learning and machine vision to reduce production costs in aquaculture. While the current focus is on the commercialisation of sea lice detection in salmon, a second algorithm under development for fish size determination has future applications in optimising feed quantities that may save 20 to 30% in feed expenses (FT Reporter 2018).

Technology Readiness Level: 6-8, Technical risk: High

Innovations with a potential for transformative performance improvement

Mixed feeding: A group of Spanish researchers have integrated a multiple-criteria methodology with a genetic algorithm to determine the best sequence of feeds to be used throughout the fattening period of Gilthead seabream. Results have shown that the combination of several feeds at precise times may improve upon one-feed strategies (Luna, Llorente, and Cobo 2019).

Technology Readiness Level: 3-5, Technical risk: Moderate

High protein diet for salmon: In a multinational, economical model comparison study on feed composition for farmed Atlantic salmon, it was found that high protein diets led to improved feed-to-carcass conversion and faster growth than the preferred high-fat diets, leading to overall reduction of production costs (Weihe *et al.* 2019).

Technology Readiness Level: 9, Technical risk: Low

Please also refer to chapter 12 ‘Waste management and valorisation’.

9.10 Nutrition research

Established around the middle of the twentieth century, fish nutrition research has evolved from nutrient requirement studies to those of feed intake and the physiological mechanisms involved in its regulation, nutrient requirements and interactions, metabolic pathways and nutrient utilisation, fish growth, immune response, reproduction and early development (Jobling 2016).

However, at present, information about the nutritional requirements of farmed fish is far from complete, and there are few, if any, species for which the requirements have been defined for all life history stages. According to one expert, there are still numerous unknowns even with regards to Atlantic salmon. With the continued expansion of intensive fish farming and changes in the composition of feeds, there will be a need to determine the amino acid, fatty acid, vitamin and mineral requirements for a wider range of fish species and life stages. One of the greatest barriers to this remains a lack of suitable models and biomarkers for nutritional requirements, as well as the facilities to test them (personal communication).

Techniques involving genomics, transcriptomics, proteomics, metabolomics and bioinformatics are increasingly being used in dietary studies to obtain holistic information relating to the effects of individual nutrients or nutrient groups on gene regulation and the downstream effects that these can exert (Jobling 2016).

9.10.1 Nutritional requirements of life stages

Nutrition has an influence on all aspects of reproduction from the onset of puberty, through gametogenesis, fecundity and to the production of viable eggs and sperm. The developing embryo and newly hatched larva of farmed fish depend upon nutrients deposited in the oocyte by the female during vitellogenesis for their growth and survival.

Broodstock and larval nutrition are amongst the most poorly understood areas of fish nutrition even though their importance is recognised. Similarly, there is a dearth of quantitative information about the nutritional requirements of fish during the critical start-feeding phase.

Indeed, one interviewed industry expert reiterated that the most critical life stage of fish is within the hatchery, where nutrition and rearing methods will dictate the survival and quality of final aquaculture products. While at 5-10% of total feed volume, hatchery feed is small in comparison to weaning and grow-out stages but the effects of nutritional deficiencies in the first three months of a fish's life can rarely be reversed (personal communication).

Innovations with a potential for transformative performance improvement

Early-life feeding strategies: Broodstock and larval feed manufacturer INVE argues that developing more efficient protocols that optimise the use of live food creates a window of opportunity that can enhance the quantity and quality of the produced fry while simultaneously reducing operational costs. Enrichment of live feed such as rotifers and artemia may result in increased final biomass, higher survival rates from salinity stress tests and fewer deformities (The Fish Site 2019g).

Technology Readiness Level: 9, Technical risk: Moderate

Please also refer to the section on Amino Acids and the section on Feeding Strategies.

Innovation with a potential for incremental performance improvement

Artificial gut simulator: Researchers from the University of Glasgow have developed SalmoSim, a continuous salmon gut fermentation system focusing on the grow-out phase or when salmon are living in sea cages. With claims to better understand the microbial ecology of the salmon gut, the simulator could help in reducing feeding cost trials in the development of prebiotics and probiotics (Feed Navigator 2019a).

Technology Readiness Level: 6-8, Technical risk: High

9.10.2 Contaminants and provenance

In addition to contamination of aquaculture products by antimicrobials and other drugs as well as pollutants, the increasing use of fishmeal and fish oil alternatives such as plant-based and processed animal proteins (PAP) presents a new scenario in which noncurrent and/or new contaminants such as pesticides and mycotoxins enter into the fish food chain as potential food safety and/or welfare risks. New, rapid forms of testing are now required (All About Feed 2018; Nácher-Mestre *et al.* 2018).

Innovations with a potential for incremental performance improvement

Contamination and provenance testing R&D: Examples of research and development into contamination and provenance testing of feed raw materials are presented below.

Antimicrobials - Data on the level of contamination of antimicrobials in aquafeed remain scarce. In one study of an Italian seabass and gilthead seabream farm using commercial ELISA assays confirmed banned antimicrobial levels exceeding the method's detection capability in all feed and tissue samples. The use of farmed fish in aquafeeds appears to compound accumulation (Oliveri Conti *et al.* 2015).

Intra-species recycling - Real-Time PCR methodologies are proposed by Spanish researchers as a means to monitor compliance of European regulations prohibiting intra-species recycling (feeding one given species the same species in feed) in the most relevant aquaculture species including Atlantic salmon and rainbow trout (Espiñeira and Vieites 2016).

Multi-contaminant testing - Given the wide range of potentially harmful contaminants threatening high-value aquaculture species such as Atlantic salmon, such as persistent organic pollutants and organophosphorus pesticides in fatty tissue, or emerging contaminants such as perfluoroalkyl substances (PFASs) in protein tissues, a group of Italian researchers propose multi-class and multi-residue liquid chromatography-high-resolution mass spectrometry (HPLC-HRMS) and gas chromatography-tandem mass spectrometry (GC-MS/MS) methods to monitor a broad spectrum of residues comparing wild and farmed salmon (Chiesa *et al.* 2019).

DNA testing of ingredient provenance - A DNA testing platform for marine ingredients has been developed by Norwegian companies Orivo and BioMar, to help to improve the transparency and traceability of the seafood value chain. The test will be commercially available from 1 January 2020. Orivo also offers subscription programmes with random analysis and mandatory next-level-in-value-chain checkpoints, batch certifications, product verifications as well as product screening and benchmarking. Future plans are to address other industry-specific issues with their technology (The Fish Site 2019b).

Technology Readiness Level: 6-8, Technical risk: Moderate

9.10.3 Growth utilisation

Although information is available, increased knowledge is needed about the physiological effects of substituting plant protein sources for fishmeals in feeds (Jobling 2016).

Innovations with a potential for transformative performance improvement

Growth utilisation assessment R&D: Examples of research and development into growth utilisation assessment technologies are presented below.

Feed conversion rate measurement - GenetiRate, a US-based start-up, has developed a technology that can predict feed conversion based on metabolic rates measured on fish larvae or muscle tissue of rainbow trout (Undercurrent News 2019b). This patent pending technology allows for “quantitative high-throughput measurement of metabolic rate to select individual aquatic animals with improved feed efficiency and growth rate.”

Gene assessment - US researchers have developed a targeted multi-tissue microfluidic array for the rapid evaluation of regulatory pathways in response to alternative feeding strategies, dietary formulations, and supplementation, as well as environmental and management effects as indicators of catfish appetite, growth, metabolism and intestinal health of channel catfish culture. This cost-effective platform may be transferred to other cultured fishes (Schroeter, Peterson, and Small 2016).

Technology Readiness Level: 6-8, Technical risk: High

9.10.4 Anti-nutritional factors

Plant ingredients have been successfully used as a sustainable alternative to fish meal for some aquaculture species. However, plants contain one or more anti-nutritional factors (ANFs) that have feeding suppressant or deterrent properties or exert negative post-ingestive effects resulting in reduced consumption, digestibility and metabolism. In addition to increased production costs, concerns exist over waste production from nutrients (e.g. nitrogen and phosphorous) not retained in biomass and released into the environment as faecal or non-faecal losses (Kokou and Fountoulaki 2018).

With the increasing adoption of plant-based ingredient alternatives, there will probably be increasingly complex interactions among feed ingredients, with important implications for the study of ingredient functionality (Turchini, Trushenski, and Glencross 2019).

Innovations with a potential for transformative performance improvement

Please also refer to Carbohydrase under section 8.4.2 on Enzymes

Anti-nutritional factors R&D: Examples of research and development into anti-nutritional factors are presented below.

Non-starch polysaccharides - While low to moderate inclusion of cellulose has positive effects in aquaculture nutrition, those benefits diminished with higher quantities (Kokou and Fountoulaki 2018). Guar gum, a binder was found to negatively impact several growth parameters in mullet and other species, including weight, fat levels and microbial communities (Ramos *et al.* 2015). These polysaccharides are said contribute most to digestive impairment and waste output. Pure protein concentrates are low in ANFs and have better nutrient retention and thus are less polluting.

Protease inhibitors - A group of Brazilian researchers have developed a tool that uses immobilised proteases (fish trypsin) to detect protease inhibitors, one of the most important ANFs (Azevedo *et al.* 2018).

Technology Readiness Level: 3-5, Technical risk: Moderate

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10 Pests and disease management

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From the SIF Executive Board

The method applied in this review has generated numerous examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently happening. It is recognised that there are existing innovations and research areas that are not included here, and new areas where future innovations may occur. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

10.1 Overview: pests and disease management

What is the challenge in the UK?

Currently the key pests and disease challenges in aquaculture in the UK is (salmon) sea lice followed by bacterial, viral and fungal infections. Sea lice have dominated the industry for the past decade and is the main barrier for the growth of the salmon farming industry in both the UK and Norway. Hence, most innovation is related to sea lice prevention or removal, as it is so important to have it under control.

What are the most promising innovation categories?

- The main topics in R&D include preventative measures and treatments for parasitic diseases, particularly sea lice, as well as the development of vaccines for fish
- Research on fish vaccination is about finding and developing new vaccines, as well as new mechanisms for fish vaccination, as current mechanisms expose the fish to high level of stress
- Rather than the development of new antibiotics to treat bacterial diseases, R&D focus is to look for alternatives to antibiotic treatments
- Genetic improvements in the stock can lead to resistance against certain diseases and research efforts to breed for resistance are ongoing
- Another research effort is in the development of rapid diagnostic kits for easy use in the aquaculture industry

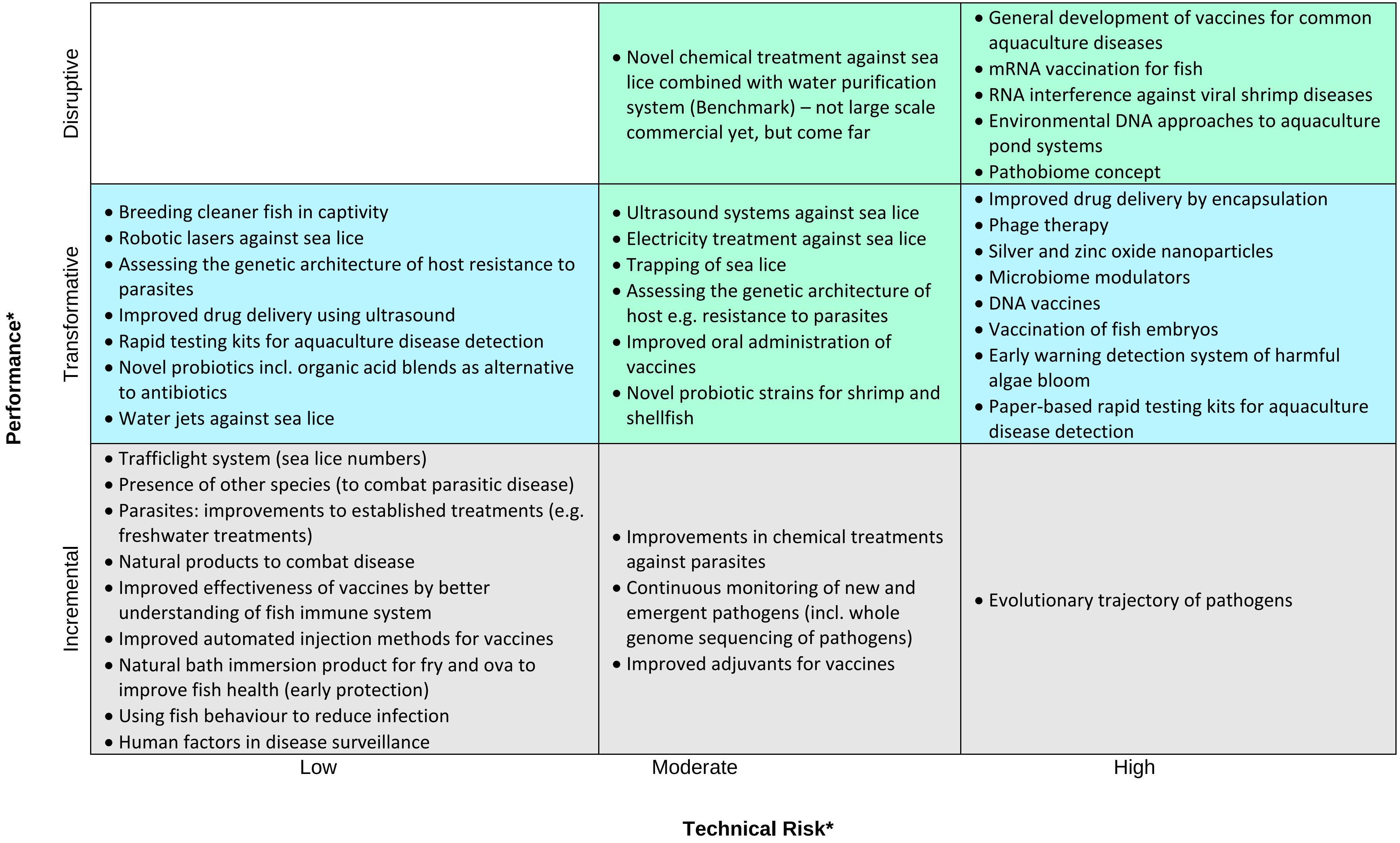
Where are important knowledge gaps?

- Important diseases with little or no available treatments or vaccines include
    - Most viral diseases affecting fish and shellfish
    - Fungal diseases

Pest and disease management is crucial in improving yields in aquaculture. In 2014 the FAO suggested that yield loss from disease amounts to more than USD 6 billion per annum. In Scotland alone there were 361 incidents killing 4.5 million fish in 2017 and 308 incidents killing 2.4 million fish in 2018 (Edwards 2019). While not all those deaths were due to disease, the most common cause of death was disease, including amoebic gill disease, salmon gill pox virus, proliferative gill disease, cardiomyopathy syndrome, pancreas disease, anaemia and fungus.

The focus of this chapter is on pest and disease management in aquaculture for improved yield and production rates and for improved sustainability of the sector. The chapter does not cover depuration technologies or general prevention of diseases relevant to humans, such as the novovirus in shellfish.

An overview of the potential performance improvement rating of recent (2015-2019) innovations in pest and disease management in aquaculture are outlined in Figure 9-1.



Performance*	Low	Moderate	High
Disruptive		• Novel chemical treatment against sea lice combined with water purification system (Benchmark) – not large scale commercial yet, but come far	• General development of vaccines for common aquaculture diseases • mRNA vaccination for fish • RNA interference against viral shrimp diseases • Environmental DNA approaches to aquaculture pond systems • Pathobiome concept
Transformative	• Breeding cleaner fish in captivity • Robotic lasers against sea lice • Assessing the genetic architecture of host resistance to parasites • Improved drug delivery using ultrasound • Rapid testing kits for aquaculture disease detection • Novel probiotics incl. organic acid blends as alternative to antibiotics • Water jets against sea lice	• Ultrasound systems against sea lice • Electricity treatment against sea lice • Trapping of sea lice • Assessing the genetic architecture of host e.g. resistance to parasites • Improved oral administration of vaccines • Novel probiotic strains for shrimp and shellfish	• Improved drug delivery by encapsulation • Phage therapy • Silver and zinc oxide nanoparticles • Microbiome modulators • DNA vaccines • Vaccination of fish embryos • Early warning detection system of harmful algae bloom • Paper-based rapid testing kits for aquaculture disease detection
Incremental	• Trafficlight system (sea lice numbers) • Presence of other species (to combat parasitic disease) • Parasites: improvements to established treatments (e.g. freshwater treatments) • Natural products to combat disease • Improved effectiveness of vaccines by better understanding of fish immune system • Improved automated injection methods for vaccines • Natural bath immersion product for fry and ova to improve fish health (early protection) • Using fish behaviour to reduce infection • Human factors in disease surveillance	• Improvements in chemical treatments against parasites • Continuous monitoring of new and emergent pathogens (incl. whole genome sequencing of pathogens) • Improved adjuvants for vaccines	• Evolutionary trajectory of pathogens

Technical Risk*

Figure 10-1: Performance and technical risk rating of innovations in pest and disease management.

**See section 4.4 for definitions of performance and technical risk rating scales.*

10.2 Parasitic diseases (finfish aquaculture)

Parasites in fish can infest the gills, skin gut or also fish muscle tissue and can be accompanied by secondary bacterial or fungal infections.

One the most common parasites relevant to the UK fishing industry are sea lice (*Lepeophtheirus salmonis*) in salmon aquaculture as well as amoebic gill disease, caused by the ectoparasite *Neoparamoeba perurans*. Another very common parasite in freshwater fish is white spot disease, caused by *Ichthyophthirius multifiliis*. This affects freshwater fish including trout and tilapia (Verner-Jeffreys *et al.* 2015).

Sea lice are the single largest economic and welfare problem for the salmon aquaculture industry worldwide, with annual losses estimated at €305M globally, and €33.6M in the UK alone (ThermoFisher 2015). An overview of approaches to sea lice management can be found on the website of the Global Salmon Initiative (Global Salmon Initiative 2019) as well as on the website of the Aquaculture Stewardship Council (Tardiff 2019). A good overview of available approaches is also given in a recent peer-reviewed publication by Bui et al (2019). These approaches include use of chemicals such as emamectin benzoate, dichlorvos, pyrethrum, hydrogen peroxide, azamethiphos and cypermethrin (Alevy 2017), physical methods including "flushing"— exposing lice-infested fish to high pressure water jets to remove sea lice (Little 2018), heat treatments such as provided by commercially available systems (e.g. Thermolicer[1] or Optilicer[2]), feeding salmon at lower depth and freshwater treatments. Improved physical barriers (e.g. bubbles and other) have also been developed – a recent development is a "Sea Lice Skirt" by Norwegian company Protan (Malm 2019). Chemical treatments have the disadvantage that the parasites may develop resistance, while some physical treatments such as flushing can cause extreme stress to the salmon.

While many new innovations in this space claim disruptive performance improvement, in reality a combination of various treatments and preventative methods are most likely going to be the most successful approach in the near future.

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[1] Thermolicer: https://www.steinsvik.no/en/products/e/seaculture/fish-health/thermolicer/

[2] Optilicer: https://optimar.no/optilice.html

Innovation with a potential for disruptive performance improvement

Novel chemical treatment combined with water purification system: UK company Benchmark developed a novel treatment against sea lice currently called BMK08 (previously called Ectosan). The treatment is a novel treatment against sea lice and in trials was 99% effective. It must be used in conjunction with a water treatment system which is also currently developed by Benchmark ("CleanTreat"). The water treatment system can also be used without BMK08 to remove residues of other treatments. The group is preparing to launch the two systems in the first half of 2021, subject to receipt of regulatory approval for the treatment product (Jensen 2019; The Fish Site 2020)

Technology Readiness Level: 6-8; Technical risk: Moderate

Innovation with a potential for transformative performance improvement

Robotic lasers: Robotic lasers have been developed by Norwegian company Stingray (Beck 2016). Sea lice which are attached to fish can be detected and targeted with laser beams. The targeted laser beams do not hurt the fish. However, it is hard for the laser beams to target lice that hide beneath gills and behind fins – they are designed to be used as a preventative technology, holding outbreaks at bay, rather than a reactive technology. It was suggested that cleaner fish and robots can work together (Little 2018). The innovation has been commercialised by Stingray since 2014, which was transformed from a basement start-up to a cutting-edge technology firm with around 50 permanent staff (Fish Farming Expert 2019a) The initial focus of the business was in Norway, where the technology is now widely used in combination with other mechanical treatments (not enough on its own), but other countries are now adapting the technology. Another Norwegian company, Ardeo, also holds IP in this area (WHEATLEY 2018).

Technology Readiness Level: 9; Technical risk: Low

Ultrasonics: A currently ongoing project, LiceSonic[1], aims to develop a system that targets sea lice by combining ultrasound technology with water quality and fish monitoring, has had positive results in its first lab tests. The project's first feasibility study resulted in a reduction of 60% in attached sea lice to salmon by using ultrasound technology combined with fish and

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[1] LiceSonic project: https://www.licesonic.com/

water quality monitoring. Different ultrasonic sound wave frequencies will ensure sea lice develop no resistance to the ultrasonic control method (World Fishing & Aquaculture 2018). A further innovation in this area has been described in a patent application filed by Steven Alevy, which combines the eradication of sea lice by ultrasound with a herding device. This means the ultrasound treatment needs to be used in an enclosed space, likely to cause stress. (Alevy 2017).

Technology Readiness Level: 3-5; Technical risk: Moderate

Electricity: Fish can be herded through tunnels and by applying electricity to the fish, the parasites detach and can be collected separately (Raúl Hernán ÁLVAREZ GATICA 2017) and (Vergara 2015). Chilean company Indesol are currently commercialising such a system (Fish Farming Expert 2019b)

Technology Readiness Level:3-5; Technical risk: Moderate

Breeding cleaner fish in captivity: Ballan wrasse (*labrus bergylta*) provide highly effective, highly natural sea lice control and are therefore in huge demand. However, the fish are typically caught in the wild to be used in aquaculture. In 2018 it was reported that for the first time sea wrasse could be reared in captivity and it is hoped that two of Scotland's biggest salmon producers will be self-sufficient in the fish in the fish in the next 3 years and not rely upon wild-caught fish any more. A commentator noted that *"… we will still require the availability of tools such as delousing technologies and other alternative methods, including veterinary medicines, when required"* (Keane 2018).

Technology Readiness Level: 3-5; Technical risk:Low

Trapping of sea lice: Norwegian company Blue Lice is developing a system which attracts and traps sea lice, similar to mosquito traps. It can be placed outside salmon pens to trap sea lice (similar to mosquito traps) which prevents them entering the pens (Salmon Business 2019).

Technology Readiness Level:6-8; Technical risk: Moderate

Water jets: The Hydrolicer is a machine that has been designed to delouse using low pressure water jets creating turbulence in treatment chambers that dislodge lice from the salmon. The system can be installed on ships in order to treat salmon in sea pens. Fish pumps are used to draw the fish into the device. The system is already in use e.g. by Scottish salmon producer Cooke Aquaculture Scotland and various commercial farms in Norway (personal communication).

Technology Readiness Level: 9; Technical risk: Low

Assessing the genetic architecture of host resistance to parasites: Recent research looked at host resistance of Atlantic salmon to sea lice (H.-Y. Tsai *et al.* 2016) as well as amoebic gill disease (Robledo *et al.* 2019). The findings should lead to improved breeding of fish with increased resistance to parasites.

Technology Readiness Level: 1-2; Technical risk: High

In-feed treatment against sea lice: A new in-feed treatment for the prevention and control of sea lice in salmon and trout has been approved by Chilean authorities, meaning that fish treated with the medication are now accepted for trade with many major export markets, including the United States, EU, Japan and Brazil. The treatment, which was developed by US company Elanco, is given in feed to fish in fresh water before they are transferred to the sea. Its application is based on studies that have shown it inhibits the formation of chitin in sea lice, which prevents the lice from developing into adults (Poley *et al.* 2018; Holland 2016).

Technology Readiness Level: 9; Technical risk: Low

Innovations with a potential for incremental performance improvement

Traffic light for regulating Norwegian salmon production based on sea lice numbers: The Norwegian Department of Fisheries and Aquaculture divided the Norwegian west coast into 13 zones (Saue 2017). Each zone is given a green, amber, or red light, based on the number of sea lice in the given area. The regulations were developed in an effort to reduce the impact of lice on wild salmon (Havforskningsinstituttet 2020). A green light means farmers might be offered production growth, whereas a red light means reduction, while amber means it has to stay where it is.

Technology Readiness Level:9; Technical risk: Low

Presence of other species: Water-borne *Paramoeba perurans,* which cause amoebic gill disease, was shown to decrease rapidly in the presence of mussels (‘Interactions between Paramoeba Perurans, the Causative Agent of Amoebic Gill Disease, and the Blue Mussel, Mytilus Edulis’ 2016).

Technology Readiness Level:3-5; Technical risk: Low

Further improvements in chemical treatments: For example, hydrogen peroxide was successfully used in trials against amoebic gill disease, reducing the need for freshwater treatments (Martinsen, Thorisdottir, and Lillehammer 2018).

Technology Readiness Level: 3-5; Technical risk: Moderate

General ongoing improvements of known treatments, e.g. freshwater treatments for amoebic gill disease and other treatments are also frequently talked about in literature.

Technology Readiness Level: 3-5; Technical risk: Low

Using fish behaviour in order to reduce infection with sea lice: A recent study suggests that host behaviour can be used to prevent infection and moderate the fitness of parasite (Bui *et al.* 2019). It advocates a shift in the current disease control paradigm from reactive-based post-infection control to pre-infection prevention approaches. The authors suggest that fish behaviour in aquaculture can be used to (i) an indicator of welfare status, (ii) a tool in prevention or control and (iii) to maintain or improve welfare. (Bui *et al.* 2019). Thus, the suggested paradigm shift away from the current control-dominated approach, is “two sided” in that it includes preventative methods that inhibit initial infections, and/or methods that improve the efficiency of a reactive treatment. Both approaches should lead to better welfare outcomes for the fish. The current strategy of parasite control only just restrains outbreaks with a tenuous leash e.g. keeping the sea lice count to below 0.5 female lice per salmon in Norway, but future growth of the industry is stymied, until sea lice infections are better prevented and controlled (personal communications). Recognising the farmed animal as a species with an evolutionary history and utilising the behaviours or already developed responses to parasites or disease pathogens, will facilitate management of their health and welfare in production systems (Bui *et al.* 2019).

Technology Readiness Level: 3-5; Technical risk: Low

10.3 Treatments of bacterial diseases – antibiotics & alternatives (finfish aquaculture)

Bacterial infections are considered the major cause of mortality in aquaculture. One of the most important notifiable bacterial diseases in the UK is bacterial kidney disease (BKD) caused by *Renibacterium salmoninarum* (IDAAD n.d.) to which there is currently no treatment available.

In freshwater fish in the UK, common bacterial diseases include rainbow trout fry syndrome (RTFS), caused by *Flavobacterium psychrophilum*, enteric red mouth disease (ERM) caused by the bacterium *Yersinia ruckeri*, and bacterial gill disease (BGD) (Verner-Jeffreys *et al.* 2015).

Disease prevention using prophylactic antibiotics has been the norm in aquaculture globally. While the practice of non-therapeutic prophylactic use of antibiotics was banned in Euope in 2006, metaphylactic use is commonplace: as it is difficult to catch single sick animals, antibiotics are often administered in feed to entire populations (Marine Scotland 2016). There is accumulating evidence indicating that unrestricted use of prophylactic antibiotics in aquaculture is detrimental to fish, terrestrial animals and human health. Of the around 51 antibiotics commonly used in aquaculture and agriculture, 39 (or 76%) are also of importance in human medicine; furthermore, six classes of antibiotics commonly used in both agriculture and aquaculture are also included on the World Health Organisation's (WHO) list of critically important/highly important antimicrobials. Various zoonotic pathogens isolated from meat and seafood has been observed to feature resistance to multiple antibiotics on the WHO list, irrespective of their origin in either agriculture or aquaculture. Data show that resistant bacteria isolated from both aquaculture and agriculture share the same resistance mechanisms, indicating that aquaculture is contributing to the same resistance issues established by terrestrial agriculture. All this has resulted in the ban of antibiotic usage as animal growth promoters in Europe and stringent worldwide regulations on therapeutic antibiotic applications (Muñoz-Atienza *et al.* 2013).

The main focus in aquaculture is on developing alternatives to antibiotic usage and there is less focus on developing novel antibiotics (potentially partly down to cost, as for human usage the industry-standard amounts of time and money to achieve a new drug is generally accepted to be 10 to 15 years and at least $1 billion) (Watts *et al.* 2017; *Wired* 2019).

Innovations with a potential for disruptive performance improvement

Phage therapy: Phage therapy is the use of bacteriophages to treat bacterial infections. This is used as an alternative to antibiotics e.g. when bacteria develop resistance. However, phage-resistant mutants exist and it is important to test the virulence of phage-resistant mutants before carrying out large scale field trials of phage therapy (Xu 2016). As an example, Bacteriophage Str-PAP-1 is an environmentally friendly agent that can prevent and treat streptococcosis caused by S. parauberis. Streptococcosis is caused by *Streptococco parauberis* and often leads to mass mortality in farmed fish. Streptococcosis has continually increased in fish farming in Korea (Kwon *et al.* 2017).

Technology Readiness Level: 3-5; Technical risk: High

Innovations with a potential for transformative performance improvement

Improved drug delivery by encapsulation: Improved drug delivery systems may provide innovative ways to improve delivery with minimal waste and improved environmental protection. New technologies, such as encapsulation and controlled release systems, can be used readily in scaled-up operations to improve the delivery of bioactives and ultimately increase production and profitability in aquaculture (Dezfooli *et al.* 2019).

Technology Readiness Level: 3-5; Technical risk: High

Improved drug delivery using ultrasound: A more recent innovation is the application of low-frequency ultrasound as a method for enhancing antibiotic uptake. Research suggests that the use of ultrasound as a technique to deliver antibiotics to fish can ultimately reduce the amount of antibiotics discharged into the aquatic environment (Cobo Labarca *et al.* 2017). Attempts to use in commercial salmon farming in Norway have been made but the technology is currently not widely used in Norway (personal communication).

Technology Readiness Level: 3-5; Technical risk: Low

Silver and zinc oxide nanoparticles: In vitro studies of the use of nanoparticles, in particular silver and zinc oxide as a replacement for antibiotics have been made, but research for this is still in early stages (Shaalan *et al.* 2017; Márquez *et al.* 2018).

Technology Readiness Level: 3-5; Technical risk: High

Passive immunisation using chicken egg yolk immunoglobulin (IgY). Passive immunisation using chicken egg yolk derived IgY is not a new innovation but it is still not fully developed and implemented in aquaculture. The use of IgY for passive immunisation against specific pathogens, both for fish and shrimp is being researched in academia (Rajan *et al.* 2017) and in a commercial context by AdBiotech[1].

Technology Readiness Level: 3-5; Technical risk: Moderate

Evolutionary trajectories of pathogens: The ability to predict evolutionary trajectories of pathogens in response to antibiotic pressure is one of the promising approaches to fight against the present antibiotic resistance worldwide crisis. In a study by researchers from China, the UK and France, real-time evolution of an *Aeromonas salmonicida* clone in response to successive antibiotic and vaccine therapies in a commercial fish farm was monitored. The researchers reconstructed the precise tempo of mobile genetic elements (MGEs) acquisition events during the period of study. It could be shown that the resistance profile provided by the acquired MGEs closely mirrored the antibiotics used to treat the outbreak, and it was further shown that two subclonal groups developed similar resistances although by unrelated MGE acquisitions. Finally, the efficiency of vaccination in outbreak management was demonstrated. The authors concluded that the study determined the temporal and evolutionary response of a pathogen's population to antibiotic and vaccination therapies in a commercial fish farm. The results are believed to provide invaluable information from outside the laboratory and will help to define efficient and sustainable therapeutic strategies to control bacterial outbreaks in aquaculture or agricultural systems (Du *et al.* 2019).

Technology Readiness Level: 3-5; Technical risk: High

10.4 Probiotics in aquaculture

Probiotics are microorganisms which are beneficial to the health of the host, here presented with a focus on fish and shellfish. Many microorganisms have been evaluated as probiotics in aquaculture, for example: *Bacillus subtilis, Lactobacillus acidophilus*, *Lactobacillus sakei,* and *Shewanella putrefaciens*. Probiotics can be added to the feed in the water tank. Efficiency of probiotics may be enhanced when using micro-encapsulation technologies

As transformative achievements have been made in understanding the importance of the microbiome in humans and terrestrial animals, probiotics have also become an important topic

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[1] AdBiotech: http://adbiotech.com/AD/company/greeting.php

of research for finfish and shellfish aquaculture. Probiotics are known to have an antimicrobial effect through modifying the intestinal microbiota, secreting antibacterial substances (bacteriocins and organic acids), competing with pathogens to prevent their adhesion to the intestine, competing for nutrients necessary for pathogen survival, producing an antitoxin effect, modulating the immune system and regulating allergic responses (Cruz *et al.* 2012). Currently, probiotics are not widely used in Norway (in some feeds) but it is accepted as a promising alternative to antibiotic and as a preventative approach. Positive results on large commercial scale are still needed and experts agree that as probiotics are beneficial for parts of the production, further research is essential (personal communications).

Innovations with a potential for transformative performance improvement

Probiotic enhancement product: For finfish a probiotic enhancement product was developed, which enhances the microbiome and improves robustness to reduce the impact of pathogenic ulcer bacteria on seawater rearing (Sørum 2019). Fish treated with this product also resulted in increased weight gain. The product is currently being commercialised by Norwegian company Previwo (Mattilsynet 2018).

Also, bacteria from e.g. *Roseobacter clade* can be used in live larval feed, which transformatively antagonises fish pathogens such as *Vibrio anguillarum* and *Vibrio harveyi* and reduce larval mortality in challenge trials (Grotkjaer *et al.* 2016).

Other innovations in this field are discussed in chapters 5, 6 and 8.

The key focus within probiotic research is on developing novel and better strains and delivery methods. Innovations over the past four years are of an incremental nature, improving the probiotic regime, with various probiotics continuously becoming more and more widely used globally, as an antibiotic alternative.

Technology Readiness Level: 9; Technical risk: Low

Microbiome modulators: With the advancement of molecular techniques, current studies are utilising culture-independent methods to monitor the microbial modulation in the gastrointestinal tract of farmed fish and shrimp. Microbiome modulators offer a technology platform that allows the modulation of bacterial behaviour using microbial signalling molecules for the local delivery of therapeutics directly inside the gut of any farmed species. The company Prospective Research, Inc[1] in the US has developed a technology to seed trillions of bacterial pharmacies into the microbiome of finfish, shrimp, and shellfish, and can selectively turn on bacterial genes encoding bioactive therapeutics inside the animal for protection against bacterial, fungal, and parasitic pathogens. More research is needed into the microbial ecology, alternative feedstuff effects and economic impacts of modulating intestinal microbiota of farmed fish e.g. tilapia (Haygood and Jha 2018).

Technology Readiness Level: 3-5; Technical risk: Low

Bacteriocins: Bacteriocins are attractive alternatives to classical antibiotic. Some lactic acid bacteria have antimicrobial/bacteriocin activity against the main Gram-positive and Gram-negative fish pathogens. However, data suggest that bacteriocin-producing (probiotic) bacteria may harbour resistance genes available for transference in different environments. From the ecological and biotechnological perspective, antimicrobial susceptibility tests must therefore always be performed when prospecting potentially bacteriocinogenic bacteria as probiotic candidates in the environment (Muñoz-Atienza *et al.* 2013) (Resende *et al.* 2017).

Technology Readiness Level: 3-5; Technical risk: Low

Metagenomics: Metagenomics (the study of genetic material recovered directly from environmental samples) has applications in the study of microbial diversity, microbial roles in microcosms, antibiotic resistance genes, novel and potential pathogens, microbial communities forming bioflocs, probiotics, identification of biomarkers and others. For instance, key metabolic biomarkers whose abundance is correlated with neomycin sulphate (an antibiotic) resistance have been identified (Xianliang Zhao *et al.* 2018)

Technology Readiness Level: 3-5; Technical risk: Low

Innovations with a potential for incremental performance improvement

Organic acid blends: Many studies have reported that some organic acids can transformatively enhance the growth performance and health status of fish. Contradictory results have also been reported, and efficacy of the use of organic acid blends seem to depend on the aquatic animal species, type and concentrations of organic acids and the culture

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[1] Prospective Research: www.prospectiveresearch.com

conditions used (Wing-Keong Ng and Chik-Boon Koh 2017). Experiments on marine fish olive flounder, *Paralichthys olivaceus* demonstrated that organic acid blends could be a promising alternative to dietary antibiotics for the preventative and/or curative health management in marine fish olive flounder aquaculture (K. Kumar *et al.* 2018).

Technology Readiness Level: 3-5; Technical risk: Low

Short-chain fatty acids: Short-chain fatty acids (SCFAs) and their salts are 'Generally Regarded as Safe' and are often used as antimicrobials in the livestock feed industry. There are gaps in existing knowledge regarding the roles of SCFAs in the growth and health status of aquatic animals and it has been suggested that this area of research merits further investigations. Formate, acetate, propionate, butyrate and their salts are among the most studied SCFAs in aquaculture. These SCFAs affect the host performance as well as physiological response upon three ways: either through effects of the feeds that are being administered, through effects on the gastrointestinal tract of the animal or through direct effects on metabolism (Hoseinifar, Sun, and Caipang 2017). Poly-ß-hydroxybutyrate (PHB), a polymer of the short-chain fatty acid ß-hydroxybutyrate, was shown to act as a microbial control agent in farmed fish and shellfish and hence, has the potential to protect against a variety of bacterial diseases (Duan *et al.* 2017; Laranja and Bossier 2019). The mechanism of PHB conferred protection to the host brine shrimp (*Artemia*) against *V. campbellii* has been shown to be through the induction of innate immune responses (Baruah *et al.* 2015).

Technology Readiness Level: 3-5; Technical risk: Low

Natural products: Natural products such as medicinal plants, marine algae, herbs and their extracted compounds are being studied for disease management in fishes and shrimp. The use of use of botanicals, such as clove, Eugenia caryophyllata (Adeshina *et al.* 2019) and seaweeds or algae extracts such as kappa carrageenan, extracted from the red algae Hypnea musciformis, have been proved to be effective for Nile tilapia (Oreochromis niloticus) but most are still at research stage (Villamil *et al.* 2019). Also, lipidic extract of the seaweed Chaetomorpha linum (Chlorophyta, Cladophorales), revealed an antibacterial activity against Vibrio ordalii and Vibrio vulnificus (Stabili *et al.* 2019). Compounds are applied either as single compounds or as a combination of two different compounds or as feed additives and administering the compounds in the form of encapsulated beads has in some studies been found to be more effective (Thanigaivel *et al.* 2016).

Technology Readiness Level: 3-5; Technical risk: Low

10.5 Treatments of viral diseases (finfish aquaculture)

Viral diseases in aquaculture are common and can be devastating. A list and description of the globally most important viral diseases for finfish and aquaculture can be found in existing publications (FAO 2018; OIE 2019).

Vaccines are available only for few viral diseases: Infectious hematopoietic necrosis virus, *A. salmonicida*, and *V. salmonicida* are some diseases that can be prevented by killed vaccines (Assefa and Abunna 2018b) Infectious salmon anaemia and infectious heamatopoetic necrosis disease viruses have been expressed in vectors as a vaccine to protect salmon. However, in many cases no vaccines or treatments are available and vaccinations against viral disases are generally lacking and a significant area of research. All options for vaccines are being considered (with traditional injection-based vaccines still being the most dominating type) including mRNA, DNA, different adjuvant different and delivery methods.

A recent success in the fight against viral diseases was the discovery of a genetic marker for resistance against infectious pancreatic necrosis (IPN), which can lead to mortality rates of 25%, by researchers of the University of Edinburgh's Roslin Institute. In 2008 the salmon-breeding company Landcatch Natural Selection (LNS) implemented marker-assisted selection (MAS) for IPN resistance when selecting its elite and commercial salmon populations. The new breeds result in a mortality rate of zero (University of Edinburgh 2016b).

Constant monitoring and surveillance is crucial as new threats can spread quickly: The Tilapia Lake Virus (TiLV) was first detected in Israel in 2009, and has now spread to countries on four continents ('New Diseases Threaten Aquaculture - SciDev.Net' 2019)

Innovations with a potential for disruptive performance improvement

Development of fish vaccines against viral diseases: see relevant section on Vaccination and other disease prevention methods in current chapter.

Innovations with a potential for incremental performance improvement

Continuous monitoring of new and emergent pathogens remains important. For example, recently three new viruses were identified which impact populations of endangered salmon in the North Pacific (The Fish Site 2019j). In order to facilitate monitoring, whole genome sequencing of bacterial and viral pathogens of aquaculture can be used to enhance the identification of pathogenes to help mitigate disease emergence and spread (Bayliss *et al.* 2017; Avarre 2017).

Technology Readiness Level: 9; Technical risk: Moderate

10.6 Fungal diseases (finfish aquaculture)

Very little evidence of ongoing R&D in this area has been found.

Saprolegnia sp. is the most important pathogenic fungi in fish (Ghiasi *et al.* 2017).

10.7 Vaccination and other disease prevention methods (finfish aquaculture)

Modern vaccines can be classified as killed, attenuated, DNA, synthetic peptide, recombinant vector, genetically modified, and subunit vaccines. Most of the vaccines do not completely prevent disease in fish (Assefa and Abunna 2018b) but good protective vaccinations have a huge positive effect on aquaculture (personal communication).

Transformative progress has been made in recent years and vaccination to prevent disease is used routinely in finfish aquaculture, especially for Atlantic salmon, while in a limited capacity (or not at all) in many other fish species due to lack of vaccines, poor performance or cost. The majority of commercial vaccines are killed whole cell pathogen preparations administered by intraperitoneal injection (Adams 2019).

One positive example of the use of vaccines in aquaculture is that the blanket vaccination of farmed salmon appears to have resulted in a transformative reduction in positive results of pancreas disease (PD) in Scotland, according to a survey by MSD Animal Health (Undercurrent News 2018c) .

For reasons not fully understood, development of effective anti-viral vaccines has proved difficult. While teleost fish (including salmon, trout, catfish, eels, cod and most well-known fish) have a functioning adaptive immune response that is comparable to higher vertebrates, they seem to lack class-switch recombination and higher-order affinity maturation that are largely attributable to the lack of germinal centres in these lower vertebrates. As fish are ectothermic, the development of their immune system is slow, especially in cold-water species like salmonids. This initial period of vulnerability is not covered by the vaccination approach (Rajan *et al.* 2017).

Administering fish vaccines in various ways can be a time and resource intensive operation. Currently used methods can stress the fish transformatively, leading to losses. Injection vaccination for example can be applied only to fish of a certain size (>10 g), and it includes crowding the fish in small tanks, anaesthesia, handling individual fish, and an appropriate recovery period. Immersion vaccination can be effective – but requires booster administration and effective application routines for cultured fish still need to be developed (Rajan *et al.* 2017).

Innovations with a potential for disruptive performance improvement

Development of vaccines for common diseases: Work is ongoing on developments for common diseases. Successful developments of vaccines for common diseases have the potential to bring disruptive performance improvement to aquaculture. For example, there are currently no licensed vaccines available in Europe against Rainbow Trout Fry Syndrome, caused by *Flavobacterium psychrophilum,* leaving antibiotics as the only course of action to contain disease outbreaks (Hoare et al 2019) against Flavobacterium Psychrophilum. Further, a recently developed anti-viral drug, LJ001, has been found to inhibit infectious hematopoietic necrosis virus (IHNV) in vitro and in vivo (rainbow trout fry). However, transmission was not completely blocked and therefore the drug may be best suited as therapeutic for aquaculture settings (‘New Anti-Viral Drug Potential Boon to Aquaculture’ 2017) and (Balmer *et al.* 2017).

Technology Readiness Level: 3-5; Technical risk: High

mRNA vaccines for fish: mRNA vaccines represent a promising alternative to conventional vaccine approaches because of their high potency, capacity for rapid development and potential for low-cost manufacture and safe administration - in human health (Pardi *et al.* 2018) as well as animal health. Currently ongoing research of this topic for fish aquaculture is limited. One project in France explores the use of mRNA vaccines as a save and eco – compatible alternative to DNA by exploring mucosal routes of vaccine delivery (Verrier 2016)

Technology Readiness Level: 1-2; Technical risk: High

Passive immunisation: In contrast to vaccination in which antigens induce an immune response, passive immunisation can be defined as administration of extraneous antibodies to induce a temporary therapeutic effect against a pathogen. This is an emerging field of interest in aquaculture. The use of chicken egg yolk derived IgY for passive immunisation against specific pathogens, both for fish and shrimp is being researched in academia (Rajan *et al.* 2017) and in a commercial context by AdBiotech[1].

Technology Readiness Level: 3-5; Technical risk: Moderate

Innovation with a potential for transformative performance improvement

DNA vaccines: DNA vaccines have high potential to generate protection against disease particularly diseases caused by rhabdoviruses (Collins, Lorenzen, and Collet 2019). The advantage of a DNA vaccine is that it is based on purified plasmid DNA carrying only a single gene from the pathogen, which makes it non-infectious as it is unable to replicate within the host. Therefore, there is no risk of transferring the actual disease with the vaccine (Assefa and Abunna 2018b). The first DNA vaccine against salmon pancreas disease was found to be very effective and was given marketing authorisation by the European Commission in 2017 (CLYNAV by Elanco). While initial reports are positive, the DNA vaccine is twice as expensive as other vaccines against this disease (O. A. Drønen 2019). DNA vaccines were also found to give high protection against fish rhabdoviruses, however, this cannot be generalised to other viruses and there is ongoing research activity in this area. Another aspect, which needs to be considered for DNA vaccines, is consumer acceptance: among European countries, only the UK, Denmark and Norway have so far stated that DNA vaccinated animals are not genetically modified (Collins, Lorenzen, and Collet 2019).

Technology Readiness Level (for non-commercial products): 3-5; Technical risk: High

Improved oral administration of vaccines: The effective administration of vaccines administered orally depends on delivery platforms which encapsulate the vaccines to protect it from parts of the fish's digestive tract. One example of such platform development is Irish company MicroSynbiotiX which is developing a microalgae-based delivery platform for oral administration of vaccines and functional feed additives for farmed shrimp and fish(Undercurrent News 2017c)

Technology Readiness Level: 3-5; Technical risk: Moderate

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[1] AdBiotech: http://adbiotech.com/AD/company/greeting.php

Vaccination of fish embryos: Injection of fish embryos by injecting the vaccination into the yolk sac. One patent found on this, but no further evidence of R&D in this area (Peterson 2018).

Technology Readiness Level: 1-2; Technical risk: High

Innovations with a potential for incremental performance improvement

Improved effectiveness / further understanding of the fish immune system: Fish vaccines have been shown to be less efficient in a commercial setting than in trials. In some cases, vaccinations are required by insurance companies, however, the administration of vaccines can stress the fish that transformative losses occur administering the vaccine. (Science Daily 2018). Due to these stresses fish vaccinated can show higher rates of infections and mortality when exposed to parasites such as sea lice: In a recent study researchers tested the efficacy of the vaccine for the bacterial pathogen *Piscirickettsia salmonis* by comparing the reaction of vaccinated and non-vaccinated Atlantic salmon when exposed to the sea louse *Caligus rogercresseyi* in the lab. Vaccinated fish showed many more signs of infection and a higher death rate compared with the unvaccinated group upon exposure to the sea lice. (Figueroa *et al.* 2017)

Technology Readiness Level: 3-5; Technical risk: Low

Improved adjuvants: Adjuvants are substances which enhance the immune response to an antigen and one of the most effective adjuvants used in aquaculture is mineral oil. However, the traditional oil-based adjuvants, such as Montanide, can cause adverse effects and research is ongoing to identify safer adjuvants (Hoare et al 2019).

Technology Readiness Level: 3-5; Technical risk: Moderate

Improved injection methods using novel devices for vaccination of fish: Innovation in this area can range from fully automated machinery, which also transport fish from one holding cage to another, to improved handheld injection devices. One example is a system developed by Norwegian company Skala Maskon[1]. Further, UK company Aqualife worked with design

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[1] Skala Maskon: https://en.skalamaskon.no/aquaculture2/vaccination

company I4PD to develop a handheld vaccination device[1]. With recent developments having bigger smolts on land there is a need for new strategy and equipment (personal communication).

Technology Readiness Level: 9; Technical risk: Low

Bath immersion for ova and fry: A natural bath immersion product for ova and fry to improve fish health was recently developed by Canadia company RPS Biologicues. The product, Supratect, is said to be a non-antibiotic alternative to maintain optimal health in fish and fish eggs. The company says that they have done a successful field trial with a very large commercial firm in Canada and they are on their way to start large scale use (Mayer 2019; PEIBioAlliance 2019).

Technology Readiness Level: 9; Technical risk: Low

10.8 Treatment of non-infectious diseases (finfish aquaculture)

Non- infectious diseases are caused by non-living factors and include environmental diseases caused by inadequacies in the physical and chemical characteristics of the water, nutritional diseases caused by excess or deficiency in fish nutritional requirements and neo plastic or genetic anomalies.

See further information in chapter 8 ‘Nutrition and feeding’ and chapter 6 ‘Farmed animal health and welfare’.

10.9 General disease management (shellfish aquaculture)

In shrimp aquaculture, global production losses are estimated to be 65% due to viruses and 20% due to bacteria, with the remainder due to fungal infections, parasites and unknown

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[1] I4PD: https://www.i4pd.co.uk/work/aqualife-fish-vaccination-system

causes. White spot virus is pandemic and leads to 100% mortality within 3 days of onset of disease signs (FAO 2018).

Just as in finfish aquaculture, surveillance is crucial for preventing the spreads of outbreaks and detecting potential novel viruses.

Innovations with a potential for disruptive performance improvement

RNA interference (RNAi) is being evaluated by several established and emerging companies as well as in academia as a remedy against viral shrimp diseases (Shawer 2019) and (D. V. Nguyen *et al.* 2018). A recent breakthrough was reported by laboratories in Israel, where animals were treated with RNAi nanoparticles and the survival of animals treated with RNAi nanoparticles exceeded 95% compared to no survival in the untreated controls (Ufaz *et al.* 2018).

Technology Readiness Level: 3-5; Technical risk: High

Passive immunisation: Particularly with regards to culturing of shellfish, which have no adaptive immune system, passive immunisation is a sustainable and effective therapeutic solution, especially in the shrimp-production cycle. Recent results using chicken egg yolk immunoglobin (IgY) showed that addition of anti-PirA-IgY in feeds could be an effective prophylactic method against Acute hepatopancreatic necrosis disease (AHPND) infection in shrimp (Nakamura *et al.* 2019).

Technology Readiness Level: 3-5; Technical risk: High

Innovation with a potential for transformative performance improvement

Improved health using probiotics: Probiotics can help enhance shrimp health and improve immunity (Cruz *et al.* 2012) (K. Kumar *et al.* 2018). Further for bivalve aquaculture of catarina scallop (*Argopecten ventricosus*) infected with *Argopecten ventricosus* it could be shown that there is a transformative higher rate of survival when exposed to a mix of *Lactobacillus* and *Bacillus* (MIX-LB) (Abasolo-Pacheco *et al.* 2017).

Technology Readiness Level: 3-5; Technical risk: Moderate

10.10 Surveillance

Surveillance of disease occurrence is important in preventing the spread of disease outbreaks and identifying new threats. While in the UK there is a reporting system is in place for several severe notifiable diseases (Defra & Cefas 2019), a recent report in Scotland found that there is little transparency in reporting mortality rates and disease outbreaks at salmon farms with only some companies reporting mortality and causes of mortality on a voluntary basis (Rural Economy and Connectivity Committee 2018).

Surveillance of fish disease outbreaks means that preventative measures can be taken early – on the effected and neighbouring farms. Improvements can be achieved by better technological options, making it easier to spot diseases early as well as improved incentives for operators to report issues.

Technological solutions of improved surveillance are mainly improved diagnostic tools, including lateral flow devices, also called lateral flow assays which could be used by farmers and/or surveillance officials as quick tests on site have been developed in some cases but research and development in these tools is ongoing. PCRD is an example of a nucleic acid lateral flow immunoassay which is already commercialised and used in the aquaculture industry for disease detection (Abingdon Health 2017).

Innovation with a potential for transformative performance improvement

Rapid testing kits for aquaculture disease detection: Examples of existing technologies for disease detection and technologies in development are presented below.

Rapid test for the qualitative detection of ISAV (salmon anaemia virus) - has been developed and is sold by Aquatic Diagnostics[1].

Lateral flow immunoassay for the rapid detection of white spot syndrome virus - which affects shrimp farms has recently been reported by researchers in India (Kulabhusan *et al.* 2017). There is however evidence that a commercially available device already exists[2].

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[1] Aquatic Diagnostics: http://aquaticdiagnostics.com/rapid-kits-further-information/

[2] Shrimple WSSV test: https://www.youtube.com/watch?v=7mrEWKR0Zy0

Tests for bacterial diseases in freshwater fish - In India ELISA kits were recently introduced into the market which allow the quick and easy identification of bacterial diseases in freshwater fish. The kits cost around INR 42 (UDS 0.65) each (J. Kumar 2018).

Technology Readiness Level: 9; Technical risk: Low

Paper-based rapid testing kits for aquaculture disease detection: Further R&D in the development of testing kits for aquaculture disease are in progress. US company Gaskiya Diagnostics[1] develops ultra-low cost, paper-based rapid diagnostic test kits with equipment-free results. Taskiya's platform technology uses bioengineered capture proteins to bind target analytes with a high degree of sensitivity and specificity. To facilitate the detection of a variety of disease types, the capture proteins can bind peptides, small molecules and nucleic acids. An array of sample types can be tested and small to large sample volumes accommodated. The bioengineered capture proteins are thermally stable and yield consistent and easy-to-interpret detection of disease targets. The captured proteins are incorporated into user-friendly, field-use diagnostic tests. Some test kits are on market and used in commercial farming settings in Norway (personal communication).

Technology Readiness Level: 6-8; Technical risk: High

Innovations with a potential for incremental performance improvement

Human factors in disease surveillance: A recent publication suggests that farmer- based syndromic aquatic disease surveillance constitutes a real opportunity to overcome barriers inherent to traditional laboratory-based surveillance. However, the authors remark that the long-term sustainability of surveillance will necessitate overcoming farmers and institutional inertia, i.e. the reluctance to change (Brugere, Onuigbo, and Morgan 2017).

Technology Readiness Level: 9; Technical risk: Low

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[1] Gaskiya Diagnostics: http://www.gaskiyadiagnostics.com/

10.11 Disease reduction by genomic editing and targeted breeding

Genomic editing procedures and targeted breeding to improve fish with increased disease resistance is ongoing. Please also refer to chapter 7 ‘Genetic improvement’.

10.12 Prevention of harmful algae blooms (HABs)

Algal blooms, the rapid growth of algae, can occur when there are transformative changes to temperature, light, or nutrient conditions and can become fatal to fish. In 2019, a particularly severe case in Norway led to the loss of a substantial number of fish (Magra 2019) and since then there has been an increase in developments in Norway to detect and prevent of such algal blooms (personal communication). For inland lakes and reservoirs algae and biofouling can be controlled by improving dissolved oxygen (possibly by using a ‘Nanobubble generator’[1]) or also using ultrasound[2].

Innovations with a potential for transformative performance improvement

Early warning detection systems: An early warning detection system for algae bloom system is currently being developed by a consortium of OTAQ, the Iain Fraser Cytometry Centre (IFCC) at the University of Aberdeen, the Scottish Aquaculture Innovation Centre (SAIC), and CENSIS (the Innovation Centre for sensor and imaging systems and Internet of Things technologies) (Ranum 2019). The system is based on microscope camera technology, a unique water sampling tool and artificial intelligence for images which will provide a near real-time reading for fish farmers and warn them about signs of coming algae blooms. The farmer can then take preventative measures, such as the activation of a bubble curtain or barrier to protect a stretch of water or early harvest.

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[1] Nanobubble generator: https://www.nanobubblesystems.com/lakes-and-pond-remediation

[2] LG Sonic: https://www.lgsonic.com/ultrasonic-algae-control-technology/

Another early warning detection system (colometric) has been developed by Microbia Environnement in France where customers, such as shellfish farmers, pay a subscription fee for the alert service. Samples are taken and analysed twice weekly with a rapid turnaround to ensure timely feedback. The system is in commercial usage in a small number of sites and has successfully provided early warnings alerts to clients (Microbia Environnement 2017).

Technology Readiness Level: 3-5; Technical risk: High

Also see the section on harmful algal blooms in chapter 25 ‘Climate change adaptation’.

10.13 Overarching approaches of disease prevention in aquaculture

In aquaculture, poor knowledge of background microbial diversity in farm systems leads to frequent emergence of previously unknown pathogens which can destroy livelihoods and create shocks in the wider value chain. A lot of measures undertaken (scientifically, but also politically) to cope with disease outbreaks are reactive, rather than preventative. A lot of effort is placed on the identification of specific pathogens and the freedom from or eradication of those pathogens. It has been suggested that whilst striving for disease freedom will remain a key aim in countries/systems where more stringent biosecurity processes are already in place, the avoidance of disease outbreaks by management of pond and animal microbiomes (rather than attempting to eliminate the presence of given pathogens) may provide a more viable means of mitigating losses in certain open systems in the future (Stentiford *et al.* 2017).

Innovations with a potential for disruptive performance improvement

Environmental DNA (eDNA): eDNA approaches to aquaculture pond systems are expected to provide a much-needed context for conditions surrounding disease emergence by detecting specific pathogens of consequence to farmed hosts or those elements of the microbiome that facilitate their emergence as disease agents (Stentiford *et al.* 2017; Bass *et al.* 2015). The approach has gained a lot of interest but is all still at experimental stage (personal communication). Understanding of eDNA is helped by techniques such as high-throughput sequencing (HTS). HTS, applied to open aquatic systems is rapidly increasing our knowledge of prokaryotic and eukaryotic diversity and the complex symbiotic arena in which they exist.

Recently, ‘Tara Ocean’[1] added transformatively to the understanding of the genomic diversity in the ocean by collecting more than 60,000 samples around the world and using high-throughput sequencing to understand more about the sea’s ecosystem (Karsenti *et al.* 2011).

Technology Readiness Level: 3-5; Technical risk: High

Pathobiome concept: Animal and plant diseases are increasingly recognised to result from interactions between host-associated bacteria, eukaryotes, and viruses, their host, and the environment (pathobiome). The improved definition of a “pathobiome” within hosts may be expected to supersede a historic focus on specific pathogens as sole perpetrators of yield-limiting disease. Multidisciplinary studies, including high-throughput sequencing ‘omics, can be used to reveal both the structure and function of pathobiomes, which may not be discernible from taxonomic analyses alone’ (Bass *et al.* 2019). This includes understanding what is in the feed / feed ingredients, as this may also have an important role and effect in relation to diseases (personal communication).

Technology Readiness Level: 1-2; Technical risk: High

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[1] Tara Ocean: https://oceans.taraexpeditions.org/en/m/about-tara/les-expeditions/tara-oceans/

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11 Production and handling technologies

Contents

From the SIF Executive Board

The method applied in this review has generated numerous examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently happening. It is recognised that there are existing innovations and research areas that are not included here, and new areas where future innovations may occur. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

11.1 Overview: Production and handling technologies

What is the challenge in the UK?

As site availability for new farms is a challenge in the UK, technologies enabling farming away from the shore – either off-shore or in-land -– will enable further growth in the sector. Globally, there is an immense effort in terms of R&D but also investment into recirculating aquaculture systems (RAS) including aquaponics (RAS in combination with growing vegetables or other plants in hydroponic systems), which can be operated inland. So far, there has been little commercial activity in the UK, but as the technology evolves and large farms become commercially viable this is expected to have an impact on the industry. Any improved automation systems, which allow remote monitoring and operating of fish farms, and therefore reduce labour cost, will likely impact the sector.

What are the most promising innovation categories?

- Innovations enabling off-shore fish farms in high energy environments
- Remote monitoring and systems allowing for automated operating of fish farms – in any location
- Improvements and scale up of RAS possibly incl. aquaponic systems

Where are important knowledge gaps?

There are knowledge gaps in the design and operation of RAS systems, particularly for smolt production in the salmon industry where the problem of sudden appearance of H_2S which can kill fish within hours is still not entirely solved. In general, the merging of computational technologies (such as AI systems) with outputs from fish monitoring systems (e.g. images and videos from cameras) needs further development

The husbandry of aquatic animals is not a new phenomenon (FAO 2000). Ancient practices based on the modifications of natural bodies of water or wetlands to entrap young fish in enclosures until harvest, have over time evolved into more systematic and scientific methods and techniques. A number of aquaculture practices are used worldwide in three types of environment (freshwater, brackishwater, and marine) for a great variety of culture organisms.

Culture systems range from extensive to intensive depending on the stocking density of the culture organisms, the level of inputs, and the degree of management. This chapter gives an overview of most recent advancements in aquaculture systems with a focus on systems of potential relevance to the UK setting.

An overview of the potential performance improvement rating of recent (2015-2019) innovations in production and handling in aquaculture are outlined in Figure 10-1.

Performance*	Low	Moderate	High
Disruptive	• Larger scale RAS facilities	• Efficient land-based fish farming with continuous seawater intake for salmon • Floating fish farms • Selective breeding of mussels	• Offshore fish farming (SalMar) • Satellite imagery to monitor farm activities • Fish farms on ships
Transformative	• Modular RAS systems • RAS with adjustable tank size • Understanding the microbiome in aquaponic systems • Increased understanding of biofloc composition and water quality parameters • Gas sensor unit, including H_2S detection • Improved understanding of effect of H_2S • Automation of water quality monitoring, incl. fish biomass, mortality and behaviour • Controlling salinity when raising juvenile fish • Nanobubble generator for use in net-pens • A fully enclosed egg-shaped tank	• Vertical farming • Use of desalination technologies in aquaponics • Eloxiras water treatment process • Semi-closed fish cage preventing sea lice and ability to pump fish out from bottom of cage • Machine vision systems in aquaculture • Detecting unusual fish behaviour using computational methods • On-fish sensors to monitor fish behaviour • Automatic evaluation of fish weight • Rearing rock lobsters in commercial hatchery setting • Automated sorting of Fingerlings • Large scale mussel farms • Transportation system for live shellfish	• Intelligent Management Systems for Integrated Multi-Trophic Aquaculture • Automated water quality control process
Incremental	• RAS with improved power management • Saltwater systems for inland aquaculture • Self-sustaining system – RAS and biofloc • Effluent sampling system for RAS • Portable aquaponics system (small, low cost) • Fish, crustaceans and bivalves in IMTA • Self-cleaning UV water treatment systems • GiliOcean submersible cages • Fish pens including sensors, cameras and mortality traps • Improvement in understanding water flow in RAS culture tanks • ROVs for inspection cage cleaning and mort removal • Real-time monitoring of offshore fish farms • Automated live fish grading and biomass evaluation	• A double recirculating aquaponic system (DRAPS) • Distributed aquaponic system • Improved control of C/N ratio using biofloc • Mullet and shrimp in RAS biofloc • Kit box to diagnose acute fish death rapidly • Energy supply for remote fish farms converting wave energy into electricity	• Various aquaponic systems at concept stage

Technical Risk*

Figure 11-1: Potential performance improvement rating of aquaculture production and handling systems.

**See section 4.4 for definitions of the performance and technical risk rating scales.*

11.2 Recirculation Aquaculture Systems (RAS)

In many instances, the inland tank type or open-pond type aquacultures need continuous supply and discharge of culture water, where the culture water quality is degraded due to waste products from feed or excrement from aquatic species and eutrophication caused by influx of nitrate and phosphate from the environment. This can be a problematic because of high water usages and the effluent going into the environment.

Recirculating aquaculture systems (RAS) overcome this problem by having a loop, where effluent water from the fish tanks is treated and recirculated back to the fish tanks in a closed system. Water can be treated either using mechanical filter media (“clearwater RAS”) or by using biofloc (“biofloc RAS”). Hybrid systems of the two also exist.

RAS technology has been widely applied in hatcheries and juvenile production for early stage growth (e.g. for salmon smolts), and for table fish, e.g. trout production in Denmark, where effluent regulations are stringent (Lasner and Nielsen 2017; EKOS 2018). There are also examples of commercially successful farms using RAS for fish all the way up to the grow-out stage, including:

- Salmon: Various salmon farms running, and some planned in various geographic locations, including Dubai (Evans 2019a)
- Sturgeon: Emirates Aquatech operates the largest sturgeon farm worldwide (George 2016)
- Barramundi (TheBetterFish 2016; White 2018)
- Saltwater fish (kingfish, sea bass, gilthead seabream) (Fresh Corporation n.d.; Davies 2016)
- Yellowtail Kingfish (Denmark) (Ramsden 2018a)
- Shrimp (Reiners 2016) (Nuttall-Smith 2015) ((FloGro in Lincolnshire (FloGro n.d.))
    - See also: Shrimp aquaculture in the Sahara Desert using Korean biofloc technology (Arirang News 2016; Service (KOCIS) 2016)

An overview of RAS farming technologies can be found in the FAO publication “A guide to recirculation aquaculture: an introduction to the new environmentally friendly and highly productive closed fish farming systems” (Bregnballe, Eurofish, and FAO 2015).

Clearwater RAS systems will generally include (Espinal and Matulić 2019):

- Devices to remove solid particles from the water which are composed of fish faeces, uneaten feed and bacteria.
- Nitrifying biofilters to oxidize ammonia excreted by fish to nitrate.
- Several gas exchange devices to remove dissolved carbon dioxide expelled by the fish as well as/or adding oxygen required by the fish.
- Additional components may include water disinfecting systems (UV irradiation or ozonation), protein skimming for fine solids and microbial control and a denitrification system to remove nitrates.

In biofloc systems, heterotrophic bacteria and autotrophs are cultured together with useful microorganisms and the aquaculture species. The term "biofloc" itself refers to a complex structure made out of 60-70% organic matter, which includes a heterogeneous mixture of microorganisms (fungus, algae, protozoans, and rotifers) and of 30 - 40% of inorganic matter such as colloids, organic polymers, and dead cells (for further detail, please see section 10.6 below).

In the UK between 2002 and 2013, 29 RAS farms registered for grow-out production (i.e. excluding hatchery and smolt production) (Murray, Bostock, and Fletcher 2014). Of these, 18 (62%) were designed for Tilapia production and most were UK Tilapia franchises. A lot of the initial farms ceased production within 2-3 years. After the initial period of learning, some upscaling took place in order to be able to supply supermarkets. However, sales volumes did not reach anticipated levels. For farming tropical shrimp, FloGro[1] in Lincolnshire is already operating. Flo-Gro holds a patent on the method of shrimp farming (Wiles, Deocampo, and Maxwell 2015) and further tropical shrimp farms had been planned around England and Wales (Hambrey and Evans 2016).

Economies of scale mean that with currently achievable RAS farm sizes, the technology tends to favour higher value seafood species rather than commodity species. Liu *et al.* studied the economic performance of a theoretical RAS farm with a capacity of 3300 tons per year, compared to a traditional net pen farm of the same capacity (Y. Liu *et al.* 2016). At such scale, the RAS operation reaches similar production costs compared to the net pen farm, but the

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[1] FloGro: http://flogrosystems.com/

higher capital investment doubles the payback period in comparison, even when the fish from the RAS farm are sold at a premium price.

Advantages of RAS systems include the relative independence on location. Farms can be situated right in urban centres near consumers. They can also be vertical, such as Singaporean company's AAG's current farm, with three stories, each one holding two 145 sqm ponds. The farm produces up to 150 - 200 kg grouper per tonne of water. For comparison, sea cage farming produces an average of 25-75 kg per ton of water. The company now plans an eight storey vertical fish farm to be completed by 2023 (Temasek 2019).

Apart from high investment cost, problems with producing fish in RAS include off-flavours and odours, which can accumulate in the fish flesh from the circulating water, resulting in a decrease in fish meat quality. Off-flavours are typically caused by geosmin (GSM) and 2-methylisoborneol (MIB), both lipophilic compounds formed as secondary by-products of bacterial metabolism. These are non-toxic compounds, but often disliked by consumers. Purging with fresh water is currently the only efficient method available to remove the off-flavours (Lindholm-Lehto and Vielma 2019).

A key technical challenge to overcome in RAS systems is the accumulation of particulate organic matter. Despite mechanical filtration, particulate organic matter can occur within hours and often found to be accumulations of microorganisms (personal communication). Negative effects of this include decreased monitoring ability for the fish farmer, but also reduced nitrification efficiency in the bioreactor, clogging of the CO_2 degasser leading to reduced stripping efficiency, biofilm growth and increased risk of H_2S formation as well as unstable microbial dynamics and bacterial blooms (Aquaculture Europe 2019b).

Further, it is known that in the past a variety of problems have occurred in RAS farms, which led to mass death of fish (EKOS 2018). Learnings from these incidents has led to a better understanding of these systems.

Aquaponics is fish production coupled with plant production, using RAS. This is discussed in a separate section below.

Innovations with a potential for disruptive performance improvement

Larger scale facilities: Larger facilities will have the advantage of reduced transportation costs (on feed, chemicals, oxygen etc.), reduced utility cost (access to industrial rates), economic viability of automation of farm processes and maximisation of the use of labour. Following the increase of economies of scale in the net pen aquaculture sector, larger RAS are being developed at scales not considered a decade ago: “The last decade has seen the construction of facilities with production capacities of thousands of tons per year, and this sheer size increase of RAS facilities is bringing new technical challenges” (Espinal and Matulić 2019).

The biggest salmon farm to date is being built in Miami, Florida, USA, by Atlantic Sapphire Inc who commissioned the Danish company Billund Aqua. The long-term aim of the company is to supply around 80% of the total US market. The first stage of the salmon farm, will provide Atlantic Sapphire with 10,000 ton capacity, and the additional stage, starting in 2020 and expected to be commissioned in 2021, will add another 10,000 ton capacity to the project (Billund Aquaculture 2019; EKOS 2018).

Technology Readiness Level: 9; Technical risk: Moderate

Innovations with a potential for transformative performance improvement

Modular RAS systems: Sterner developed a module-based RAS system[1], where each tank unit has its own recirculation plant. Compared to traditional centralised RAS systems, the modular solution has the following advantages: Each unit is biosecure, provide full temperature and salinity control, the modular design allows for future expansion and has extremely low running costs compared to traditional RAS. The plant combines a moving bed biofilm reactor (MBBR) with submerged fixed bed reactor (SBR).

Technology Readiness Level: 9; Technical risk: Low

RAS with adjustable tank sizes: RAS 2020 by Krüger and Veolia is a design, which allows for adjustable tank sizes to secure optimal fish density. The system is designed as a module with a capacity of up to 1,200 tonnes 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 - 350 litres per kg feed per day. The design also enables uniform flow velocity in the water column, and a “vacuum CO_2 stripper”. Recently the Danish company Sashimi Royal opened a new plant using the RAS 2020 for grow-out production of Yellowtail. The RAS 2020 allows farmers to achieve a farm-to-table strategy, by locating facilities on land

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[1] Sterner RAS system: https://www.sterner.co.uk/aquaculture-products/recirc/

near key markets. This reduces shipping costs and shortens delivery times, whilst offering consumers a superior, fresher product (State of Green n.d.; Veolia n.d.; EKOS 2018).

Technology Readiness Level: 9; Technical risk: Low

Vertical farming: Singaporean company Apollo Aquaculture Group (AAG) successfully prototyped a three-storey fish farm using their closed-system water reticulation technology. The prototype currently holds about 100,000 fish and fry. Surbana Jurong's Floating Ponds concept can increase this to six storeys or more and potentially yield almost 5,000 tonnes of food-fish per year when in full operation (Surbana Jurong 2019).

Technology Readiness Level: 9; Technical risk: Moderate

Saltwater systems for inland aquaculture: German company Neomar[1] developed the Oceanloop® technology, which allows the production of marine organism inland, independent of access to natural sea water. The technology has been successfully trialled by the company "Meeresfischzucht Völklingen".

Technology Readiness Level: 9; Technical risk: Low

Innovations with a potential for incremental performance improvement

Fish tank effluent sampling system: Fish tank effluent sampling system in particular for use in recirculating aquaponic systems, has been developed by researchers at the University of California (Jay-Russell *et al.* 2019).

Technology Readiness Level: 3-5; Technical risk: Low

Improved power management: AquaMaof is an Israeli company specialising in RAS technology, claiming to have efficient power management, which dramatically reduces cost and energy. The advanced AquaMaof Minimal Liquid Discharge (MLD) technology[2], utilises several water treatment patents and filtering techniques to cut water consumption (Snir and Myers 2019).

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[1] Neomar: https://www.neomar.de/en/

[2] AquaMaof Minimal Liquid Discharge: https://aquamaof.com/technology/

Technology Readiness Level: 9; Technical risk: Low

Improvement in understanding water flow in RAS culture tanks: Recent investigations, to optimise the hydrodynamic characteristics in large octagonal tanks used for salmon smolt production, looked at the effect of fish biomass, geometry and inlet and outlet structures in large tanks used in Norwegian smolt facilities. The researchers concluded that improving suspended solids control in such systems may dramatically reduce the oxygen consumption and CO_2 production (Gorle *et al.* 2018).

Technology Readiness Level: 3-5; Technical risk: Low

A self-sustaining system: A self-sustaining system uniting the positive characteristics of recirculation systems with the qualities of the biofloc system, and the development of a new technique for the creation of an integrated tilapia (or other species) production system is described by Brazilian inventors (Poggere & Paulert. 2015).

Technology Readiness Level: 6-8; Technical risk: Low

11.3 Aquaponics

Aquaponic systems are a branch of recirculating aquaculture technology in which plant crops (in a hydroponic unit) are included to either diversify the production of a business, to provide extra water filtration capacity or to provide a combination of the two. Apart from fish and plants, also nitrifying bacteria are an important part of the system and finding the right combination pose a serious challenge (Suhl *et al.* 2016). Aquaponic systems are typically not completely independent from the outside and require some external input of nutrients. In one review, aquaponics was defined as a system where the majority (> 50%) of nutrients sustaining the optimal plant growth, are derived from waste originating from feeding aquatic organisms (Palm *et al.* 2018).

While the basic technology for aquaponics is reasonably well understood and there is some level of commercial activity, often the business cases for aquaponic farms do not hold. It has been pointed out that the products (fish and vegetables) from aquaponic systems in Europe still need to compete with Tilapia from China and tomatoes from large greenhouses in the Netherlands, which currently they do not (personal communication).

One example of a relatively small company, which so far has survived, is ECF Farm Systems[1], which developed from an actual aquaponics farm to becoming a company implementing aquaponic projects. The first project in Berlin[2] grows perch and basil, a rooftop farm in Switzerland produces trout, lettuce and herbs and another rooftop farm in Brussels produces bass as well as lettuce and herbs.

In order to supply cost competitive products, aquaponics need to benefit from “economies of scale” and there are currently few examples of large-scale facilities. Currently, the largest aquaponics facility is Superior Fresh in Wisconsin[3], USA. The company grows Atlantic Salmon and a variety of green vegetables (EKOS 2018). Superior Fresh uses a “semi-decoupled system”, which has interconnected but separate greenhouse and aquaculture operations, with the same water flowing through both, which is then cleaned and recirculated. Water parameters ranging from temperature to nitrates and micronutrients are automatically controlled and there is the option to completely decouple the systems, in which case the systems run independently, but nutrients from fish waste can still be utilised (Hein 2018). The plant is currently ongoing an extension, which will see yearly production increase from 160,000 pounds of fully grown Atlantic Salmon to 1.5 million pounds.

Recently with the help of EU funding, 68 researchers from 29 countries contributed to an open-access book in Aquaponics. The book discusses systems and technologies, feeding, regulation as well as education in aquaponics (Goddek *et al.* 2019).

Saltwater Aquaponics systems are also in development. Those systems combine saltwater aquaculture with the hydroponic cultivation of saltwater or salt resistant/tolerant aquatic plants and have been reviewed in an article by Gunning *et al.* These systems are typically practiced in a controlled manner (e.g. controlled flow rates; located in greenhouses), are often recirculatory in nature and have organic and/or mechanical biofilters, providing a better opportunity for intensive cultivation, water reuse, and reduced wastewater production, when compared with traditional crop and fish production methods (Gunning, Maguire, and Burnell 2016).

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[1] ECF Farm Systems: http://www.ecf-farmsystems.com/en/

[2] ECF Berlin: https://www.ecf-farm.de

[3] Superior Fresh: https://www.superiorfresh.com

Innovations with a potential for transformative performance improvement

Understanding the microbiome in aquaponic systems: While the technology of aquaponic systems is well understood, it is known that plants grow better when fed fish-water compared to plants grown in pure hydroponic systems (personal communication). Research is underway in gaining understanding in the microbial processes involved in aquaponics (Joyce *et al.* 2019; Bartelme *et al.* 2018; Eck *et al.* 2019).

Technology Readiness Level: 1-2 Technical risk: Low

Innovations with a potential for incremental performance improvement

A double recirculating aquaponic system (DRAPS): DRAPS consists of two independent recirculating units – a recirculating aquaculture unit for fish production and a closed hydroponic cycle for plant production. This allows the use of fish wastewater as nutrient supply for plants in hydroponics and its optimisation for plant growth by fertiliser supply without negative effects on fish rearing. In a constructed DRAPS research facility, first investigations with tilapia and tomato production were conducted in 2015. During an annual production, it was demonstrated that in the DRAPS system comparable tomato yields were produced as obtained for conventional hydroponics. Even fruit parameters such as contents of lycopene and ß-carotene resulted in the same quantity, when both systems were compared. Furthermore, the fertiliser use efficiency was increased by 23.6% in favour of the DRAPS. The total fresh water use efficiency was also increased (Suhl *et al.* 2016).

Technology Readiness Level: 3-5; Technical risk: Moderate

Distributed aquaponic system: Japanese company "Horimasa City Farm" has built a pilot aquaponics farm in Oita prefecture, Japan. On its 3000m^2 premises, three separate facilities have been built and connected through underground circulated pipes system. In the facility the plant growth environment can be completely controlled (temperature, humidity, CO_2 level, LED lights). The aquaculture facility, which is separate from the main building has four fish tanks and one large filtration structure. Currently, rainbow trout are grown under different conditions. A greenhouse, which is approximately 1000m^2 was built to practice aquaponics and hydroponics under semi-controlled conditions. The company Horimasa City Farm patented the technology (堀, Hori, and 堀 2017; Horimasa City Farm n.d.).

Technology Readiness Level: 6-8; Technical risk: Moderate

Portable aquaponics system: A portable aquaponics farming method was developed by US company Bridge Communities. The system is a recirculating system with a gravel biofilter. The Oasis[1] is an ultra-low-cost aquaponics system that requires minimal assembly prior to use. While the Oasis was designed with developing world farmers in mind, Bridge Communities claims that it is useful to anyone wishing to grow their own food with a low impact on the environment. A functional prototype exists, which can be plugged into the grid or connected to a solar panel. Previous prototypes used Tilapia fish and grew vegetables (Leach and Ortiz 2019)

Technology Readiness Level: 6-8; Technical risk: Low

Use of desalination technologies: Aquaponic systems require high nutrient levels for the plants and low nutrient and particulate loading in the fish tanks. Therefore, frequently suspended matter in the aquaculture component needs to be discharged and fertiliser needs to be added to the plants. Researchers in The Netherlands have explored whether desalination technology could be used to improve the nutrient balances in multi-loop aquaponics systems. (Goddek and Keesman 2018)

Technology Readiness Level: 1-2; Technical risk: Moderate

Various concepts of aquaponics systems: Various concepts of aquaponics systems have found to be patented, but the exact development status of these is unclear. Some examples of these are:

- *Solar greenhouse aquaponics, black soldier fly composter and auto-fish feeder*. This development involves a solar greenhouse containing a fish tank, a plant growing area and a mushroom growing area. The system also includes a black soldier fly composter. The larvae of the black soldier fly can climb up a ramp and drop into the fish tank as fish feed. Further, a mushroom growing area is housed in the solar greenhouse (Villamar 2019).
- *Generating water using the humidity generated by the growth of plants and/or fungi in a closed loop*. A system has been developed in which evaporated water is recirculated in container-based farming systems, specifically also aquaponic systems. The

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[1] Oasis system: http://www.bridge-communities.org/oasis.html

technology was developed and patented by US company Zero Mass Water (Friesen and Hooper 2019).

- *An aquaponic system*, combining, as well as renewable energy and heating sources, hybrid aquaculture and growing beds, vertical growing towers, and the breeding of butterflies for pollination. All has been developed in shipping container module format, developed and patented by US company “Revolution Agriculture”. This is said to be able to grow anything from fruits and vegetables, to culinary herbs, to corn and hay. Since the system is closed, drought, seasonal changes, or insects (pests) aren't an issue, and the system can be placed virtually anywhere - from deserts to places like Alaska. It is envisioned to run entirely on renewable energy (Brion 2019; Mahoney 2017).
- *An aquaponic system with a circular multi-storey structure around a pole* was designed and patented by US company Aquatree Global. No evidence of its implementation could be found during the course of this work (Higgins 2019).

Technology Readiness Level: 1-2; Technical risk: High

11.4 Integrated multi-trophic aquaculture (IMTA)

Integrated multi-trophic aquaculture (IMTA) provides the by-products, including waste, from one aquatic species as inputs (fertilisers, food) for another. Farmers combine fed aquaculture (e.g., fish, shrimp) with inorganic extractive (e.g., seaweed) and organic extractive (e.g., shellfish) aquaculture to create balanced systems for environment remediation (biomitigation), economic stability (improved output, lower cost, product diversification and risk reduction) and social acceptability (better management practices) (Wikipedia 2019).

While there are examples of small-scale operations, so far no major breakthroughs for IMTA systems on a larger commercial scale have been observed (personal communication).

Innovations with a potential for incremental performance improvement

Fish, crustaceans and bivalves in IMTA: OnHand Agrarian[1] is a Singaporean company rearing fish, crustaceans and bivalves in environments that replicate their natural ecosystem, operating a closed loop system, thereby reducing the need for fertilisers and chemical feed.

Technology Readiness Level: 9; Technical risk: Low

11.5 Land-based systems with seawater or freshwater intake

Land-based systems with seawater or freshwater intake need less technology than complete RAS, as fresh water is continually provided from the outside.

Innovations with a potential for disruptive performance improvement

Efficient land-based fish farming: A land-based fish farm, with a land-based saltwater flow-through pool fed by seawater intake, has been described by Andfjord Salmon AS. The company claims increased efficiency, by control of temperature, waste treatment and lack of disease (Pettersen and Eriksen 2019). Early 2019 the company raised EUR 15.3 m to start construction at the world's largest flow-through site for salmon farming. The farm is said to take water from a depth of 160 m, avoiding sea lice. The site will have 100% flow-through fresh seawater, not recycling or purifying water. The first fish is planned to enter the plant by 2020.

Technology Readiness Level: 6-8 ; Technical risk: Moderate

Floating fish farms: Eco-Arc is a floating fish farm, which was commissioned in November 2019 in Singapore. It is a fish farm floating at sea to rear barramundi, red snapper and hybrid grouper. Around 30 tonnes of fishes are housed in four cultivating tanks, each with a capacity of 475,000L. A filter system works round the clock to minimise bacteria, pathogens and waste. As fish are in tanks, they are not vulnerable to changes in water temperatures, oxygen levels,

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[1] OnHand Agrarian: https://www.onhandagrarian.com/imtras

bacteria levels and environmental concerns (e.g. oil spills). Eco-Ark, which cost S$4 million to set up and will be fully operational “shortly”, will generate a higher yield of fish within a smaller space requirement than other coastal farms. The farming process at Eco-Ark consumes less energy than coastal farms or other closed-containment farms located on land (Elangovan 2019).

Technology Readiness Level: 9; Technical risk: Moderate

11.6 Biofloc water treatment systems

Biofloc applies to a complex structure made out of 60-70% of organic matter, which includes a heterogeneous mixture of microorganisms (fungus, algae, protozoans, and rotifers) and of 30-40% of inorganic matter such as colloids, organic polymers, and dead cells. Biofloc systems are typically used to grow species which have a high tolerance to solids, e.g. shrimp, tilapia, carps and catfish (Prabu, E et al, J. of Aquaculture in the Tropics, 2017 and personal communication).

The biofloc is able to convert toxic nitrogenous wastes into the useful microbial protein, which helps improve water quality in zero water exchange systems (Ahmad *et al.* 2017). Biofloc systems are particularly successful for species which have a high tolerance to solids and thus, nearly all biofloc systems are used for growing shrimp, tilapia and carps, which all have relatively high tolerance to solids in the water (Prabu, E et al, J. of Aquaculture in the Tropics, 2017).

With regards to patents in this area, it was observed that Korean innovators hold a high number of patents relating to biofloc technology in aquaculture. The sector has received funding from the Korean government. One Korean farmer commented that with biofloc technology he could produce ten times more shrimp than other aquaculture farms of the same size (Arirang News 2016).

Innovations with a potential for transformative performance improvement

Increased understanding of biofloc composition and water quality parameters: There is ongoing research in order to further understand biofloc formation, the microbes involved and the effect it has on the aquaculture systems (H. Liu *et al.* 2019; Alfiansah *et al.* 2018; Halim, Nahar, and Nabi 2019).

Technology Readiness Level: 1-2; Technical risk: Low

Innovations with a potential for incremental performance improvement

Urban biofloc culture and plant cultivation system using aquaponics: Researchers in Korea patented a closed RAS combined with a biofloc tank for symbiotic breeding of aquatic species and plant species. The culture water, drained out of the composite aquaculture tank, is firstly purified by microorganisms using biofloc technology, secondly purified after being transferred into aquaponics plant growing apparatus, where the waste products in the culture water are used as nutrients for plant species, and then directed back to be recycled as culture water for growing aquatic species (Kim, Jang, and LIM 2016).

Technology Readiness Level: 6-8; Technical risk: Moderate

Improved control of C/N ratio using biofloc: An aquaculture system controlling the C/N ratio by using biofloc technology was patented by Nippon Suisan Corporation, a Japanese seafood company (Minami 2019).

Technology Readiness Level: 6-8; Technical risk: Moderate

Mullet and shrimp in RAS biofloc system: Researchers in Brazil integrated the farming of mullet and shrimp in a biofloc system. They showed an increased yield up by 11.9% and also reported that the integration of shrimp and mullet in a biofloc system was ecologically more efficient and increased phosphorous retention by 16.8%. The authors concluded that “these experimental-scale results demonstrate that the integration of shrimp and mullet in biofloc systems increase yield and phosphorous retention, without compromising fish health and shrimp growth”. They recommend replicating this integrated system over a longer period and at commercial scale, supporting an economic analysis (Legarda *et al.* 2019).

Technology Readiness Level: 1-2; Technical risk: Moderate

11.7 Water quality sensing

In order to control water quality, gas sensors are an integral part of aquacultures systems. Separate sensors sense nitrogen, dissolved oxygen, carbon dioxide and H_2S. They can be separate or can be part of combined systems. They can also directly interact with control systems for fully automated operation procedures.

There are more than 40 water quality parameters than can be used to determine water quality in aquaculture (Timmons and Ebeling 2010 as cited here - Espinal and Matulić 2019). Of these only a few are traditionally controlled in the main recirculation processes:

- Dissolved oxygen (DO)
- Ammonia
- Biosolids (originate from fish feed, faeces and biofilms)
- Carbon dioxide (CO_2)
- Total gas pressure (the sum of the partial pressures of all the gases dissolved in an aqueous solution)
- Nitrate (NO_3)
- Alkalinity

While nitrogen, and CO_2 increase relatively slowly with decreasing DO, H_2S can appear relatively sudden in RAS systems and can become a big problem resulting in farmers losing fish. The H_2S is formed by a sulphate reducing bacteria. In RAS systems problems typically appear when fish are temporarily starved prior to relocating them from the farm to the sea, as the change in the water composition due to the lack of feed has an immediate impact on the microbial system (personal communication). H_2S can also be a problem in pond systems where it can form in pond bottom sediment (Boyd 2014). A biological treatment for pond systems is commercially available (PondDtox by Novozymes), which contains *Paracoccus pantotrophus,* which oxidizes H_2S into harmless compounds. Seawater contains more sulphates than fresh water, which is why more problems are encountered in systems which introduce seawater.

Innovations with a potential for transformative performance improvement

Combined sensor unit, including H_2S detection: Blue Unit is a Danish company offering sensors for H_2S detection (at levels low enough to be relevant for fish health) as well as for detection of other gases. The company has patented technology and also sells a combined hardware and software solution to provide “access to 10 vital water quality parameters from up to 12 separate locations on a fish farm (Blue Unit n.d.; OWEN 2019; Thomsen 2018).

Technology Readiness Level: 9; Technical risk: Low

Innovations with a potential for incremental performance improvement

Better understanding of the effect on H_2S on fish: NIVA, the Norwegian Institute for Water Research and DTU (Technical University of Denmark) have entered into a collaboration to clarify some of the problems surrounding H_2S and the chronic effect on fish, which so far have not been well understood (Thomsen 2018).

Technology Readiness Level: 1-2; Technical risk: Low

System for measuring nitrites and nitrates in fish tanks: The Austrian company S::can[1] provided an experimental research and learning environment at a Finnish fish farm with nitrogen sensors, so that harmful NO_2 can be detected immediately.

Technology Readiness Level: 9; Technical risk: Low

Point of use tests for ammonium, nitrite and nitrate quantification: Such tests are developed by Portuguese start-up company Nitrogen Sensing Solutions (NSS)[2]. The company claims to revolutionise the way aquafarmers control the levels of toxic nitrogen-based compounds generated by fish waste. By optimising fish feeding and water management, aquafarmers will then be able to increase biomass production, minimise operational costs and run. The sensor, NOxAqua comprises of a portable reader and disposables chips. It can measure the ammonium, nitrite and nitrate levels in fish and shrimp ponds in less than 5 minutes. Nitrite sensors have also been developed by other groups, e.g. researchers in the Netherlands, and China (Cordis 2015; Wang *et al.* 2018).

Technology Readiness Level: 6-8; Technical risk: Moderate

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[1] Scan: https://www.s-can.at/environmental-monitoring/item/171-nitrate-no3-nitrite-no2-sensor-water-recirculating-aquaculture

[2] Nitrogen Sensing Solutions: https://www.nitrogensensing.com

11.8 Removing nitrogen compounds

Ammonia has traditionally been treated in recirculation systems with nitrifying biofilters, devices that are designed to promote microbial communities (nitrifying bacteria) that can oxidize ammonia into nitrate ($NH_4^+ \rightarrow NH_2OH \rightarrow NO_2^- \rightarrow NO_3^-$) (Chen *et al.* 2019). This can be followed up by using a filter with anaerobic denitrifying bacteria that convert nitrate to nitrogen gas ($NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2$). Operators of aquaculture systems may also flush out nitrates by exchanging the water. Nitrifying bacteria grow slowly (replication occurs 40 times slower than for heterotrophic bacteria) and are easily outcompeted by heterotrophic bacteria if organic carbon, mostly present in biosolids suspended in the culture water, can accumulate.

Nitrifying bacteria can either be suspended (biofloc) or grow on media where bacteria can attach for growth. Generally, attached growth systems provide more surface area for bacterial attachment than suspended growth systems, and do not produce significant solids in their outflow, which is one of the main reasons why attached growth biofilters have been so commonly used in RAS (Espinal and Matulić 2019).

See section ‘Biofiltration by nitrification’ in chapter 12 ‘Waste management and valorisation’.

11.9 Removing CO_2

CO_2 from the fish’s respiratory system accumulates in the water in closed systems and needs to be removed. While there are systems available, more efficient systems (higher removal rates at lower cost) are needed (personal communication). According to one recent publication (EKOS 2018), 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.

There remains uncertainty in the definition of acceptable CO_2 levels, particularly for salmonids (EKOS 2018)

While more efficient CO_2 removal had been identified as a priority for R&D by at least two sources, very little evidence of recent activity in this sector has been found during the course of this project. It is assumed that R&D is ongoing behind closed doors in the commercial sector. One of the leading companies in providing CO_2 degassing systems for the aquaculture sector is Sterner[1].

11.10 Oxygenation

The control of dissolved oxygen in modern RAS aims to increase the efficiency of oxygen transfer and decrease the energy requirements of this process. Increasing the oxygen transfer efficiency can be achieved by devising systems, which retain oxygen gas in contact with water for longer, while a decrease in energy requirements may be achieved by the use of low-head oxygen transfer systems or using systems which do not use electricity at all, such as liquid oxygen systems connected to oxygen diffusers operating only by pressure (Espinal and Matulić 2019).

Innovations with a potential for transformative performance improvement

Archae to increase oxygen in aquaculture: The Ireland-based company Univiv is culturing a particular strain of archaea, a type of microorganism, as an aquaculture pond additive. Trials have shown that using archaea can increase production and reduce inputs such as aeration needs (Moore 2019).

Technology Readiness Level: 6-8; Technical risk: High

Nanobubble generator for use in net-pens: Netting which protects against sea lice may have the effect of reduced oxygen availability for the salmon as there is insufficient water flow. A nanobubble generator can generate small bubbles, which are stable enough to remain in the water for prolonged periods (Fantom 2019; Nanobubble Systems n.d.).

Technology Readiness Level: 9; Technical risk: Low

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[1] Sterner vacuum degasser: https://www.sterner.co.uk/aquaculture-products/degassing/

11.11 Water disinfection systems

UV and ozone are often used to treat and disinfect water in RAS. While water exposure to UV has an effect on microbes in the water, the effect stops as soon as the UV is switched off.

Ozone, however, is introduced directly into the water and can be toxic to aquatic organisms. The technology has been investigated for use in destroying invasive or nuisance species, whilst other research has highlighted negative effects of residual ozone in the water. Typically, ozone and ozone-produced oxidants used in aquaculture are removed from water prior to entry into tanks with stock animals. However, direct applications of ozone, the exposure to residual ozone and ozone-produced oxidants to cultured species of fish, have been investigated by various researchers and ozone can be employed as a beneficial technology due to proven enhancement of hygiene and water quality (Powell and Scolding 2018).

Innovations with a potential for transformative performance improvement

Eloxiras: Eloxiras[1] is a process developed by Spanish company APRIA systems for the treatment and reuse of marine and brackish water. It is developed to enhance the productivity and to reduce the environmental impact of RAS. The core of the process is electrochemical, but overall, the process is made up of the following three steps (Rodriguezet al. 2017):

- pre-treatment (filtration of the water)
- main treatment by means of electrochemical oxidation reactors for the removal of ammonia, nitrite, organic matter, and pathogens
- post-treatment for the elimination of oxidation by-products and the balance of gases.

Technology Readiness Level: 6-8; Technical risk: Moderate

Innovations with a potential for incremental performance improvement

Self-cleaning UV water treatment systems for hatchery: Aquafine, a corporation with solutions to various industries including aquaculture, food and beverage, oil and gas, has

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[1] Eloxiras: https://www.eloxiras.com/about-us/

modernised and re-installed the UV water treatment system in the largest RAS fish farm in Chile in 2015. UV disinfectant machinery included models with self-cleaning mechanisms, which reduce maintenance and help to ensure the proper UV dose is delivered at all times (Aquafine 2015).

Technology Readiness Level: 9; Technical risk: Low

11.12 Integrated water quality control systems

Integrated water quality control systems automatically sense water quality parameters and act in order to sustain a perfect environment for the fish. Such systems can be custom-made for farms by system integrators.

Innovations with a potential for transformative performance improvement

Automated water quality control process: A process for continuous and simultaneous water disinfection, oxidation of off-flavour agents, minimisation of trihalomethane (THM) production, reduction of nitrate and nitrite production and oxidation of ammonia in freshwater and saline based RAS was developed by researchers in Israel (Lahav *et al.* 2019) . Researchers from the same institution also patented a novel process to remove nitrogen species from fresh water or high salinity water in RAS systems (Lahav *et al.* 2017).

Technology Readiness Level: 6-8; Technical risk: High

11.13 Tank and cage design

While some improvements are made on tank design, innovations such as modular or adjustable tanks have been covered in the RAS section.

The main innovative activity for this section was found to be in the area of offshore aquaculture, where improvements are being made for cages and peripheral technology to operate in high-energy environments. The cages in these environments must withstand high loads and at the same time allow for easy handling of the cultured aquatic product. The physical parameters at the location, such as significant wave height, current velocities, depth and wind, play an important role. There are new innovative approaches for longlines for mussel culture, some of which focus on system design, buoyancy (controlled by smart devices) and orientation in relation to wave and current direction.

Site selection is a particularly important aspect for cage systems. The required data sets must be collected over long periods to determine the maximum loads as accurately as possible. In order to reduce the loads, new technologies must be developed to reduce biofouling, as diving is dangerous and expensive and current automatic cleaning systems can damage the culture device as well as the cultured organisms during rough weather.

With regards to site selection, there is an area of research exploring "multi-use aquaculture" or aquaculture on "multi-use sites", for example aquaculture on the sites of offshore wind-farms. While there have been successes on a technical, biological, social and economic level, remaining challenges include permissions for implementation or clear legislation, affordable robustness for fish aquaculture systems, as well as a system design allowing cages to be easily submerged and raised (Aquaculture Europe 2019b; Buck and Langan 2017; MSP 2017). Satellite-based data collection can also be supportive for site-selection.

Innovations with a potential for disruptive performance improvement

Offshore fish farms by SalMar: SalMar developed 'Ocean Farm 1'[1], described as "the world's first offshore fish farm". As a full-scale pilot facility, Ocean Farm 1 is designed to test out both the biological as well as the technological aspects of offshore fish farming, Ocean farm 1 having a diameter of 110 m. A new concept has been proposed by the same company ('Big Dipper') with a diameter of 160 m and a capacity to produce between 15,000 and 20,000 t of salmon a year (Evans 2019c).

Technology Readiness Level: 6-8; Technical risk: High

Fish farms on ships: Norwegian company Pure Atlantic AS is planning a fish-growing ship measuring 1,600 feet (521 m) in length. It will be powered by wind turbines mounted on the back of the vessel and water will flow through the ship into built-in channels in the fish cages. The vessel would be able to produce 50,000 tonnes of salmon a year. The Norwegian government recently rejected a licence for this ship to be built (Mayer 2018; Naley and Larsen 2017). Another concept is by German company Next Generation Cargo, who is planning to farm Atlantic salmon on huge sailboats (540 ft long). The sailboats would be able to produce

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[1] Ocean Farm 1: https://www.salmar.no/en/offshore-fish-farming-a-new-era/

5.5 million pounds of salmon per year. It has been reported that the first vessel is already being built at a Chinese shipyard. The company claims that “this configuration gives the flexibility of calling at ports with the highest market prices at any given time” (Ramsden 2018b; Welch 2019).

Technology Readiness Level: 6-8; Technical risk: High

Innovations with a potential for transformative performance improvement

Semi-closed fish cage preventing sea lice and ability to pump fish out from bottom of cage: Aquatraz, by the Canadian company Seafarming Systems[1], is a semi-closed fish cage, preventing sea lice and escapes and improving fish welfare. Two cages from the first generation Aquatraz have been tested in full production cycle with promising results. In late 2019, two more cages from the improved second generation Aquatraz will start their first production cycle. For harvest, the cages can be lifted out of the water and fish can be pumped from the bottom of the cage into a boat, preventing unnecessary stress. The company developed other similar fish cage products.

Technology Readiness Level: 6-8; Technical risk: Moderate

A fully enclosed egg-shaped tank as alternative to open pen systems: The system, developed by Hauge Aqua and trialled by Mowi (formerly Marine Harvest) is said to address the issues of sea lice, escapees and waste (by collecting nutrient-rich faeces). The latest news (2019) suggested Mowi may not go ahead with the project due to high cost (Lyngøy 2019; Evans 2019b; Blank 2017).

Technology Readiness Level: 6-8T; Technical risk: Low

Offshore semi-submersible salmon cages: Semi-submersible fish farming cages to work on offshore locations and able to withstand waves of up to 15 metres have been developed by oil rig specialist Aker Solutions. Norway Royal Salmon has recently won permission to use those pens at Fellesholmen off the coast of Tromsø (Lundberg 2019; Jakobsen *et al.* 2019).

Technology Readiness Level: 9; Technical risk: Low

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[1] Seafarming Systems: https://seafarmingsystems.com/en/aquatraz-semi-closed-fish-cage/

Innovations with a potential for incremental performance improvement

Submersible cages: Israeli company GiliOcean developed the 'Subflex system'[1], a system of cages which are attached to the seabed by a single anchor, which enables each cage to rotate around itself 360° degrees. This allows the system to follow the currents and waves rather than resisting them, which will increase the systems life span and durability in harsh weather conditions. The system can be submerged for bad weather conditions (Craze 2019).

Technology Readiness Level: 9; Technical risk: Low

Fish pens including sensors, cameras and mortality traps: US company InnovaSea[2] developed fish pens with traps for dead fish. Their 'SeaStation' cages are submerged tensioned nets, which keep their shape and remain stable in all conditions. Dead fish can be removed by shallow water dives due to the special traps. Sensors and cameras provide real-time monitoring of "environmental conditions and other fish health factors, such as current and waves, dissolved oxygen, salinity, temperature, depth, rope tension, biomass, and fish behaviour" as well as data analysis (Gace and Kelly 2019).

Technology Readiness Level: 9; Technical risk: Low

11.14 Monitoring and maintenance systems for fish and fish farms

A fast-growing technological innovation, incorporated in blue economy growth, is the development of real-time remote monitoring systems. Parameters to be monitored depend on the fish species - however, water temperature monitoring is almost always required. Moreover, dissolved oxygen concentration, water current, pH, salinity, turbidity or hardness are other water properties commonly required for suitable fish growth (Lobley 2019). These parameters can be measured manually with handheld instruments or with increasing levels of automation up to fully automated systems.

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[1] Subflex system: https://www.giliocean.com/selected-projects

[2] InnovaSea: https://www.innovasea.com/about-us/

Fish health and fish biomass can also be measured, again ranging from purely visual inspections by the operators to using underwater cameras (which can be mounted on remotely operated vehicles (ROVs)), to using the outputs of the cameras combined with computational methods including artificial intelligence technology, in order to get an understanding of the state of the fish with as little human operator time as possible.

All these measurements can be connected via the Internet of Things, to give real-time information and to participants across the value chain (Antonucci and Costa 2019).

Innovations with a potential for disruptive performance improvement

Satellite imagery to monitor shrimp farms: Dynaspace is a private Norwegian company, that uses satellite images, machine learning and artificial intelligence to provide timely and rich insights, that help shrimp farmers and shrimp production industry to gain advantage and maximise opportunities, e.g. by having accurate control of shrimp farming and being better prepared to negotiate prices. The technology delivers pond identification and mapping, an overview of active and inactive ponds, historical development of ponds and an overview of shrimp stock and production cycles (Dynaspace 2019).

Technology Readiness Level: 6-8; Technical risk: High

Innovations with a potential for transformative performance improvement

Smart biomass camera: The “Go Smart®” Biomass camera[1], together with software, calculates the accurate fish weight in addition to the distribution of cage population. Together with the integrated oxygen and temperature sensors, it provides the farmer with the optimal information necessary for the correct daily feeding calculation. In addition, it can connect directly to the feeding boat/centre of operations in real-time to have live observation during the feeding task. The system is designed to operate at all weather conditions without any human interference, running on solar energy and can be controlled remotely via a user-friendly web application. The underlying technology is patented (Saleh *et al.* 2019).

Technology Readiness Level: 9; Technical risk: Low

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[1] Go Smart Biomass camera: https://www.gosmartfarming.com/

Machine vision systems in aquaculture: Monitoring of fish state and behaviour during cultivation may help to improve profitability for producers and reduce the threat of severe loss because of disease and stress incidents. Optical sensors and machine vision system provide the possibility of developing faster, cheaper and non-invasive methods for in situ and after harvesting monitoring of quality in aquaculture. A recent review by Czech researchers describes the most recent technologies and the suitability of different optical sensors for the fish farming management and assessment, measurement and prediction of fish products quality. The authors conclude, however, that there is still a need for new algorithms, methods and re-engineered sensors to be developed to meet real-world requirements (Saberioon *et al.* 2017).

Technology Readiness Level: 3-5,6-8;9 (product dependent) Technical risk: Moderate

On-fish sensors: A device, developed by researchers in Spain, is attachable to fish of 600 mg and allows to monitor fish from 30 -35 g and up. The device is able to monitor physical activity by measurements of movement accelerations in *x*- and *y*-axes, while records of operculum beats (*z*-axis) serve as a measurement of respiratory frequency. Currently, the device is on proof-of-concept stage, showing that miniaturised devices are suitable for non-invasive and reliable metabolic phenotyping of farmed fish to improve their overall performance and welfare. Further work is underway for improving the attachment procedure and the full device packaging (Martos-Sitcha *et al.* 2019).

Technology Readiness Level: 3-5; Technical risk: Moderate

Real-time monitoring of offshore fish farms: OxyForcis[1], designed and manufactured by Smalle Technologies, is a remote monitoring system, currently operating in both marine and freshwater fish farms in Spain. The system measures dissolved oxygen and temperature. The system is self-powered using a small solar panel. Data can be recorded in the unit and sent to a remote server on the internet using wireless communications, at user-defined intervals (Lobley 2019)**.**

Technology Readiness Level: 9; Technical risk: Low

Remotely operated vehicle (ROV) for mort removal*:* ROVs have been used in aquaculture for several years. Recently a system, “Foover” was developed with a collection cage, which

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[1] OxyForcis: https://smalletec.com/oxyforcis-2/

can “hoover up” dead fish from the bottom of fish pens. The system can collect up to 750 kg of fish (approx. 150 large salmon). The process of collecting a full load of dead fish only takes 6 minutes (from a depth of 25 m). The “Foover” system can be installed on-board of typical workboats. It is controlled with a joystick from the wheelhouse of the boat (Underwater Contracting 2018).

Technology Readiness Level: 9; Technical risk: Low

Innovations with a potential for incremental performance improvement

Monitoring fish and removing dead fish: Israeli company GiliOcean developed the GO Smart® Mortality Counter[1], a system which can count and separate dead fish out of a cage (rather than using divers to do the same task). The device is conically shaped and located underneath each cage. The sinking dead fish are gathered and collected in a stainless-steel box, which isolates them from fish within the cage and other aquatic animals such as seals, dolphins and sharks. Data about the dead fish is transmitted in situ and the farmer is made aware of the mortality numbers at all times.

Technology Readiness Level: 9; Technical risk: Low

Detecting unusual fish behaviour using computational methods: Jian Zhao, from the Zhejiang University (China), proposed a new methodology to detect, localise and recognise unusual behaviours of farmed tilapias (Oreochromis niloticus). The methodology is based on Graph Networks and Recurrent Neural Networks (RNN) and may provide a successful alternative of computer vision-based tracking, for on-site monitoring of fish behaviour and assessment of fish welfare without tracking and foreground segmentation (Aquaculture Europe 2019b).

Technology Readiness Level: 3-5; Technical risk: Moderate

Automatic evaluation of fish weight of fish in pens using image recognition: Hiramasa farm in Miyazaki Prefecture, NEC tested an intelligent image evaluation technology that measures the length and width of individual fish and, based on these results, automatically calculates their weight. This enables the farmers to adjust feed quantities and feeding times

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[1] GO Smart Mortality Counter: https://www.gosmartfarming.com/

more precisely to the actual needs of the fishes. The technology has been extended to include tuna, and the developers believe that it will also be suitable for other fish species (Tyler n.d.).

Technology Readiness Level: 7-8; Technical risk: Moderate

Automated live fish grading and biomass evaluation: Icelandic company Vaki have developed a live fish grading system, by which the fish are pumped from one tank into another via a grading machine, which also estimates their weight. Trials show that the weight estimates have an error of less than 3% when compared to the real values (Vaki n.d.; López Riveros 2017; Hakonarson *et al.* 2017).

Technology Readiness Level: 9; Technical risk: Low

Interface between underwater ROVs and pens: Remotely operated underwater vehicles can undertake tasks, which were previously done by divers e.g. cage cleaning and inspections. AKVA[1] has developed an interface between their ROVs and all types of pens which enables facilitates automatic cleaning of the pens (Haugerud 2019).

Technology Readiness Level: 9; Technical risk: Low

11.15 Aquaculture innovation specifically relevant to shellfish

While much of the technical innovation of aquaculture production and handling systems (for example RAS systems) is not necessarily specific to either finfish or shellfish, some innovations are specifically geared to the shellfish industry.

Innovations with a potential for disruptive performance improvement

Selective breeding of mussels: New Zealand's Greenshell^{TM} mussels (known as mussels in the UK) rely on wild-caught spat for its marine farms. A recent program enabled selective breeding of high performing mussels at a commercial hatchery and seeks to improve spat retention rates on marine farms. Recently, trial results demonstrated that hatchery mussels

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[1] Akva ROV systems: https://www.akvagroup.com/pen-based-aquaculture/rov-

can grow up to twice as fast as those caught in the wild, which is expected to be worth about NZD 200 million a year to the wider New Zealand economy (SpatNZ n.d.; O'Connell 2019).

Technology Readiness Level: 6-8; Technical risk: Moderate

Larger scale mussel farms: Offshore Shellfish Ltd[1] in Brixham, South Devon, is developing the UK's first large-scale offshore farm for the blue mussel (*Mytilus edulis*), a species that is native to Lyme Bay, where the mussel farm is based. Once fully developed, three sites will cover nearly six square miles in total and produce up to 10,000 tonnes of mussels each year. Helical seabed screw anchors and bespoke designed ropes were imported from New Zealand, while John Holmyard designed two specialist harvesting vessels and a float design concept based on a vertical-axis system. The farm was reported to have a positive impact on the surrounding ecosystem (Waycott 2018)

Technology Readiness Level: 9; Technical risk: Moderate

Innovations with a potential for transformative performance improvement

Transportation system for live lobsters and other shellfish: A transportation system was recently developed by UK company Todd Fish Tech. The system, designed for lobsters, langoustine and crab, requires less space and water than alternative systems and the survival rates are 99 % compared to an industry average of 85% (McLaren 2019; Todd and Todd 2016).

Technology Readiness Level: 9; Technical risk: Low

11.16 Technologies for hatcheries

A fish hatchery is a place for artificial breeding, hatching, and rearing through the early life stages of the animals. Hatcheries produce larval and juvenile fish, shellfish, and crustaceans, primarily to support the aquaculture industry.

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[1] Offshore Shellfish: https://offshoreshellfish.com/

R&D in this sector is mainly on feeding regiments during larvae feeding (please refer to chapter 8 on Nutrition and feeding) and less on novel technologies (Aquaculture Europe 2019).

Some research effort has been made specifically to breed eels in captivity. EEL-HATCH[1], a project lead by the Technical University of Denmark, was a project with the overall vision “to establish breeding and hatchery technology for future commercial production of glass eels, leading to sustainable and profitable eel aquaculture”. It was envisaged that captive breeding and hatchery technology will generate a new commercial activity that ultimately can re-establish the highly profitable eel market for the Danish and European aquaculture industry. The project period was from 2014 to 2017. A European project with similar aims is PRO-EEL[2].

Innovations with a potential for transformative performance improvement

Providing optimal salinity: Salinity might have a key influence on fish physiology and production efficiency, since working at an optimal salinity, organisms will save energy for osmoregulation. Research showed that optimal salinity will increase growth and survival of grey mullet juveniles and European eel survival during early larval stages, respectively (Aquaculture Europe 2019b).

Technology Readiness Level: 2-5; Technical risk: Low

Rearing rock lobsters through their larval phase in a commercial hatchery setting: The Institute for Marine and Antarctic Studies (IMAS) based in Australia has recently for the first time developed a scalable method to rear rock lobsters through their larval phase in a commercial hatchery setting. This provides immense opportunities to establish a sustainable lobster aquaculture industry. The technology is particularly advanced with the tropical rock lobster species, Panulirus ornatus, which is a faster growing species than the eastern and southern rock lobster, which are also grown and studied at the IMAS facility (University of Tasmania 2017).

Technology Readiness Level: 6-8; Technical risk: Moderate

Automated sorting of fingerlings: A project in Japan between Kindai University’s Aquaculture Research Institute and partner company, Toyota Tsusho as well as Microsoft Japan, aims to develop a control system to automate the sorting of fingerlings. The system

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[1] EEL-HATCH project: https://www.eel-hatch.dk/

[2] PRO-EEL project: http://www.pro-eel.eu/

automatically regulates the flow of water through pumps that transfer fingerlings from their pens to conveyor belts for sorting. Continuous monitoring and flow adjustments are done using Internet of Things and artificial intelligence tools.

Already the system has eased the workload of staff at the university's Aquaculture Research Institute, who used to hand-sort as many as 250,000 seabream fingerlings a day. "The next step is [understanding] how AI stores the fish selection criteria," Ryota Sakishita of the Aquaculture Technology and Production Center at Kindai University told Hatchery International. He said the completion date for this phase has not been determined (Gonzalez 2019; BBC World 2019).

Technology Readiness Level: 6-8; Technical risk: Moderate

11.17 Handling systems of fish

On land-based farms, fish handling is often required for various reasons e.g. for grading, to reduce stocking densities, to transport fish across growing departments (i.e. from a nursery to an on-growing department) or to harvest fish, when they are market ready. Handling methods include:

- active methods such as fish pumps e.g. Euskan[1]; Bedford Pumps[2].
- passive methods such as the use of visual or chemical signals that allow the fish to move themselves from one place on the farm to the next.

Commercial systems in place include tanks sharing a common wall in order to passively transfer fish through the farm and harvesting using a 'pescalator' (Archimedes screw pump) at the end of a swimway (Espinal and Matulić 2019). The RAS2020 concept from Krüger (Denmark) uses bar graders / crowders permanently installed in a donut-shaped or circular raceway tank to move and crowd the fish without the need for fish pumps or other handling (Espinal and Matulić 2019). For further examples, please refer to chapter 6 Farmed animal health and welfare.

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[1] Euskan: http://euskan.com/

[2] Bedford Pumps: http://bedfordpumps.co.uk/fish-friendly

Please refer to chapter 6 Farmed animal health and welfare.

11.18 Other technology for aquaculture

In this section other technology for aquaculture is presented.

Innovations with a potential for incremental performance improvement

A kit box to diagnose acute fish death: Researchers at the Norwegian Institute for Water Research (NIVA Aquaculture) developed a kit box, which can be used in cases of acute fish death to help analysis and diagnosis. It is intended to be kept on site for readiness to take samples in case of a mortality incident. Reasons for acute fish death can include:

- Use of salt instead of seawater – the salt may contain an anti-caking agent in the form of a cyanide, which when illuminated with UV will form toxic hydrogen cyanide.
- Aluminium: when water contains a lot of humus, the humus "draws metal", which will bind to humus particles. When salt is added to the water, aluminium may be released which goes into fish gills and can create problems (Thomsen 2018).

Technology Readiness Level: 6-8; Technical risk: Moderate

Energy supply for remote fish farms: A small-scale wave electricity generator ("eForcis") was developed by Small Technologies. The generator can provide electricity to buoys and marine monitoring devices in a clean and renewable way. It has been tested in several Mediterranean locations, such as Barcelona and Castellon, in a buoy of the Spanish national port authority located in Mahon, and in the Atlantic coast of Ireland (Lobley 2019; Escribano *et al.* 2019).

Technology Readiness Level: 6-8; Technical risk: Moderate

11.19 Production concepts with implications for aquaculture

This section describes concepts for farm and sector management, which were developed mainly independently of the sector and / or for general agriculture but with potential impacts on the fishing industry.

Integrated production (IP): IP is a relatively new production regime that supports environmental, labour, and management issues through the production process. Researchers in Brazil, where the shrimp industry has recently been impacted by environmental and sanitary issues, describe how IP principles could provide tools to improve the productivity in a systemic method. They compared a hypothetical IP shrimp farm with the conventional cultivated marine shrimp production (CP) and identified possible challenges that IP would face if adopted as an alternative production regime for the Brazilian shrimp farming scenario.

IP introduces transformative superior forces compared to CP e.g. (i) the adoption of a systemic view of the productive chain, (ii) the traceability of products and processes, (iii) the reduction of barriers to environmental licensing of aquaculture farms, (iv) the reduction of risks and damages caused by diseases, and (v) the optimisation in the use of natural resources, inputs, and energy), the major challenges for IP in Brazil were identified as: (i) the absence of specific technical standards (STS) for the certification of shrimp farms, (ii) the possibility of increasing investment costs for implementation and operation of certified farms, and (iii) non-differentiation in the internal market of certified and non-certified products (Cozer *et al.* 2019).

Technology Readiness Level: 1-2; Technical risk: N/A

Precision aquaculture: Precision agriculture / aquaculture is a management concept based on observing, measuring, and responding to spatial and temporal variability of production processes. The scope of precision aquaculture is to apply control-engineering principles to the production, to direct farmers to a better monitoring, control, and documentation of biological processes in fish farms. Technologies used in this context include computer vision for animal monitoring, environmental monitoring tools, and sensor network (i.e. wireless sensor network, and long-range), robotics, and finally data interpretation and decision tools (i.e. algorithms, Internet of Things, and Decision Support Systems). Authors of a recent review conclude that: “To increase the production and ameliorate the fish product quality and animal welfare issues, it is becoming even more important to monitor and control the production process” (Antonucci and Costa 2019).

Technology Readiness Level: 1-2; Technical risk: N/A

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12 Species diversification

Contents

From the SIF Executive Board

The method applied in this review has generated numerous examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently happening. It is recognised that there are existing innovations and research areas that are not included here, and new areas where future innovations may occur. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

12.1 Overview: species diversification

What is the challenge in the UK?

Currently, a limited range of species are farmed in the UK, due to limited consumer tastes, high production costs and regulatory restrictions. Historically, aquaculture development of both native and exotic species in a variety of systems have been erratic and often resulted in failure. Success, however, may still be possible on a small-scale serving niche markets.

What are the most promising innovation categories?

- Extractive species (shellfish and algae) and cleaner fish to complement salmonid farming
- Captive breeding for domestic use or export
- Culture systems (IMTA, RAS, co-location, etc.) to maximise use of space

Where are their important knowledge gaps?

- Successful and viable closed-lifecycle breeding
- Suitability of species in UK waters

Species diversification in aquaculture entails the adoption or wider use of new species, in research and development (R&D) and/or production. Currently, diversification is primarily pursued in search of new social and economic opportunities, but increasingly is considered a hedge against economic, social, and environmental volatility, including climate change (Harvey *et al.* 2017).

The diversification of species is thought to comprise two components: 1) *richness*, i.e. the number of species and 2) *evenness* across species, each with their own unique adaptation opportunities. In terrestrial agriculture, diversification of farmed products is usually at the level of breed, variety or cultivar, with a few species accounting for the majority of production. Those species have been domesticated over millennia and are now represented by thousands of distinct livestock breeds and plant varieties.

On the other hand, although aquaculture is significantly more diversified than agriculture and livestock farming in terms of species number and farming systems, the contribution of each species in aquaculture to overall production (species evenness) is highly skewed with 30 species representing 90% of global aquaculture production - far fewer than the close to two thousand species that contribute to capture fisheries.

Diversification can be achieved by a variety of means, including the introduction of new species or strains; increasing the number of farmable species; and farming species in novel locations. The primary focus of this chapter will be on these innovations, rather than on farming systems or post-production processes, which is covered in separate chapters.

Historically in the UK, aquaculture development of both native and exotic species in a variety of systems have been erratic and have often resulted in failure. Between the late 1980s up to 2010, examples included: haddock, signal crayfish, whiteleg shrimp, Atlantic cod, chub, rudd, Mozambique tilapia, queen scallop, North African catfish, brook trout, barramundi, Mediterranean mussel, tench, grooved carpet shell, freshwater bream, crucian carp, roach, cupped oyster. More recently, sea bass can be added to the list (Hughes 2017).

Of these, a classic example is Atlantic cod. Despite initial, rapid expansion with robust sales, the onset of the global financial crisis of 2007-2008 resulted in the loss of financing, leading to the collapse of the entire sector. This illustrates how financial pressures alone can be just as damaging as consumer or technical barriers.

Success, however, is still possible, even on a small-scale serving niche markets. An example is Gigha Halibut, the last remaining halibut farm in the UK, producing premium, restaurant-quality products (personal communication). Yet, the question remains whether such species are amenable to large-scale production - in addition to the UK, large-scale halibut production has failed to take off in Norway, Iceland and Canada, despite an ideal annual coastal temperature regime for production. Slow growth and high production costs are said to inhibit its scalability. Ultimately, there must be sufficient market ‘pull’ as at present, the UK faces numerous challenges in finding financially viable customers for some wild-caught species alone, of which more may be landed post-Brexit (personal communication).

With regards to barriers to entry the following section lists the ones that have been identified as key barriers in the UK. The first hurdle in working with new species is completing the lifecycle and spawning in captivity (personal communication). As will be discussed in the following sections, for some species with complex lifecycles, this has continued to elude researchers for decades.

Additional challenges that constrain diversification pertain to the market. Native or introduced, farmed seafood generally has less appeal than their wild-caught counterparts. British consumers are also said to have narrow tastes, despite increasing concern for sustainability and animal welfare. Furthermore, in the wake of economic uncertainty and competitive wild-caught prices, British consumers will ultimately opt for the cheaper option (personal communication).

The high cost of new species development and time to bring a species to market are also deterrents. Further resources may be needed on culture design, marketing, regulatory modifications and post processing modifications. Regulations that restrict species introductions and exports, genetic technologies and areas available for farming too, may limit diversification.

In terms of the future approach in the UK, according to Bjørn Myrseth of Vitamar A.S. (Harvey *et al.* 2017), there are two general schools of thought with regards to how research and development should proceed:

1. Invest in existing aquaculture species by diversifying strains, areas and growing systems; be cautious with new species and introduction of already-farmed species into new areas.
2. Work on new species and/or strains to accommodate or even stimulate shifts in consumer preferences.

At present however, private industry was not seen to support diversification of species. Indeed, the focus of aquaculturists in North America and Europe tends to be on efficiency, system improvement, adding value and building corporate responsibility that relates less to “what” is farmed and more to “how” it is farmed. The former is largely driven by research and development groups, academia and governments. Governments may thus have important roles to play in supporting research, developing public/private partnerships, creating an enabling environment that considers communities and native resources, and promoting promising species, should sufficient market potential be demonstrated.

A recent success story is the “fast-track domestication” of the Ballan wrasse, spearheaded by the University of Stirling, which successfully closed the lifecycle of the cleaner fish in 2018. Unusually, this is a long-term collaboration between academia, industry and government, backed by £50 million of funding from various sources. A major driver was undoubtedly the potential benefit to the Scottish salmon industry, who are major stakeholders in the programme (Personal communication).

Ultimately it must be recognised that in the UK, Atlantic salmon farming is and will continue to be the dominant aquaculture industry (R. Fletcher 2017). There is, however, an appetite for alternative farmed products, albeit on a smaller scale, and thus, the domain of micro- and small-scale enterprises, as seen with halibut. Farming a new species, however, carries significant risk, especially for smaller businesses. Past success and failures show that collaborative development alongside long-term strategic support is crucial. For larger-scale production as a sector, sights must be set on the global export market for economies of scale and greater security, as demand within the UK is insufficient (personal communication).

With regards to promising species, there is suggestion that for table finfish, focus should be on “species that consumers want but cannot easily get” (R. Fletcher 2017). Although marine species are an easier sell within the context of the UK consumer, conflicts over production space present new opportunities in freshwater aquaculture, such as sturgeon. Considerable expansion potential was also recognised in molluscan and algal species, which do not conflict with the salmonid industry. The latter opinion was also mirrored by British industry stakeholders in integrated multi-trophic aquaculture (IMTA), who saw market potential in oyster, scallops and sea urchins for their high value, as well as seaweed for low production costs and ease (Kleitou, Kletou, and David 2018). It was mentioned that there might be opportunities in seeding and ranching but with limited consumer demand and space within the UK (personal communication).

The key to species diversification in the UK may be to *“not try to find the next ‘salmon’, but something that will not conflict with, and even complement the salmon industry,*” such as cleaner fish (personal communication). A variety of niche products are presented, and focusing on a small number of “new” species for diversification is considered more viable than spreading research funds over many candidate species, new farming or processing systems and marketing strategies (Harvey *et al.* 2017).

Once a new species is pursued, the first step is to close the lifecycle, which requires the necessary facilities and capital expenditure before farming can even begin. Substantial cost savings can be made by recycling the aquaculture facilities of defunct businesses, as seen with lumpfish and wrasse farms on Anglesey (Hughes 2017; Fish Farmer 2019a).

Doing so, however will require cross-sectoral partnerships for greater efficiency as well as research funding to underpin technical advances and maintain skills at the leading edge.

An overview of the potential performance improvement rating of recent (2015-2020) innovations in species diversification in aquaculture are outlined in Figure 11-1.

Performance*	Low	Moderate	High
Disruptive		• Sturgeon (ethical caviar) • Tropical prawn (RAS) • Spiny lobster • Amphipod IMTA • Co-location	• Eel breeding • Octopus breeding
Transformative	• Wakame brown kelp	• Fry, smolt, ova, spat hatchery (general) • Hake & lumpfish breeding • Ballan wrasse • Finfish/shellfish/seaweed IMTA	
Incremental	• Sea urchin • Sea trout • Seabream • Sea bass	• Seaweed • Clam	

Technical Risk*

Figure 12-1: Performance and technical risk rating of innovations in species diversification in aquaculture.

**See section 4.4 for definitions of performance and technical risk rating scales.*

12.2 Introduced species

Identification and development of new species for aquaculture is an ongoing process, driven by perceived market opportunities or other needs and opportunities. However, a significant amount of time, in the order of 10–15 years, may be required to introduce some new species or strains to aquaculture and develop the necessary technologies, which is prohibitively time-consuming and/or costly for most private industry (Harvey *et al.* 2017; R. Fletcher 2017). Governments that are driving diversification might choose to subsidize these efforts, as seen with tuna and cod, but as these examples illustrate, with no guarantee for success.

A search of the literature relevant to species diversification of aquaculture in Europe shows the focus is very much on southern Europe, primarily in the Mediterranean Sea, with species such as meagre (*Argyrosomus regius*), greater amberjack (*Seriola dumerili*), Senegalese sole (*Solea senegalensis*) and wreckfish (*Polyprion americanus*). In general, there appears to be few other novel species under serious consideration for aquaculture development in the region, likely due to the aforementioned barriers to entry.

According to the FAO (2017), new candidate species should:

- have reliable seed supply and survival to harvest;
- be euryhaline and/or eurythermal;
- tolerate low oxygen and pollution;
- come from lower trophic levels;
- have cost-effective feed conversion;
- have short production cycles;
- comply with biosafety requirements; and
- be culturally acceptable and reflect evolving consumer preferences.

With feed representing approximately 50% of total production costs, production will favour species that require lower priced feed with low inclusion rates of marine ingredients, or those that command a high market price (Aquaculture Europe 2019a).

There are plenty of learnings from history of the negative impact of introduced (also known as alien, non-native) species on local ecosystems. In response, countries, including the European Union, have strict legislation in place to limit introduction of a non-native species in aquaculture, with some exception to closed recirculation systems (European Commission

2016). Other challenges include poor performance and production in transplanted sites, or low social acceptance (Harvey *et al.* 2017).

Despite this, as seen with salmon and trout, success with introduced species appears to lie largely in farming already popular species with a truly restricted supply, which make it easier for consumers to accept farmed versions.

Innovations with a potential for disruptive performance improvement

Sturgeon caviar: Sturgeons are a valuable aquacultural commodity as sources of boneless meat and highly prized caviar, but despite a worldwide ban on wild caviar in 2006, 85% of all sturgeon are at risk of extinction. There are a number of caviar farms throughout the UK, but KC Caviar is notable as the self-professed only farm producing sustainable, cruelty-free caviar, “from hatchery to retirement” (Perraudin 2017). KC Caviar has obtained a license for a non-invasive method of egg extraction developed which involves injecting the fish with a signalling protein to induce ovulation and later extracting the eggs via massage. Older sturgeon are then retired in lakes throughout Europe.

Technology Readiness Level: 9 limited adoption; Technical risk: Moderate

Tropical prawn: 2019 saw the establishment of Great British Prawns, a land-based, RAS clear-water (versus bio-floc) facility farming the Pacific whiteleg shrimp (*Litopenaeus vannamei*, also known as king prawn) that will be able to deliver fresh prawns to the British plate within hours of harvest (The Fish Site 2019c; *BBC News* 2019). The Stirlingshire, Scotland-based facility houses in excess of 300 tonnes of water capable of rearing up to one million prawns. It sits adjacent to a dairy farm with an anaerobic digestion plant, which significantly reduces energy bills. In addition to sustainability, considerable attention is also given to animal welfare. However, in 2019 prawn imports were plagued by an outbreak of hypodermal and hematopoietic necrosis virus (IHHNV), resulting in approximately 50% mortality during transport and further culls on site. The focus will be on building up breeding stock and completing the first harvest in the near future (The National 2019).

Technology Readiness Level: 6-8 limited adoption; Technical risk: Moderate

Innovations with a potential for transformative performance improvement

Fry and smolt (various spp.): Despite negligible tilapia aquaculture activity in the UK, Three-Sixty Aquaculture, a Welsh hatchery specialising in genetically male tilapia (developed by

Swansea University) is able to export fry to the Americas and throughout Europe (The Fish Site 2017). There may also be additional opportunities with salmonid ova and smolt in the UK (Seafish 2016). These represent examples of how species diversification can be achieved within the *earlier* stages of aquaculture production and R&D, and as the tilapia example illustrates, can benefit upstream genetics and biotechnology sectors and strengthen the UK as a leader in these areas. However, while juvenile supply for export is possible, it is considered risky. The sector is dominated by a handful of large multinational companies such as AquaGen, and much of the technology is in the public domain and thus implemented worldwide. For biosecurity and logistical reasons, it was recommended to be as close to the marketplace as possible (personal communication).

Technology Readiness Level: 6-8; Technical risk: Moderate (species dependent)

Wakame brown kelp: *Undaria pinnatifida* is a kelp species native to Asia that was first introduced into Europe but has since spread to the British Isles and more recently, to Ireland (GB Non-native Species Secretariat 2019). Although, both fouling and competitive with native species, wakame is of considerable economic importance as human food. In a recent Irish study, it was determined that from a physical, social and economic point of view, wakame can be cultivated in Ireland (Kraan 2017).

Technology Readiness Level: 6-8; Technical risk: Low

Innovations with a potential for incremental performance improvement

Rainbow steelhead (large) trout: Rainbow trout is farmed extensively throughout the UK, but predominantly in freshwater systems (British Trout Association 2016). Only a small proportion of their anadromous counterparts, steelhead (or large) trout, are raised in sea pens, exclusively in Scotland. There is also expanding production in Denmark and Norway. In 2015 the British Trout Association was involved in a scientific study to explore how marine aquaculture could be developed in England (Fish Farming Expert 2015). While there may be opportunities in Northern Ireland, it was suggested England and Wales lack suitable sites for competitive production, and would be better suited to concentrate on supply of parr and/or fingerlings (Seafish 2016).

Technology Readiness Level: 9; Technical risk: Low

Experience from previous failed attempts at the aquaculture of introduced species within the UK and Europe has likely inhibited innovation in this area. The sturgeon and king prawn examples above illustrate that innovation lies in *how* high-value seafood can be reared, with animal welfare and sustainability at the forefront. Meanwhile, aquaculture of juveniles, live feed and cleaner fish for established aquaculture species is gaining momentum and decreasing reliance on foreign or wild-caught broodstock. Algal R&D is still in its infancy and approaching commercialisation.

12.3 Native species

While native species may require investment in new technologies, their use could lessen the need for introductions and transfers of alien species (Harvey *et al.* 2017). Diversification can also be achieved through culturing species that have been fished unsustainably, particularly if the wild-caught species products are in short supply, seasonally limited or expensive.

However, culturing a local species is not without environmental risk: escapes can have serious ecosystem implications with regards to disease transmission and genetic interaction (Personal communication). Furthermore, as illustrated with the collapse of Norwegian Northern cod farming, farming of native species must be cost-effective and able to compete with wild stocks.

Similar to introduced species, the focus of aquaculture diversification is on native species that are either extractive (non-fed) or are herbivorous/omnivorous to lower dependence on costly fishmeal-based feeds. There is some concern, however, that most commercially-viable molluscan species have already been explored (personal communication).

Innovations with a potential for disruptive performance improvement

European spiny lobster: The high-value spiny lobster (*Palinurus elephas*), or crawfish was overfished in the 1980s in Wales to the point of 90% population loss. In 2012, RAS Aquaculture Research Ltd (RASAR) and Anglesey Sea Zoo collaborated to establish a spiny lobster breeding programme, later with support from the European Fisheries Fund Programme, to tackle the challenge of captive breeding (Williams 2019). Success was achieved in 2019, a first for the species in Europe. Farming the spiny lobster in land-based farms may offer fishermen an additional income source while also helping to finance restoration projects. Further work is required on the risk assessment to wild stock. The slow growth of crustacea may also be an issue (personal communication).

Technology Readiness Level: 6-8; Technical risk: Moderate

European eel: Eel farming has been conducted worldwide for decades, with innovations such as recirculation systems providing conditions for optimum growth. However, the industry continues to rely of wild stock juveniles (glass eels), as their complex anadromous lifecycle has kept artificial stock breeding out of reach. Over-fishing coupled with threats of climate change and shifts in ocean currents will compound pressures on the European eel (*Anguilla Anguilla*) and other species (The Fish Site 2015a). In response, the Eel Reproduction Innovation Centre[1], a global consortium comprising academia and industry was formed in 2016 to work together to overcome issues in captive breeding, including broodstock conditioning and larval feeds (Lokman and Palstra 2017).

Technology Readiness Level: 3-5; Technical risk: High

Octopus: With global fisheries of octopus under threat of collapse, attention has turned to farming. With innovations in rearing and feed technology, teams in Spain (Spanish Institute of Oceanography), Japan (National Research Institute of Fisheries and Environment of Inland Sea) and Mexico (National Autonomous University of Mexico), amongst others are currently racing to establish the world's first commercial octopus farm, with projections for success in 2020 (TIME 2019; NHK 2019). In the UK, the endemic common octopus (*Octopus vulgaris*) could be a potential candidate, though the fragile paralarval stage is a bottleneck. Ethical concerns (sustainability of fish and shellfish-based diets and animal welfare) and limited UK consumer demand will require consideration (McKie 2019).

Technology Readiness Level: 3-5; Technical risk: High

Innovation with a potential for transformative performance improvement

European hake: As one of the most commercially valuable fisheries in the Atlantic Northeast, attempts for the domestication of the European hake (*Merluccius merluccius*) since the early 2000s have been hampered by bottlenecks in early feeding and larval management (Nande *et al.* 2017). A 2015 article suggests that advancements in feed technologies could make hake farming feasible within five years (Undercurrent News 2015), supported by research by the Spanish Institute of Oceanography in Vigo. However, there were suggestions to allow industry

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[1] Eel Reproduction Innovation Centre: https://www.eelric.eu/en/eelric.htm

to first take hake aquaculture forward, due to barriers such as low market value and the unsuitable rearing temperature of UK waters (personal communication).

Technology Readiness Level: 3-5; Technical risk: Moderate

Ballan wrasse: Thanks to a “fast-track domestication” programme, spearheaded by the University of Stirling, the lifecycle of the cleaner fish Ballan wrasse was successfully closed after six years of concerted efforts. Cleaner fish are an example of species that can complement the salmon industry. Recycling disused aquaculture facilities can significantly reduce capital expenditure costs (Hughes 2017). However, the welfare of this and other cleaner fish species may become a priority in the future (OneKind 2018).

Technology Readiness Level: 6-8; Technical risk: Moderate

Lumpfish: Demand for lumpfish (*Cyclopterus lumpus*) has grown exponentially over the last decade, both for their roe and increasingly as cleaner fish for the salmon industry. Eggs are mostly obtained via wild-caught broodstock and as some populations are very small and have low genetic diversity, they are particularly vulnerable to over-exploitation and genetic introgression. Protective measures advocated include closing the breeding cycle of native species in captivity, use of sterile males for salmon farming, restricting the translocation of genetically distinct populations, and limiting the risk of farm escape (The Fish Site 2018d; Whittaker, Consuegra, and Garcia de Leaniz 2018b). In 2019, Mowi Scotland purchased the UK’s largest lumpfish farm on Anglesey (Fish Farmer 2019a). However, the welfare of this and other cleaner fish species may become a priority in the future (OneKind 2018).

Technology Readiness Level: 3-5; Technical risk: Moderate

Ova, spat and smolt (various spp.): Further opportunities for species diversification in the earlier stages of aquaculture production and R&D are in mussel spat and salmonid ova and smolt hatcheries in the UK (University of the Highlands and Islands n.d.; Seafish 2016). However, while juvenile supply for export is possible, it is considered risky. The sector is dominated by a handful of large multinational companies such as AquaGen, and much of the technology is in the public domain and thus implemented worldwide. For biosecurity and logistical reasons, it was recommended to be as close to the marketplace as possible (Personal communication). Mussel spat hatcheries were viewed as a welcome addition, but there were concerns over their economic viability (personal communication).

Technology Readiness Level: 6-8; Technical risk: Moderate (species dependent)

Innovations with a potential for incremental performance improvement

Sea urchins: Despite having native edible species, there has not been a major sea urchin fishery in Scotland in recent times. In preparation, both Scottish Association for Marine Science (SAMS) and Ardtoe Marine Laboratory (AML) have sea urchin aquaculture research programmes in place, covering the species *Psammechinus miliaris*, *Echinus esculentus*, and *Paracentrotus lividus* (Kelly *et al.* 2015). In another study, the microalgae genus *Rhodomonas* presented nutritional advantages to *Paracentrotus lividus* larvae. As *Rhodomonas* spp. is already used in oyster culture, this may enable oyster farmers to diversify into echinoculture (Castilla-Gavilán *et al.* 2018).

Technology Readiness Level: 9; Technical risk: Low

Clams: In a recent Portuguese study, hatchery production of the striped venus clam (*Chamelea gallina* (Linnaeus, 1758)) and surf clam (*Spisula solida* (Linnaeus, 1758)) were demonstrated, although the former exhibited greater larval success (Joaquim *et al.* 2016). Economic viability compared to more mainstream rope-grown mussels has been questioned, however (personal communication).

Technology Readiness Level: 3-5; Technical risk: Moderate

Seaweed: Seaweed culture is currently at the early and pilot stages in the UK with very small volumes of several species produced for experimental use and for speciality food ingredients (Black and Hughes 2017). Established in 2019, the first seaweed farm in the UK is Biome (Algae) Ltd, which at present cultures the native species sugar kelp (*Saccharina latissima*) and oarweed (*Laminaria digitate*) for mainly non-table applications (South Hams Gazette 2019). The Scottish Association for Marine Science (SAMS) is also currently running two experimental farms focusing on the cultivation of *Alaria esculenta, Saccharina latissima, Laminaria hyperborea, Palmaria palmata* and *Ulva* (SAMS n.d.). Additional Scottish research projects include the Algal Microbiome – Friends and Foes (ALFF) (SAMS 2018), as well as GlobalSeaweed (SAMS 2017). While there have been some comments on the UK's "extensive and under-utilised coastline" making it an "ideal environment for seaweed production" (Capuzzo 2016), others question the actual availability of space, citing conflicting interests in, for instance, Sussex, Devon and Norfolk. Furthermore, the destruction of kelp beds in the English Channel by recent storms suggest that some hydrological and weather conditions are not suited to commercial-scale operations (personal communication). An expert in British aquaculture has also warned of *"very tight margins"* (personal communication).

Technology Readiness Level: 6-8; Technical risk: Moderate

Sea trout: The majority of brown trout are farmed to restock rivers, lakes and lochs.There is expanding production of its anadromous counterpart, sea trout (NB: also used interchangeably with anadromous rainbow, or steelhead trout) in Scotland, Denmark and Norway. While there may be opportunities in Northern Ireland, it was suggested England and Wales lack suitable sites for competitive production and would be better suited to concentrate on supply of parr and/or fingerlings (Seafish 2016).

Technology Readiness Level: 9; Technical risk: Low

Gilthead seabream: At time of print, no activity in seabream aquaculture was confirmed in the UK. Mainly the preserve of southern Mediterranean producers such as Greece, Turkey, Spain and Italy, there are approximately 20 seabream grow-out farms in France, some of which are in close proximity to the UK along the English Channel (IFREMER 2011). The survival of France's seabream industry is attributed to its "quality-driven'' policy, production of large size fish and juvenile exports. However, the FAO reports little improvement in the market for farmed seabream so far in 2019, with oversupply (predominantly from Greece and Turkey) and low prices prevailing (FAO 2019b). One interviewed expert felt that the UK, at the northern extremes of the seabream's (similarly with sea bass) natural habitat, could not compete with the numerous, well-established enterprises in warmer Mediterranean waters achieving better growth. Furthermore, consumers prefer smaller table fish, well below the size point in which to turn a profit (Personal communication).

Technology Readiness Level: 9; Technical risk: Low

Sea bass: The UK's only known sea bass farm, a £12 million pound facility on Anglesey folded in 2015, unable to compete with the oversupply of low-cost sea bass from Turkey and Greece. It has since been taken over by salmon producer Mowi Scotland to farm the cleaner fish, Ballan wrasse (Hughes 2017). The FAO has confirmed this current trend for oversupply and low prices, and while recovery is in sight, the species, as with gilthead seabream is at risk of boom and bust cycles (FAO 2019b). (Please also see interview comments in seabream above).

Technology Readiness Level: 9; Technical risk: Low

The challenge of closed-lifecycle breeding of numerous species has eluded academia and industry for decades, but R&D progress thanks to concerted international efforts suggest commercialisation is within reach, as seen with octopus, European hake and European eel. Seaweed culture is currently at the early and pilot stages in the UK with very small volumes of several species produced for experimental use and for speciality food ingredients.

12.4 Novel strains and genetic improvement

Please refer to chapter 7 ‘Genetic improvement’.

12.5 Increasing farmable species and farming in novel locations

Although the addition of species is a key tenet of diversification, diversity can also be achieved by increasing species evenness within a location, or farming in novel locations, as illustrated in earlier sections with the farming of anadromous trout in marine systems. New and emerging culture systems allow the possibility to farm more species, sometimes in novel locations. The following examples explore emerging opportunities.

12.5.1 Polyculture and IMTA

Integrated Multi-Trophic Aquaculture (IMTA) refers to the associated culture of several species from different trophic levels. IMTA allows uneaten feed and by-product particulate wastes and dissolved nutrients to be re-captured by extractive co-cultivars and converted into energy, feed or fertiliser (Kleitou, Kletou, and David 2018).

This section specifically explores the role of IMTA in relation to species diversification. For more technical information, please refer to section 11.4.

In the UK, exogenously fed seafood species cultivated using IMTA include: European bass (*Dicentrarchus labrax*), Atlantic cod (*Gadus morhua*), Atlantic halibut (*Hippoglossus hippoglossus*), Ballan wrasse (*Labrus bergylta*), Atlantic salmon (*Salmo salar*) and Turbot (*Scophthalmus maximus*). Extractive species include algae (brown, green and red); suspension feeders such as mussels (*Mytilus edulis*), oyster (*Cassostrea gigas*) and scallop (*Aequipecten opercularis*); and deposit feeders such as shrimp (*Psamechinus miliaris*).

In a recent survey of stakeholders with IMTA involvement, “Diversification” (note: general diversification) was ranked amongst the least important reasons for IMTA application (Kleitou, Kletou, and David 2018).

Despite the implementation of IMTA on an industrial scale for decades in Asia (particularly in China, Japan and South Korea), adoption in Europe has been slower, with questionable levels of profitability (Kleitou, Kletou, and David 2018). This is attributed to barriers to entry stemming from a lack of both working technical knowledge, species diversity and cost-effective infrastructures and design, as well as legislative bottlenecks. Furthermore, the development of commercially viable IMTA projects in Europe has been hampered by a lack of support from governments, industry and funding agencies (The Fish Site 2018c).

Bottlenecks and obstacles faced by British IMTA stakeholders include:

- Biological - Lack of general knowledge regarding IMTA species; Biofouling; Pests and disease.
- Environmental - Low light/temperatures.
- Market - Profitability uncertainty; Undeveloped market.
- Operational - Multi-operation complexity; Logistical constraints.
- R&D - Time to progress.

There were also concerns relating to limited industry interest, and thus it was recommended that needs for further applied research should be brought forward by this sector (personal communication).

IMTA seafood species with the highest potential for the UK were identified as:

- Seaweeds – low production costs, increasing demand, easy and fast grow, various species/products, multiple uses.
- Oyster (*Crassostrea gigas*) – Existing producers, high commercial value.
- Scallop (*Aequipecten opercularis*) – Plentiful wild supply, great market potential.
- Sea urchins – Plentiful wild supply.

Innovations with a potential for disruptive performance improvement

Amphipods: Pilot experiments have shown that amphipods (*Jassa* and *Caprella* spp.), commonly found during farm fouling, could be introduced within offshore IMTA facilities as suitable, live and natural aquaculture feed and even food supplement for human consumption (Fernandez-Gonzalez *et al.* 2018).

Technology Readiness Level: 6-8; Technical risk: Moderate

Innovation with a potential for transformative performance improvement

Finfish/shellfish/seaweed: IMTA was explored for the first time in Scottish salmon farming by the Scottish Salmon Company and Loch Fyne Oyster Company in conjunction with the Scottish Association for Marine Sciences. There is some indication, however, that this trial has since halted due to expense and lack of success (personal communication). Shellfish cultivation is a relatively small industry in Scotland but with growth potential. Species explored include mussels, oysters and queen scallops (Zero Waste Scotland 2016).

The EU-funded INTEGRATE initiative (2017-2019) aimed to scale up IMTA to an industrial scale across the European Atlantic. One of the pilot sites brings together sea bream, oysters and two algae species. Preliminary results reveal that oyster production volume has quadrupled. Species diversification and localising farmed species to the environment of the country are the next step (IntraFish 2019b).

Technology Readiness Level: 6-8; Technical risk: Moderate.

12.5.2 Recirculation aquaculture systems

Recirculating aquaculture systems (RAS) are contained aquaculture systems on land. This technology has the potential to deliver fish very close to markets and would remove farming space as a limiting factor, in addition to other negative social and environmental impacts.

However, RAS remains a marginal economic activity requiring considerable further innovation before being able to compete in non-niche sectors such as salmon. There is limited potential, in the short and medium term, for large scale RAS production of table fish and crustaceans due to high production costs. While there is some success in its application in trout and salmon smolt and fingerling production and aquaponics in urban areas, it has largely failed in the culture of exotic and warmer water table species due to cash flow problems and overseas competition (Black and Hughes 2017; Seafish 2016).

This section specifically explores the role of RAS in relation to species diversification. For more technical information, please refer to chapter 10.

Innovations with a potential for disruptive performance improvement

Salmon smolts: In December, 2019, the first salmon smolts from Scottish Sea Farms’ new £55 million Barcaldine RAS hatchery were safely transferred to sea pens. The smolts, which arrived at Barcaldine as eggs in January, were hatched and reared using RAS. They had an average weight of 160g – more than double that of smolts grown by the company when using traditional hatchery methods (Fish Farmer 2019b).

Technology Readiness Level: 9; Technical risk: Low

Innovations with a potential for incremental performance improvement

Seaweed: A British seaweed company (identity unknown) trialed land-based macroalgae farming but ceased production recently due to the prohibitively high costs of the energy-intensive production method (Personal communication).

Technology Readiness Level: 9 limited adoption; Technical risk: Moderate

With exception to salmon smolts, only a small amount of fish production currently takes place in RAS in the UK, with limited commercial success. There is limited commercial activity in sea trout farming in the UK.

12.5.3 Co-location

The concept of co-locating commercial aquaculture farms with established and emerging open ocean private sector activities, such as ocean wind farms and oil and gas drilling, has been proposed in recent years, especially in Germany (Corbin, Holmyard, and Lindell 2017). Co-location of different activities is seen as a means by which the use of space can be maximised, and an example of integrated marine planning around the coastline. There are concerns, however, regarding the suitability of high-energy, UK project sites for aquaculture, as well as other technical, practical, legislative and financial issues. Moving forward, the potential impact to animal health and welfare will also require investigation (personal communication).

While strong analytical arguments have been made for incorporating aquaculture into the planning of wind farms and to some extent oil and gas platforms, actual demonstrations are few and small scale. The concept is in its infancy and is an example of the way in which UK industry is approaching the development of the aquaculture industry, as well as marine planning in a strategic and holistic manner (Defra 2015). In 2014, a study funded by the Shellfish Association of Great Britain explored the possibility of co-locating blue mussel aquaculture with Welsh offshore wind farms. Feasibility and environmental impact are yet to be determined (The Fish Site 2014).

Innovations with a potential for disruptive performance improvement

Marine spatial planning: A team of Spanish researchers have developed a methodology that integrated several selection criteria responding simultaneously to the needs and limitations of marine aquaculture and renewable energy production of specific sites, aiming to identify long-term opportunities for the co-location of these activities (Weiss *et al.* 2018). Another variant combined GIS and multi-criteria evaluation techniques to index suitable sites and identify possible candidate species in a German exclusive economic zone (Gimpel *et al.* 2015).

Technology Readiness Level: 6-8; Technical risk: Low

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13 Waste management and valorisation

Contents

From the SIF Executive Board

The method applied in this review has generated numerous examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently happening. It is recognised that there are existing innovations and research areas that are not included here, and new areas where future innovations may occur. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

13.1 Overview: waste management and valorisation

What is the challenge in the UK?

Waste management is a major challenge for both marine and land-based aquaculture due to the implications for fish welfare, ecosystem impacts and operational costs. Waste feed and excreta are the most significant waste streams with innovations focusing on ways to maximise the utility of the nutrients available in these waste streams.

What are the most promising innovation categories?

- Improvements to feed delivery systems
- Biofiltration by algae, plants and detritivores
- Biofiltration by nitrification

Where are their important knowledge gaps?

- Potential for integrated multi-trophic aquaculture in nearshore aquaculture

'Aquaculture waste' is considered to be all materials or nutrients which are not retained as fish biomass and are not removed during harvesting (Cripps and Bergheim 2000). The main waste streams that occur at aquaculture facilities are:

Feed and excreta - Waste feed and excreta can have a major impact on the local water quality and on the local environment through benthic enrichment.

Morts – A percentage of fish will die prematurely and must be disposed of quickly in order to prevent spread of pests and diseases and to avoid attracting predators.

Effluent – For land-based aquaculture systems, used water and effluent are discharged.

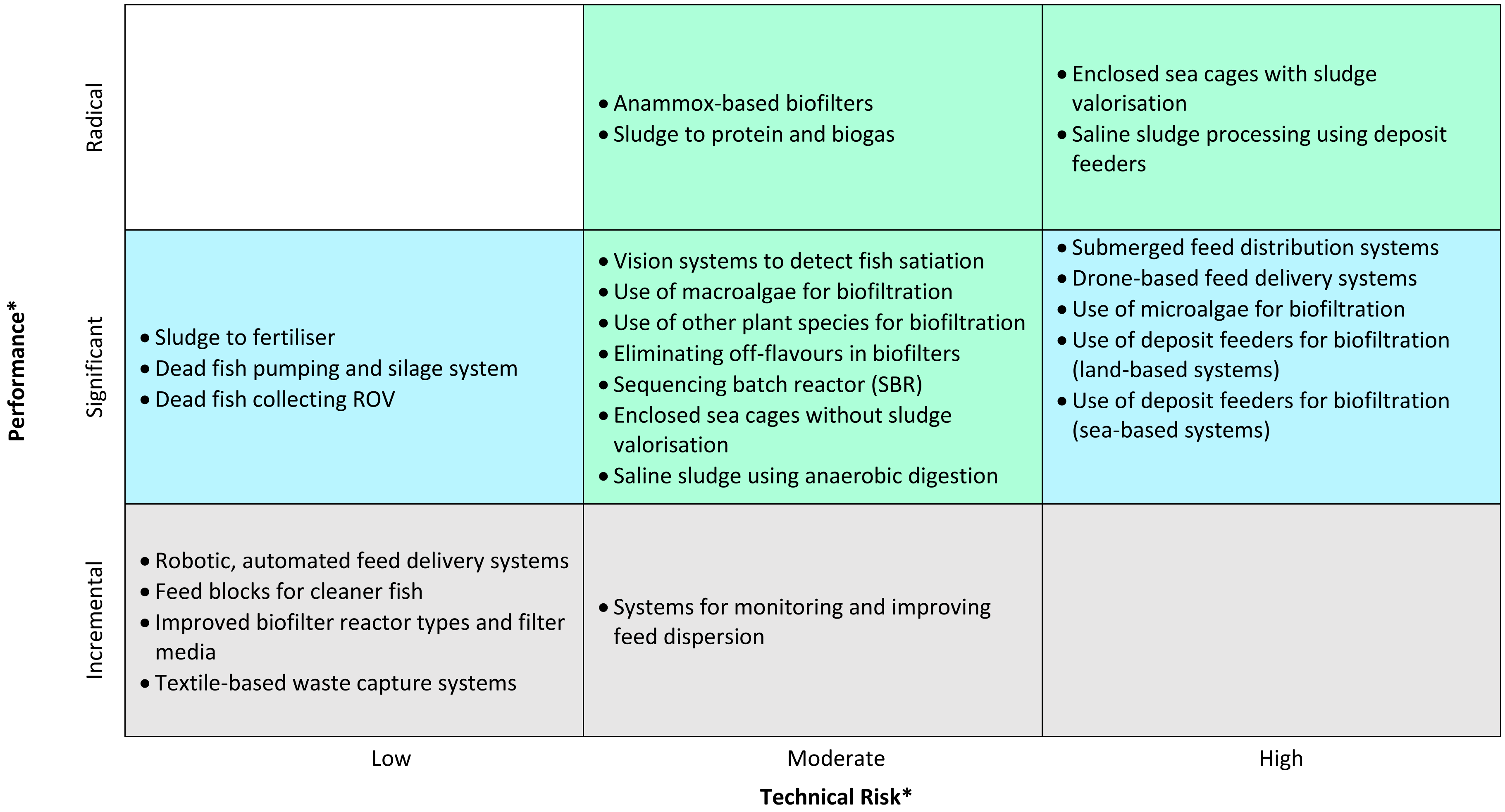
Chemicals and medicines – Antibiotics and chemicals used primarily in the treatment of pests and diseases can be released into the marine environment.

Waste linked to cage cleaning and anti-fouling treatments – Cage cleaning can release large quantities of organic waste and anti-fouling coatings into the marine environment.

Aquaculture facilities will produce a wide range of other sources of waste, such as packaging materials, end of life cages and nets, waste chemicals etc. These other sources of waste are not considered in this review as it is assumed that they are less significant in terms of their volume and potential environmental impact (if disposed of through standard waste management processes).

The concept of the ‘waste hierarchy’ from the field of resource management is relevant to aquaculture. It emphasises that innovation efforts should first be directed to reducing the amount of waste produced. Only once options to reduce waste production have been explored and implemented to the maximum extent possible should attention turn to other strategies lower down the waste hierarchy (such as reuse or recycling) to deal with any residual waste.

An overview of the potential performance improvement rating of recent (2015-2019) innovations in waste management and valorisation in aquaculture are outlined in Figure 12-1.



Performance*	Low	Moderate	High
Radical		- Anammox-based biofilters - Sludge to protein and biogas	- Enclosed sea cages with sludge valorisation - Saline sludge processing using deposit feeders
Significant	- Sludge to fertiliser - Dead fish pumping and silage system - Dead fish collecting ROV	- Vision systems to detect fish satiation - Use of macroalgae for biofiltration - Use of other plant species for biofiltration - Eliminating off-flavours in biofilters - Sequencing batch reactor (SBR) - Enclosed sea cages without sludge valorisation - Saline sludge using anaerobic digestion	- Submerged feed distribution systems - Drone-based feed delivery systems - Use of microalgae for biofiltration - Use of deposit feeders for biofiltration (land-based systems) - Use of deposit feeders for biofiltration (sea-based systems)
Incremental	- Robotic, automated feed delivery systems - Feed blocks for cleaner fish - Improved biofilter reactor types and filter media - Textile-based waste capture systems	- Systems for monitoring and improving feed dispersion	

Technical Risk*

Figure 13-1: Performance and technical risk rating of innovations in waste management.

**See section 4.4 for definitions of performance and technical risk rating scales.*

13.2 Improvements to feed delivery systems

Within an aquaculture system typically around 1/3 of feed nutrients provided are digested, absorbed and utilised in metabolic processes while the rest is excreted as faecal or non-faecal losses into the environment (Schram *et al.* 2014). In keeping with the waste hierarchy, the primary focus in addressing this problem should be on reducing waste at source. In this case, the theoretical ideal is that 100% of the feed that is delivered is consumed and that, once consumed, 100% of the nutrients are taken up and utilised within the fish/target organism. This section presents innovations in feed delivery systems whilst chapter 9 'Nutrition and feeding' covers innovations in the content of the feed itself to improve digestibility of feeds and nutrient uptake.

Innovation with a potential for transformative performance improvement

Submerged feed distribution systems: For sea cages that spend significant periods submerged (to reduce the impact of waves and reduce sea lice infestations), there is a need for feed distribution systems that can operate underwater. Innovasea have developed a patented system that involves a helix shaped tube through which pelletised feed is pumped and dispersed through aperture at various points along its length and at various depths (Dwyer *et al.* 2019).

Technology Readiness Level: 9; Technical risk: High

Vision systems to detect fish satiation: Whilst software models can often be used to estimate feed requirements, the appetite of fish can vary on day to day basis due to a variety of external factors (Zhou *et al.* 2018). This can lead to feed waste if a surplus of feed is delivered. To help prevent this, vision systems can be installed that monitor fish behaviour to track the movements in individual or groups of fish that indicate satiation. Machine learning techniques have been applied to enable automatic detection of fish satiation. When the majority of the population are displaying signs of satiation, the feed system can be stopped. A variety of vision systems are available that support fish satiation detection and can also be used for applications including fish counting, mass estimation, health and welfare monitoring, gender detection etc

Technology Readiness Level: 9; Technical risk: Moderate

Drone-based feed delivery systems: For offshore aquaculture, the harsh environment can be unsuitable for the robotic systems described above and so aerial drones are being investigated as an alternative approach to deliver feed to cages. Drone-based systems might help to ensure even dispersal of feed throughout the cage and could also be used adapted to deliver other farm inputs like medicines, vaccines and fertilisers (Reshma B. and S. S. Kumar 2016).

Technology Readiness Level: 3-5; Technical risk: High

Innovations with a potential for incremental performance improvement

Robotic, automated feed delivery systems: For land-based aquaculture, robotic systems operating on rails can be used to delivery feed to multiple tanks, eliminating the need for feeders at each tank and avoids the risk of feed expiring due to the high turnover of feed (Antonucci and Costa 2019).

Technology Readiness Level: 9; Technical risk: Low.

Systems for monitoring and improving feed dispersion: For marine aquaculture in particular, ensuring that feed pellets are dispersed effectively within a cage can be challenging due to the large area to be covered, the potential for uneven distributions of fish within the cage, plus the effects of wind and sea currents (Skøien 2017). Researchers are investigating the distribution patterns from conventional feed distribution systems (Lien *et al.* 2019) and how to improve the design of feed distribution systems to ensure appropriate dispersion.

Technology Readiness Level: 6-8, Technical risk: Moderate

Feed blocks for cleaner fish: Feed blocks have been developed specifically tailored to the feeding habits of cleaner fish, such as lumpfish and wrasse. The blocks are dropped into sea cages on lines allowing the cleaner fish to graze on the blocks at their leisure. This helps to reduce the aggressive behaviour that can sometimes be evoked by conventional feed delivery systems as the larger fish can eat to satiation before the smaller fish move in (The Fish Site 2019).

Technology Readiness Level: 9, Technical risk: Low

13.3 Biofiltration by algae, plants and deposit feeders

The biofiltration process can be achieved by algae and deposit feeders whereby the nitrous compounds produced by the primary species are consumed as a nutrient for lower trophic species. This form of biofiltration is being developed within integrated multi-trophic aquaculture and recirculating aquaculture systems. Note that the potential for IMTA-based biofiltration in marine aquaculture appears to be an interesting opportunity that has seen little commercial uptake to date (Buck *et al.* 2018). However, the MERMAID project, involving studies of Scottish salmon farms, concluded that in well-flushed open water aquaculture sites the rapid nutrient dispersal would not favour commercial seaweed growth and would not eliminate more than a few percent of the ammonia released (Møhlenberg and Birkeland 2016).

Innovations with a potential for transformative performance improvement

Use of macroalgae: *Ulva lactuca* (sea lettuce) has been identified by a number of studies as being an effective and practical species for this biofiltration application, showing good growth rate, good retention of phosphate and ammonia as well as the ability to cope with variation in water flow rates (Nardelli *et al.* 2019; Shpigel *et al.* 2019). Use of multiple trophic levels prior to the macroalgae filtration stage (e.g. fish then mussels) can help to increase dissolved inorganic nitrogen and therefore macroalgae growth rate (Nardelli *et al.* 2019). The algae produced have been shown to be a good source of proteins, polysaccharides, pigments and functional compounds (Martinez-Espineira *et al.* 2016) and can be used in a variety of applications including fertiliser, food supplements, cosmetics and food.

Technology Readiness Level: 6-8, Technical risk: Moderate

Use of microalgae: Microalgae are also being explored for their potential for biofiltration. These include diatom species such as *Synedra*, which have shown promising results in nitrate and phosphate retention (Xiao-li *et al.* 2017). A study on the use of microalgae for biofilitration in intensive shrimp aquaculture found that *Platymonas helgolandica, Chlorella vulgaris* and *Chaetoceros mulleri* were all effective in reducing total ammonia nitrogen concentration whilst *Platymonas helgolandica* produced the highest average weight, shrimp yield and survival rate (Ge *et al.* 2016).

Technology Readiness Level: 6-8, Technical risk: High

Use of other plant species: Other plant species used for biofiltration include *Vetiveria zizanioides* (Delis *et al.* 2015) as well as some species that are already present in the UK, such as *Salicornia dolichostachya* and various forms of duckweed (Undercurrent News 2018). Plant-based biofiltration has been applied within a combined RAS-IMTA aquaponic system using European Sea Bass and three types of halophyte plant species to produce an edible plant harvest that is microbially safe and approved for human consumption (Waller *et al.* 2015).

Technology Readiness Level: 6-8, Technical risk: Moderate

Use of deposit feeders for land-based systems: Deposit feeders, such as sea cucumbers (Zamora *et al.* 2018), sea urchins and polychaetes, can help with processing of finfish waste and in some cases are also cultivated as a high value species in their own right. The potential for co-culture of the sea cucumber species *Holothuria forskali* with sea bass in a RAS system has been successfully tested at pilot scale (Zamora *et al.* 2018).

Technology Readiness Level: 6-8, Technical risk: High

Use of deposit feeders for sea-based systems: The use of deposit feeders is also being explored for use in sea-based systems. Cubillo et al (2016) have assessed the theoretical potential for marine IMTA featuring various combinations of California sea cucumber with Atlantic salmon, oysters and kelp using a computational modelling approach. Taking into account the dispersion of organic material due to currents, the study suggests that certain IMTA scenarios featuring the sea cucumber can reduce the particulate organic carbon loading to the bottom by up to 86% whilst profit increased from $50 per m^2 per year for monoculture of Atlantic salmon up to $1,413 per m^2 per year for the best IMTA scenario.

Technology Readiness Level: 3-5, Technical risk: High

13.4 Biofiltration by nitrification

Biofiltration is the use of bacteria or other organisms to process the nitrogenous compounds (ammonia, nitrate, and dissolved organic nitrogen) produced within the aquaculture process. Biofiltration through nitrification is covered in this section whilst the use of algae, plants and deposit feeders for biofiltration is covered in the following section.

Biofiltration by nitrification is the oxidation of ammonia into nitrite and nitrate by microorganisms (ammonia-oxidizing bacteria and ammonia-oxidizing archaea). It is commonly applied within land-based aquaculture, in combination with mechanical filters and separators, as part of a Recirculating Aquaculture System (RAS) where the closed nature of the system means that accumulation of ammonia can quickly reach levels that are lethally toxic for the fish in not treated.

Biofiltration by nitrification requires careful monitoring and management as the bacteria must first colonize the filter media (start-up phase) and then increase in colony size to match the increasing ammonia output, which increases with the size of the fish. There are further challenges for the biofilter when fish are harvested from a tank as the bacteria in the biofilter are left without a source of ammonia.

Innovations with a potential for radical performance improvement

Anammox-based biofilters: Anaerobic ammonium oxidation (‘Anammox’) makes use of the unique properties of certain bacteria, such as *Kuenenia stuttgartiensis*, that enables them to convert nitrite and ammonium ions directly into diatomic nitrogen and water. This can reduce the energy consumption and cost of the process – with studies from other areas of wastewater treatment identifying cost savings of up to 60% (Gichana *et al.* 2018).

Technology Readiness Level: 9, Technical risk: Moderate

Innovations with a potential for transformative performance improvement

Eliminating off-flavours: Off-flavours in the flesh of aquaculture fish is caused by geosmin and 2-methylisoborneol (MIB) compounds, which are secondary metabolites produced by certain bacteria that are present in biofilters. The conventional treatment is to move the fish before harvest to a clean RAS system or flow-through system until the off-flavour compounds decrease to a level below the sensory threshold. This can take up to two weeks. Alternative treatments being investigated include ozonation, advanced oxidation processes, adsorbents (such as activated charcoal), photocatalysts (titanium dioxide) and specially tailored biofilters (addition of *Bacillus subtilis* and *Candida sp.)* (Lindholm-Lehto and Vielma 2019). BioFischency, an Israeli company, have developed an electrochemical process that performs the nitrification process and simultaneously eliminates off-flavours (BioFishency 2019). A patent for this technology has been filed (Lahav *et al.* 2019) but the commercial implementation status is unclear. Please also see chapter 10 for further detail.

Technology Readiness Level: 6-8, Technical risk: Moderate

Sequencing batch reactor (SBR): Conventional biofiltration systems require separate tanks and equipment for the various steps of the biofiltration process. Within SBR systems multiple stages of the process can be performed using the same tank and equipment, helping to reduce costs, and can be used as part of a biofloc system (details of biofloc technology can be found in section 11.6).

Technology Readiness Level: 6-8, Technical risk: Moderate

Innovations with a potential for incremental performance improvement

Improved reactor types and filter media: For fixed film biofilters, there are multiple alternative designs being developed for biofilter reactors. These include rotating biological contactors, fixed beds, fluidised beds and trickle filters (Dauda *et al.* 2019). Research continues into the optimum choice of design for a given application. The design of filter media is also being refined to increase the specific surface area to enable a large area of biofilm to establish.

Technology Readiness Level: 9, Technical risk: Low

13.5 Sludge capture and treatment technologies

The sludge produced by aquaculture systems contains fish faeces and waste feed. For land-based aquaculture, disposal of the sludge to landfill is the typical management method for this waste source but this can be costly for the farmer and is a waste of this nutrient-rich waste stream. For marine based systems, a number of 'enclosed' systems are being developed and tested that capture the sludge, which can then be pumped up to a support vessel or directly to land, where it can be processed. This section presents technologies that enable the capture and valorisation of sludge from land and marine aquaculture systems.

Innovations with a potential for radical performance improvement

Sludge to protein and biogas: Hyperthermics, a Norwegian company, have developed a bioreactor and biogas reactor that can process aquaculture sludge into a high protein powder and biogas. The process yields around 4 tonnes of protein powder for every 10 tonnes of sludge (Hyperthermics 2019). The powder can be used as a feed ingredient, although EU regulations prevent feed produced from the waste materials of one species from being fed to the same species. The company is therefore focusing on the use of sludge from salmon farms to produce feed for lumpfish and shrimp (IntraFish 2019). Hyperthermics have at least one commercial scale implementation operating but it is not in the aquaculture sector. N.B. it is not clear if this technology is suitable for saline sludge or sludge from freshwater systems.

Technology Readiness Level: 9, Technical Risk: Moderate

Enclosed sea cages with sludge valorisation: A number of companies are developing enclosed sea cages that are essentially sealed to the outside environment apart from water inlet and outlet pipes. The water inlet pipes take water from depth (20m+) as water from deeper waters should be free from sea lice. The waste feed and faeces sludge generated is captured at the bottom of the enclosure, from where it can be pumped to a support vessel or directly to land. Examples of enclosed sea cages include, the 'egg' from Hague Aqua[1], the 'Marine Donut' from Mowi (Witzøe 2019), and concrete cages developed by AkvaFuture[2]. Whilst the sludge recovered from these systems can be sent to landfill (as is commonly the case with sludge recovered from land-based aquaculture systems) there is potential for disruptive innovation if the sludge is valorised in some way to recover the important levels of nutrients present in the sludge. For instance, the sludge from three sites across Norway that have adopted the AkvaFuture system is being "…recycled to produce biogas, fertilisers and other renewable products", although no further details of the recycling system are available (Navarro 2018). Note that the current level of production using this system is very low, with 3,000 tonnes of Atlantic Salmon produced in 2018 reported with plans to expand to 6,000 tonnes by 2020.

Technology Readiness Level: 9, Technical Risk: High

Saline sludge processing using deposit feeders: The enclosed sea cages described above offer the potential for better management of sludge from marine aquaculture but the saline nature of sludge from marine aquaculture remains a challenge for the valorisation of this waste stream. One option being explored is the use of deposit feeders. Robinson et al (2018) report on the use of sea cucumbers (Holothuria scabra) to process sludge from an abalone (Haliotis midae) RAS system. They found that after 14 days of feeding the sea cucumbers on diluted sludge the organic-carbon content, total nitrogen and carbon-nitrogen ratio in the sediment did not increase. This approach has the potential to be disruptive as it is providing mechanism for dealing with aquaculture waste whilst also producing high-quality protein in the form of sea cucumbers, which have a high market value in Asian markets.

Technology Readiness Level: 3-5, Technical Risk: High

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[1] Hague Aqua: http://www.haugeaqua.com/Technology/

[2] AkvaFuture: https://www.akvafuture.com/

Innovations with a potential for transformative performance improvement

Enclosed sea cages without sludge valorisation: The enclosed sea cages, introduced above, are also being used without sludge valorisation. For example, a small-scale (20mx30m) system featuring enclosed concrete cages has been implemented by Engesund Fish Farm. Waste feed and excreta are vacuumed up by a robotic cleaner and pumped back to shore for disposal (IntraFish 2018). It should be noted that even this small-scale system requires a concrete cage with a mass of 1,500 tonnes and would therefore require a long operational lifetime to justify the investment in such large quantities of carbon intensive materials from a sustainability perspective. This disbenefit will need to be considered against the benefits in terms of reduced ecosystem impacts in the region around the sea cages.

Technology Readiness Level: 9, Technical Risk: Moderate

Sludge to fertiliser: Norwegian company, Bioretur[1], has developed a sludge management system that uses energy-efficient drying systems to concentrate and dry aquaculture sludge from 0.1% dry matter to 90%. The dried material can then be processed offsite into a fertiliser.

Technology Readiness Level: 9, Technical Risk: Low

Saline sludge using anaerobic digestion: Another option being explored for the processing of anaerobic digestion. Luo et al (2015) report on a laboratory study of the treatment of saline sludge from a Jade Perch RAS system. Using an ultrasonic pre-treatment of the waste and addition of a carbon source in the form of glucose, the total chemical oxygen demand removal efficiency was increased to 85%. Quinn et al (2016), have identified a halotolerant microbial consortium that was tested with sludge from gilthead seabream. The process was successful in reducing over 90% of digestible proteinaceous marine fish waste biomass to methane and carbon dioxide at saline concentrations of 15 g per litre.

Technology Readiness Level: 3-5, Technical Risk: Moderate

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[1] Bioretur: https://bioretur.no/english-3/

Innovations with a potential for incremental performance improvement

Textile-based waste capture systems: A Tasmanian company is trialling the use of a textile-based waste capture system, which is a physical barrier installed underneath the cages to capture falling waste (ABC News 2017). The waste captured is then periodically pumped up to a support vessel to be disposed of at a waste management facility (Salmon 2017). The trial system cost AUD$ 500,000 to implement but was a condition of the production quota. However, there are concerns that these systems will not reduce the overall impact as the faecal mounds captured by the system will still contribute to localised oxygen depletion.

Technology Readiness Level: 9, Technical Risk: Low

13.6 Dead fish removal and processing

Despite good welfare standards, a small percentage of fish will die prematurely during the aquaculture process and must be disposed of quickly in order to prevent spread of pests and diseases and to avoid attracting predators. This can be particularly problematic in sea cages and often requires experienced ‘mort divers’ to recover the dead fish from the cages, which is a significant cost for the farmer.

Innovations with a potential for transformative performance improvement

Dead fish pumping and silage system: The Mortex[1] mortality extraction system developed by Steinsvik uses a dead fish trap mounted at the base of the cage that is combined with a pumping system to recover the dead fish to a tank at the surface. The company also provides equipment for fish grinding and silage production to enable the fish carcasses to be valorised.

Technology Readiness Level: 9, Technical Risk: Low

Dead fish collecting ROV: UK company Underwater Contracting have developed the Foover, a remotely operated underwater vehicle (ROV), for collecting dead fish. The system can collect fish up to 5kg in weight and can de-mort 24 standard cages in a day (Fletcher 2018). The system is in use at two farms in Scotland.

Technology Readiness Level: 9, Technical Risk: Low

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[1] Mortex: https://www.steinsvik.no/en/products/e/seaculture/seaculture-equipment/dead-fish-handling/mortex

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Theme 2: Marine and diadromous fisheries

14 Fishing effort and fuel consumption

Contents

From the SIF Executive Board

The method applied in this review has generated numerous examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently happening. It is recognised that there are existing innovations and research areas that are not included here, and new areas where future innovations may occur. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

14.1 Overview: fishing effort and fuel consumption

What is the challenge in the UK?

In order to strive for efficient production, using as little resource as possible (in monetary terms and environmental terms) fishing effort per volume of catch and fuel consumption of the fleet should be minimised.

While fishing effort is an important tool to understand the efficiency of fisheries, there is relatively little groundbreaking innovation in this area, and most innovation is in finding better ways of measuring and monitoring fishing effort.

Fuel consumption is a key driver in most fisheries and there has been steady progress in technical innovations to reduce fuel consumption through improved engine efficiency, hull design and gear modifications. Whilst many of these measures require significant financial investments, behavioural aspects can also deliver significant improvements in fuel efficiency but have received relatively little attention.

What are the most promising innovation categories?

- In the far future the possibility of having off-shore docking stations to re-fuel ships is expected to have a disruptive impact on the fishing industry
- Improved fuel consumption monitoring of fishing vessels was shown to have an impact and reduced yearly fuel consumption by 7-20%
- Otherwise most innovation are thought to bring incremental improvements, e.g. improved methods of calculating fishing effort and combining fishing effort data with vessel satellite monitoring data

Where are their important knowledge gaps?

- Selecting the best ways to calculate and monitor fishing effort for specific circumstances
- Innovations to support behavioural changes towards more fuel efficient fishing practices

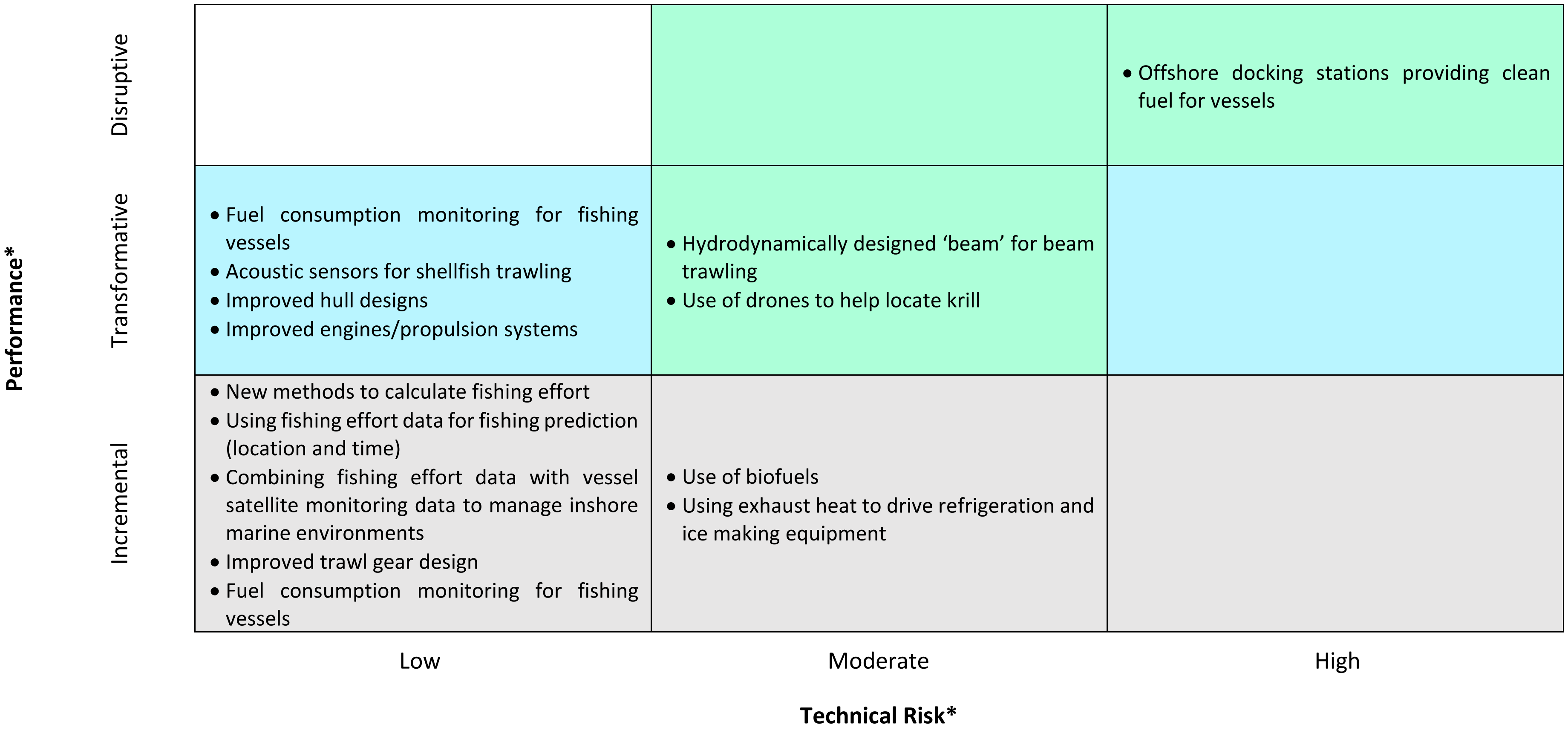
Fishing effort is a parameter, which allows to measure and compare the efficiency of fishing. Depending on the type of fishing, fishing effort can have different units: for example, the amount of fishing gear used, the amount of time spent at sea or a combination of input parameters. When two or more kinds of gear are used, or when the same gear is used by different classes of vessels, the respective efforts must be adjusted to some common standard before being comparable. This standard is sometimes referred to as effective fishing effort (FAO 1997).

The European Union defines fishing effort as fleet capacity (tonnage and engine power) x days at sea (time; t); the formulas are GT x t and kW x t (OECD 2003).

Restrictions in fishing effort (e.g. size vessels, type of and amount of fishing great or number of open fishing days) is one of three approaches to sustain stocks. The other being regulating catch and fishing mortality (e.g. quotas) and regulating special access. Restriction in fishing effort is particularly useful in situations where governance and enforcement capacity are limited or not cost-justified (Anderson *et al.* 2019).

The efficiency of the global fleet, in terms of watt days of fishing effort per tonnage of wild marine catch, is now less than in 1950 despite the considerable technological advances, and expansion throughout the world's oceans, that has occurred during this period of time (Bell, Watson, and Ye 2017). In fact, between 1950 and 2015 the effective catch per unit of effort (CPUE) has decreased by over 80 % for most countries (Rousseau *et al.* 2019).

An overview of the potential performance improvement rating of recent (2015-2019) innovations in fishing effort and fuel consumption are outlined in Figure 13-1.



Performance*	Low	Moderate	High
Disruptive			• Offshore docking stations providing clean fuel for vessels
Transformative	• Fuel consumption monitoring for fishing vessels • Acoustic sensors for shellfish trawling • Improved hull designs • Improved engines/propulsion systems	• Hydrodynamically designed ‘beam’ for beam trawling • Use of drones to help locate krill	
Incremental	• New methods to calculate fishing effort • Using fishing effort data for fishing prediction (location and time) • Combining fishing effort data with vessel satellite monitoring data to manage inshore marine environments • Improved trawl gear design • Fuel consumption monitoring for fishing vessels	• Use of biofuels • Using exhaust heat to drive refrigeration and ice making equipment	

Technical Risk*

Figure 14-1: Performance and technical risk rating of innovations in fishing effort and fuel consumption.

**See section 4.4 for definitions of the performance and technical risk rating scales.*

14.2 Fishing effort

Measuring fishing effort is important for assessing the environmental sustainability of fish stocks and the socio-economic efficiency of fishing activity (Marine Scotland Directorate 2017).

However, different fisheries require different ways of measuring fishing effort. Often these measurements are extremely specific, and few transferable overarching innovations in this area have been identified during this programme.

Innovation with a potential for incremental performance improvement

New methods to calculate fishing effort: Fishing effort can be measured in a variety of ways and should be applicable to the situation of a specific fishery. Hence a large variety of different methods of measuring fishing efforts can be found and are continuously added to. One example is a spatial method to calculate small-scale fisheries effort in data poor scenarios, which was developed by researchers for fishers operating in the Gulf of California. Although, small-scale fisheries land approximately the same amount of fish for human consumption as industrial fleets globally, methods of estimating their fishing effort are comparatively poor. The method uses simply the number of boats and the local coastal human population. Based on the researchers estimates, at any one time in the Gulf of California there were 4,562 more panga vessels operating than the maximum number (13,277) estimated to produce total catches without diminishing returns. The researchers could therefore show that the small-scale fishing fleet is at over capacity considering the amount of fish recorded in official catch reports (Johnson *et al.* 2017).

Technology Readiness Level: 9; Technical risk: Low

Using fishing effort data for fishing prediction (location and time): Patents filed by Shanghai Ocean University use modelling to predict fishing grounds of flying squid (*Ommastrephidae*) and skipjack tuna (*Katsuwonus pelamis*). The model uses historic statistical data, including location, fishing effort (in the number of nets) and the catch (in ton), as well as sea surface temperature and sea surface temperature anomalies. The historic production statistical data are matched with the corresponding environmental data (sea surface temperature) and the models can forecast best locations for fishing (X. Chen *et al.* 2019; X. J. Chen, Wang, and Lei 2019).

Technology Readiness Level: 9; Technical risk: Low

Combining fishing effort data with vessel satellite monitoring data to manage inshore marine environments: Data on fishing effort collected by interviewing 1914 fishermen between 2007 and 2010 was analysed by researchers in the UK. The data was combined with data from European vessel satellite monitoring data. The authors concluded that "effective management of the inshore marine environment requires up-to-date, high-resolution and holistic maps of fishing effort that can be obtained only through validated interpretation of inshore Vessel Monitoring System data" (Enever *et al.* 2017).

Technology Readiness Level: 9; Technical risk: Low

14.3 Fuel consumption

Fuel consumption in fisheries is due to motorised vessels. By 2015, 68% global fishing fleet was motorised. Although the global fleet is dominated by small powered vessels under 50 kW, they contribute only 27% of the global engine power, which has increased from 25 to 145 GW (combined powered-artisanal and industrial fleets) (Rousseau *et al.* 2019).

The median fuel use intensity of global fishery records since 1990 is 639 litres per tonne. Fuel inputs to fisheries vary by several orders of magnitude, with small pelagic fisheries ranking among the world's most efficient forms of animal protein production and crustaceans ranking among the least efficient (Parker and Tyedmers 2015).

Fuel use of course is directly linked to emissions. According to one study, emissions by the global fishing industry grew by 28% between 1990 and 2011, while the average emissions per tonne landed also grew by 21%. Growth in emissions in this timeframe was driven primarily by increased harvests from fuel-intensive crustacean fisheries (Parker *et al.* 2018). Another recent study calculated that global CO_2 emissions from the main engine combustion of fuel in marine fisheries amounted to approximately 207 million tonnes of CO_2 in 2016, compared to 47 million tonnes of CO_2 in 1950 (Greer *et al.* 2019).

The type of gear used can have a significant impact on the emissions of a fishery. For example, small pelagic fisheries account for around one-fifth of reported landings by mass but contribute only 2% of global fishery carbon emissions, with less than 80 litres of fuel per tonne of catch when using purse seine gear (McDermott 2018). Crustacean fisheries, on the other hand, accounted for only 6% of landings but over 22% of emissions. Fisheries for lobster and shrimp harvest relatively low volumes per trip compared to those targeting finfish and, particularly in the case of trawl fisheries that target crustaceans, consume substantial quantities of fuel in the process (Parker and Tyedmers 2015). Of course, changing gear types is not an option for most fishers due to the very high investment costs and the significant learning curve required to master a new gear type.

Recently, trends in Europe and Australia since the beginning of the 21st century suggest fuel use efficiency is improving. Even though management decisions, technological improvements and behavioural changes can further reduce fuel consumption it was suggested that the most effective improvement to fisheries energy performance will come as a result of rebuilding stocks where they are depressed and reducing over-capacity (Parker and Tyedmers 2015).

Behavioural factors have received relatively little attention, although the ‘skipper effect’ has been identified, which suggests that the experience and knowledge of individual skippers can have an impact on fishing performance and fuel use (Ruttan and Tyedmers 2007; González-García *et al.* 2015). A survey of UK fishers and boat owners in 2006 found that only 14% of vessels surveyed had adopted reduced steaming speed as a measure to reduce fuel costs (Curtis, Graham, and Rossiter 2006). Given that behavioural changes can cost little money to implement, there may be opportunities for innovation to encourage fuel efficient fishing practices.

It has been noted that the regulatory framework for energy efficiency in the fishing sector is unclear. The International Maritime Organisation (IMO) has intensified the regulations on energy efficiency for ships to guarantee greenhouse gas emission reduction from shipping (IMO, 2009a; IMO, 2009b). However, the fishing sector is exempted from such measures (Basurko, Gabina, and Quincoces 2016).

Innovation with a potential for disruptive performance improvement

Offshore docking stations providing clean fuel for vessels: Finnish company Wärtsilä-led ZEEDS (Zero Emission Energy Distribution at Sea) is a program which envisions an ecosystem of offshore clean fuel production and distribution hubs. While the project addresses issues of the shipping industry as a whole, this could also have implications for offshore fishing operations. The infrastructure as imagined by all companies involved in this programme, is composed of fuel hubs set up next to offshore wind turbines, built as two-level platforms: The energy produced by the wind turbines would be used to produce hydrogen from water on the first level of the platform; while on the second level, ammonia, a clean fuel, would be made from hydrogen and nitrogen extracted from the air (Prtoric 2019).

Technology Readiness Level: 1-2; Technical risk: High

Innovation with a potential for transformative performance improvement

Hydrodynamically designed 'beam' for beam trawling: The SumWing[1] is a hydrodynamic wing-shaped 'beam' that replaces the conventional cylindrical beam in beam trawl gear. The arrangement of the attachment points of the net below the attachment points for the fishing lines has the effect of tilting the SumWing downwards to quickly descend the gear to the seabed. Once it reaches the seabed the 'feeler', which projects out from the front of the SumWing, contacts the seabed and tilts the device back into a neutral position and helps to maintain the SumWing at a consistent distance from the seabed. Within minimal seabed contact, the drag of the gear is reduced significantly resulting in a fuel consumption reduction of around 20% (Haasnoot, Kraan, and Bush 2016). An important side benefit of the reduced seabed contact (84% less than a standard beam according to the manufacturer) is the significant reduction in disturbance of the benthic environment.

Technology Readiness Level: 9; Technical risk: Moderate

Acoustic sensors for shellfish trawling: Over the course of a three to four-hour trawl, shellfish is usually only caught for 15-45 minutes. Without any feedback to guide their decisions, skippers typically aim to cover as wide an area of seabed as possible, using a systematic pattern, to maximise the chances of a good haul of shellfish. The Notus ECHO[2] is an acoustic sensor that is fitted to the rear of the metal bycatch reduction grid in a demersal trawl. The sensor picks up on the noise made by the shellfish as they rattle through grid into the cod end (although stones and debris can generate false readings). The signal is transmitted back to the wheelhouse, so that the skipper knows when they are trawling in an area with high densities of shellfish and when they are not. This enables the skipper to alter the trawl pattern to focus on areas of high shellfish density, resulting in improved catch per unit of fuel.

Technology Readiness Level: 9; Technical risk: Low

Improved hull designs: Innovations in hull designs are enabling reductions in fuel consumption as well as improved handling performance. Examples include a new range of

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[1] SumWing: http://www.sumwing.nl/SumWing_EN.pdf

[2] Notus ECHO: https://www.notus.ca/echo

trawlers developed by the Ulstein Group that feature their inverted bow design, known as 'X-Bow' (Ship & Offshore 2018). Another example is the 191-foot freezer longliner F/V Blue North, designed by Norway-based naval architecture firm Skipsteknisk AS. The vessel has a moulded hull construction for decreased resistance (Philips 2015).

Technology Readiness Level: 9; Technical risk: Low

Improved engines/propulsion systems: Recently Finnish company Wärtsilä announced a new optimised stern trawler design which is expected to reduce fuel consumption and notably increase overall vessel efficiency compared to currently available designs. The propulsion system is based upon the Wärtsilä 31 engine, which has been recognised by Guinness World Records as being the world's most efficient 4-stroke diesel engine (Farnsworth 2017). Other improvements in this area include the use of electric-diesel hybrid engines**.** Exactly how much fuel could be saved using a hybrid propulsion system depends on the fishery, vessel operating procedures, and design details. Based on recorded hydraulic, electric and propulsion loads, as well as several assumptions about the performance of a hybrid system, a freeze troll vessel with an auxiliary generator could reduce its fuel consumption by approximately 30% with a hybrid drive (AFDF 2019; Aarsaether 2017).

The uptake of more efficient engines can be supported through policy measures. A scheme in Mexico targeted at the artisanal fleet has seen almost 21,000 2-stroke engines replaced with more efficient 4-stroke engines between 2008 and 2015, resulting in avoided emissions of 1.3 million tonnes CO_2e (Martínez-Cordero and Sanchez-Zazueta 2017).

Technology Readiness Level: 9; Technical risk: Low

Use of drones to help locate krill: Aker BioMarine have developed a solar powered data drone, known as Sailbuoy, to help locate Antartic krill (Aker BioMarine 2020). It is equipped with an echosounder and environmental sensors and can transmit live data back to the fishing vessel. These data are being used to inform decisions as to when and where to fish – reducing time spent searching for fish and saving fuel. Solar panels charge the onboard battery meaning that the drone can operate independently for up to a month. Whilst krill fishing is not relevant to UK fisheries, the principle of using drones to help locate fish could be relevant to some fisheries.

Technology Readiness Level: 9; Technical risk: Moderate

Innovation with a potential for incremental performance improvement

Improved trawl gear design: A number of aspects of the design of trawl gear are being investigated in order to reduce drag and fuel consumption whilst maintaining or improving fishing performance. These include:

- Using higher strength net materials to enable smaller diameter twine and larger mesh size (Tait 2015; Parente *et al.* 2016).
- Increasing the horizontal mouth opening in demersal trawl gear and use two or three codends to significantly increase the swept area and catch per unit fuel (Tait 2015).
- Improved trawl door design (Jonsson *et al.* 2016).

These improvements are being enabled by a combination of improved computational methods, which are being used to predict and optimise drag performance (Jonsson *et al.* 2016), and the use of flume tanks, which are being used to validate the predicted drag performance and assess overall stability using scale models (Tait 2015; Swan Net Gundry 2020).

Technology Readiness Level: 9; Technical risk: Low

Fuel consumption monitoring for fishing vessels: Spanish technology centre AZTI Tecnalia has developed two fuel monitoring devices for fishing vessels: the GESTOIL ("an onboard fuel consumption measurement and management system") addressed for larger trawlers and purse seiners, and the SIMUL (”low cost Open Source monitoring system") for artisanal fleet. Both devices monitor fuel consumption and register the vessel positioning with data collection frequency of one sample every 10 seconds. In trials vessel fitted with these devices achieved 7- 20% of annual fuel savings (Basurko, Gabina, and Quincoces 2016).

Technology Readiness Level: 6-8; Technical risk: Low

Use of biofuels: The use of biofuels for fishing vessels has been under consideration for many years. A detailed assessment of the potential for biofuel usage in the Norwegian fleet was conducted in 2007 (Opdal and Hojem 2007). More recently, there has been significant interest and investment by shipping companies in biofuel development (DFDS 2019), primarily due to of the introduction of the 2020 sulphur emissions cap by the International Maritime Organisation Diesel (IMO 2019). An example of the current research activities is the study conducted by Technobothnia in which biodiesel produced from rainbow trout fish gut waste and biodiesel made from animal fat was used in the tested in laboratory conditions. Compared to diesel, the biofuels are cleaner on all emission points with the exception of nitrogen oxides.

Higher nitrogen oxides emissions are partly due to the fact that the viscosity of biodiesel is higher, i.e. has a high density and partly due to a lower cetane number (Skog 2015).

Technology Readiness Level: 3-5; Technical risk: Moderate

Using exhaust heat to drive refrigeration and ice making equipment: Refrigeration and ice making equipment can add significantly to fuel consumption for large vessels that spend multiple days at sea. There is now a growing number of proposals for refrigeration and ice making equipment that is driven by exhaust heat from the main engines (Xu *et al.* 2017). A key challenge for these systems is ensuring stable operating temperatures and reliability with fluctuating engine usage and the limited space available on fishing vessels.

Technology Readiness Level: 3-5; Technical risk: Moderate

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15 Fish welfare in wild-capture marine fisheries

Contents

From the SIF Executive Board

The method applied in this review has generated numerous examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently happening. It is recognised that there are existing innovations and research areas that are not included here, and new areas where future innovations may occur. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

15.1 Overview: fish welfare in wild-capture marine fisheries

What is the challenge in the UK?

Main challenge with regards to welfare in wild-capture marine fisheries in the UK (and rest of the world) is that it is data poor with regards to the effect of the different stressors, which the fish are exposed to during the different phases of the capture to slaughter process. For target species exploited in commercial fisheries, welfare measures are slow to implement, due to current technology not yet fully adapted to the scale and environment at sea. With the high survivability exemption from the EU Landing Obligation, there is an increased interest in robust data on discard survival, representing yet another fish welfare angle.

What are the most promising innovation categories?

- Welfare education (focus on retrieval and handling) and market pull – highlighting link between welfare, quality, shelf-life and sustainability
- Training fishers in release of unwanted catch
- Electrical stunning
- Slipping
- Vision systems used on fishing gear (robust data capture of welfare parameters)

Where are their important knowledge gaps?

- Data on the different stressors for wild caught fish
- Evidence that it is possible to promote survival of unwanted catch through handling procedures including release methods

In contrast to terrestrial farming or aquaculture, there is still little welfare regulation that constrains how aquatic animals are handled or killed in wild-capture marine fisheries (Metcalfe 2009; Diggles 2011; 2019; Kaiser and Huntingford 2009). Welfare in wild-capture fisheries is moving up the public agenda, partly driven by developments in aquaculture (Benjaminsen 2016).

A major and important difference between aquaculture and wild-capture marine fisheries is that in aquaculture it is possible to talk about improving welfare whilst fisheries will generally only impinge on welfare of the fish when caught, and improved welfare is therefore about reducing negative impact during the capture process to minimise stress and injury, and the number of individuals affected (personal communications). Be it an ethical or scientific debate, a suggested approach is that even where a given taxon or species are convincingly shown to be devoid of the ability to feel pain or devoid of consciousness, that fact must not diminish the importance of welfare considerations (Browman *et al.* 2019). Hence, welfare in this chapter refers to capture and handling methods that minimise the physical damage to any retained fish, until after they are either slaughtered or released, and thus promote the likelihood for post-release survival and / or good product quality.

The welfare aspect of wild-capture marine fisheries was first specifically addressed in the 1980s through research on stock assessment e.g. looking at escape mortality from trawls (Mike Breen and Cook 2002; FAO 2019; Ashley 2007; Huntingford *et al.* 2006) and through fish quality studies, where it has been shown for numerous species that the quality of the fish meat is higher with less stress / higher welfare (Lambooij *et al.* 2003; Vis *et al.* 2003; Benjaminsen 2016). More recently, there is an increasing understanding (at least amongst experts working directly with fisheries) that improving welfare will not only have ethical benefits, but also tangible benefits for the fishery, including improved sustainability, product quality and longer shelf life, and hence profitability (Breen et. al. in press, personal communications).

In recent years there has been an increasing focus on accounting for what happens to fishes caught in wild-capture marine fisheries in order to identify where the main animal welfare issues exist (Veldhuizen *et al.* 2018). The different capture and release stressors include physical contact with fishing gear, crowding, predation, change in environmental factors e.g. temperature and pressure, air exposure, light exposure, noise exposure, transport and handling. Thus, the captured animal is likely to encounter: hypoxia, exhaustion, barotrauma, temperature shock, osmoregulatory distress, physical trauma/injury, displacement and predation (both in and out of the water) (M Breen and Nin 2017).

The different capture and release stressors result in cumulative stress from the point of capture to slaughter (Welfare of fish released from demersal trawls, M. Breen, 2019). Research addressing these different capture and release stressors and their impact on the fish is still limited and hence there is little insight into how the development of catch welfare in commercial fisheries. With the introduction of a Landing Obligation, under the EU Common Fisheries

Policy (European Commission 2016), there has been vested interest in reducing the capture of unwanted catches, primarily through the use of more selective capture methods (Eliasen 2018) (please refer to chapter 19 ‘Selectivity of gear and avoidance of unwanted catches’). There are certain exemptions from the landing obligation (i.e. de minimis, high survivability or damaged fish) (European Commission 2016), and research addressing capture and release stressors in relation to discard survival estimates are valuable for several reasons. There is therefore a substantial and growing body of literature on the fate and vitality of released animals from commercial fisheries.

Discard survival rates for regulated species will inform fisheries managers on the likely benefit of the Landing Obligation in terms of shifts in harvesting patterns and resulting changes in fishing related mortality; Data on the fate of non-regulated and protected species that continue to be released after capture will be useful for interpreting the effect of the Landing Obligation across the wider ecosystem; and Robust data on discard survival will help identify species that may be applicable for a “High Survival Exemption”.

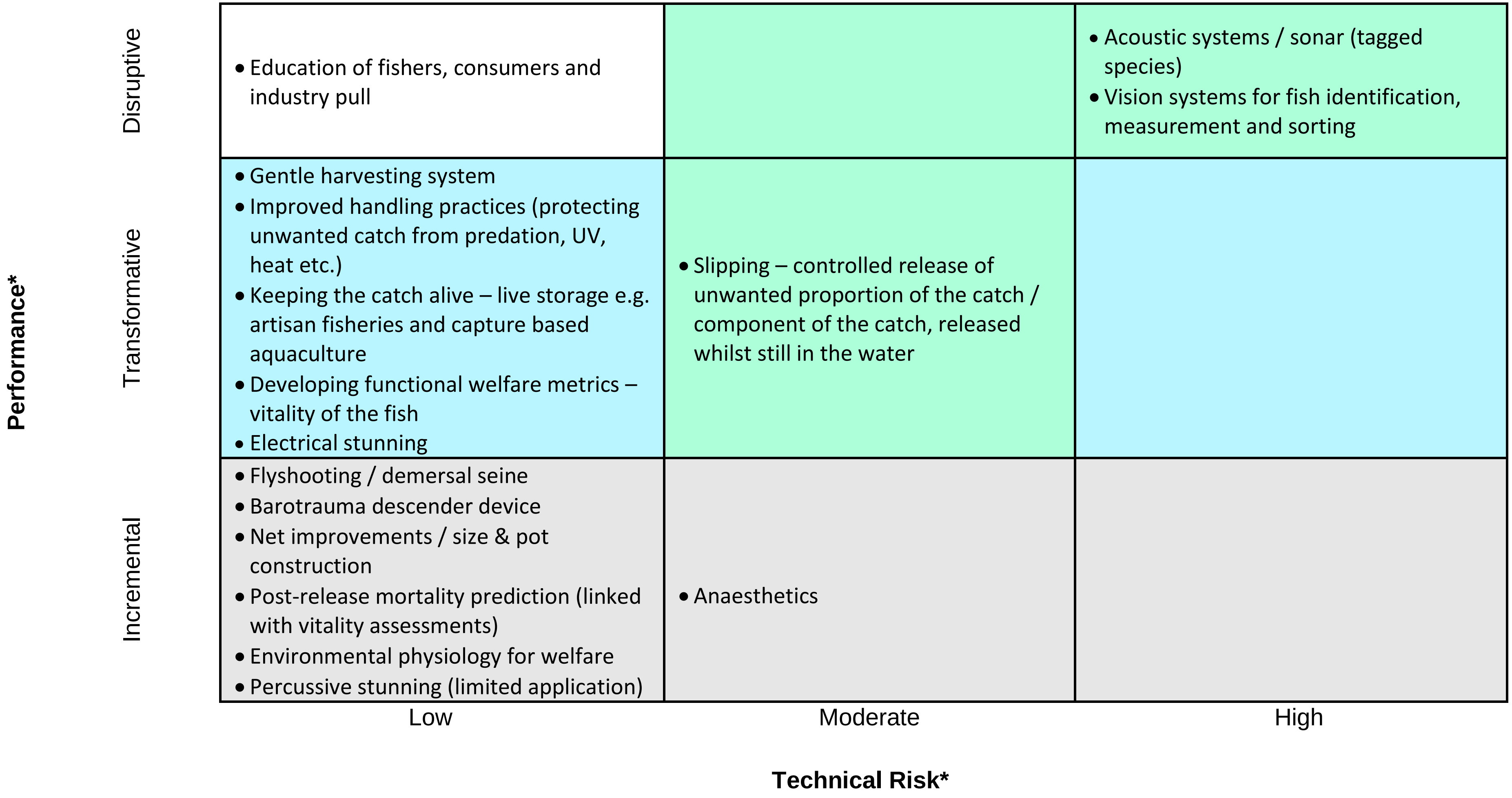
There are several determinants in the survival of any released animals, including: species, capture method, and their interactions, as well as the environmental conditions and handling practices during the capture and release process. Most research has focused on trawls and hooks with some case studies of demersal trawls, dredges, surrounding nets (boat & purse seine) and entangling nets (trammel nets) (Veldhuizen *et al.* 2018). As the capture methods have different modes of operation, they affect the animals encountering them in different ways (Breen and Nin 2017).

Key areas where there is potential for innovation and technical advancements to lead to improvement of survival of released unwanted catch and hence improved welfare include: avoidance of unwanted catches, further improved gear selectivity, limited duration of fishing operations, smaller catch volumes, handling the animals with urgency and care, avoiding direct sunlight exposure, avoiding emersion, avoiding seabird predation, appropriate release location and assisted recompression (Breen and Nin 2017).

The greatest potential for reducing capture-related stressors is to reduce the stress during the retrieval and handling phases. The capacity to mitigate these stressors is however limited due to efficiencies and scale – e.g. to retrieve a net slow enough for fish not to suffer from barotrauma would simply take too long. Therefore, experts have pointed out that one priority in marine wild-capture fisheries should be facilitating the release of the unwanted catch as early in the capture process as possible before retrieval (personal communication).

Another important factor to consider when addressing animal health and welfare in marine fisheries is the diversity of the fishing fleets. For the large demersal or pelagic vessels there is potentially more scope for innovations associated with e.g. cost or capacity, whereas these are out of scope for many small-scale fisheries. Thus, small-scale coastal fisheries are faced with limitations different from those on larger vessels (including weight of equipment and ease of handling, or safety) (Olivier 2007), but due to e.g. the lower speed of the operations / smaller volumes handled, small-scale fisheries represents a promising area for handling based innovations, with regards to reducing negative impact on harvested animals (minimising stress and injury). Most small-scale fisheries have in the recent decades been driven by economies of scale targeting generic and standardised markets. This market can absorb the great volumes but is also characterised by an intense price competition, which favours the large demersal and pelagic fisheries. In order to switch small-scale fisheries towards more specialised and dedicated, higher price markets, new skills, investments and mindsets will have to be developed (Hultman and Nordisk Ministerråd 2018). Animal welfare potentially has an important enabling role in this transitioning.

An overview of the potential performance improvement rating of recent (2015-2019) innovations for health and welfare in wild-capture fisheries are outlined in Figure 15-1.



Performance* \ Technical Risk*	Low	Moderate	High
Disruptive	• Education of fishers, consumers and industry pull		• Acoustic systems / sonar (tagged species) • Vision systems for fish identification, measurement and sorting
Transformative	• Gentle harvesting system • Improved handling practices (protecting unwanted catch from predation, UV, heat etc.) • Keeping the catch alive – live storage e.g. artisan fisheries and capture based aquaculture • Developing functional welfare metrics – vitality of the fish • Electrical stunning	• Slipping – controlled release of unwanted proportion of the catch / component of the catch, released whilst still in the water	
Incremental	• Flyshooting / demersal seine • Barotrauma descender device • Net improvements / size & pot construction • Post-release mortality prediction (linked with vitality assessments) • Environmental physiology for welfare • Percussive stunning (limited application)	• Anaesthetics	

Figure 15-1: Performance and technical risk rating of innovations in wild-capture marine fisheries health and welfare.

**See section 4.4 for definitions of the performance and technical risk rating scales.*

15.2 Capture

For innovations in capturing methods please refer to chapter 19 on ‘Selectivity of gear and avoidance of unwanted catches’. This chapter only reviews novel methods that specifically address welfare. For ghost fishing, which also has the potential to affect fish welfare, please refer to the chapter 15 on ‘Ghost fishing and marine litter from fishing gear’.

There is growing evidence indicating that larger animals within a species have a higher probability of surviving capture and release from fishing gears. Specifically, the survival of trawl caught animals, both discarded and escaping, has been observed to be significantly correlated with size (length) in several species supporting the hypothesis that swimming ability is an important survival trait (Mortality of fish escaping trawl gear, FAO Fisheries Technical Paper, 2005). This is an important consideration with regards to the management of a fishery and its discarding practices, because typically it is the undersized animals that are selectively returned to the sea.

In relation to bycatch, most advancements have been made to avoid unwanted catch by developing and using more selective methods during capture process e.g. mesh size allowing smaller fish to escape (please refer to chapter 19 on ‘Selectivity of gear and avoidance of unwanted catches’). Fishers also adapt capture methods to the behaviour of the target species and to allow unwanted catch to escape before the catch is out of the water. None of the existing techniques are 100% effective but they can significantly reduce unwanted catch.

In relation to target species, novel capturing technologies, developed specifically with animal welfare in mind, are still few and far in between.

Innovation with a potential for disruptive performance improvement

Vision systems for fish identification, measurement and sorting: Developments to assess catch, welfare and survival of fishes “in situ” are being developed and trialled e.g. in the SMARTFISH H2020 project[1]. This include innovations such as Deep Vision, a subsea vision system for identifying and measuring fish under water, enables live feedback to the crew on the composition of the catch. This is currently only available for research, but the

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[1] SMARTFISH H2020 project: http://smartfishh2020.eu/seas/

company aims to release a version suitable for commercial use in 2020. The ultimate aim is to integrate this technology with active “automated” sorting, although no details of how this system might work are provided at the time of writing (Scantrol Deep Vision 2016).

Please also refer to the chapter on Selectivity of gear and avoidance of unwanted catches for further detail of innovations within selective gear.

Technology Readiness Level: 6-8; Technical risk: Moderate

Seatronics TrawlCAM: Claims to be the only commercial headline camera system that presents live video footage from the trawl for commercial trawlers. Providing footage in real-time, the system offers a live video stream of the trawl mouth whilst towing. An encrypted video signal is returned to the vessel in monochrome via a low loss single coaxial from the systems subsea multiplexer. The TrawlCAM[1] has been developed over the last three years and has been trialled on board Scottish trawlers fishing the East Coast and deep waters off the West Coast of Scotland, including the Continental Shelf and Rockall. The system provides the end-user with real-time footage of fish species going into the trawl, the condition of the net and any foreign debris being dragged by the hoppers.

Technology Readiness Level: 6-8; Technical risk: Moderate

Acoustic systems / sonar (tagged species): In order for fishers to get a better understanding of catch size (e.g. for purse seine) acoustic or sonar systems are constantly being further developed to improve resolution of catch estimates before the catch is pumped onboard. Another use for sonar include examples of real-time receivers that can detect signals from transmitters on tagged (endangered) fish (for further information please refer to the chapter on Marine Habitat, environment and ecosystem monitoring and impacts).

Innovation with a potential for transformative performance improvement

Gentle harvesting systems: Tiaki[2] is a new fishing method from New Zealand. The Tiaki modular harvesting system is a method and handling system developed by Precision Seafood

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[1] TrawlCAM: https://seatronics-group.com/equipment-sales/fishing/trawl-mounted-camera-systems/seatronics-trawlcam/

[2] Tiaki: http://www.tiaki.com/

Harvesting have been approved and are now in use in New Zealand for deep water and inshore fish species.

Technology Readiness Level: 9; Technical risk: Low

Slipping methods: Operational improvements in slipping practices have been shown to significantly reduce stress and mortality in the released unwanted catch. Thus, slipping practices have been developed to safely allow catches to be released from the net whilst still in the water, with minimal risk of mortality (Anders, Breen, *et al.* 2019; Uhlmann, Ulrich, and Kennelly 2019). It has been demonstrated that the survival of sardine can be significantly improved if the school is allowed to escape through a purposely formed opening in the net, rather than by slipping them over the floatline (Marçalo *et al.* 2018). A best practice slipping procedure was developed with the Norwegian Fisheries Directorate, in which it is recommended to use the bunt-end of the net to form a controllable release opening (with minimum dimensions, i.e. length > 18 m), from which the fish can be allowed to swim freely. It has been shown that the behaviour of herring and mackerel released in this manner indicate good level of welfare, as the fish typically retained an ordered schooling behaviour (albeit disordered behaviour was observed as well, typically later in the slipping process and mostly only in relation to large catch sizes) (Best practice in slipping from purse seines, FHF-project report 2017 Uhlmann, Ulrich, and Kennelly 2019).

Technology Readiness Level: 9; Technical risk: Moderate

Innovation with a potential for incremental performance improvement

Flyshooting: Flyshoot fishing is an old fishing technique which has recently been revisited and now seeing a growing fleet (VCU 2019). There is limited literature on flyshoot fishing but it is known that this technique is much less damaging than trawl as only the stronger fish are herded into the net when the fishing boat approaches and the net is raised. The method allows undersize fish to remain free and as it is a slow-fishing method, the catch consists primarily of undamaged fish and uses less fuel. Hence, flyshoot fishing is renowned for being more environmentally friendly and economical. If damage is seen as a measure for welfare, using this technique has a positive impact on fish welfare in wild-capture marine fisheries (FAO 2019).

Technology Readiness Level: 9; Technical risk: Low

Net improvements: Various parameters have been developed and improved for trawl, purse seines, gill- and trammel nets in order to reduce bycatch and increase welfare of catch e.g. knotless woven nets (Breen *et al.* in press). Please refer to chapter 19 on 'Selectivity of gear and avoidance of unwanted catches' for details.

Technology Readiness Level: 9; Technical risk: Low

Size and construction of pots: Sustainability of commercial fisheries is best achieved when fishing gears are selective and have low impacts on bottom habitat. Pots (baited traps) are a fishing technology that typically has lower impacts than many other industrial gears, pots can be designed to produce little bycatch and have a higher fish welfare than many other fishing methods. Having a large enough size of pot to accommodate the catch, will reduce crowding effects, thereby reducing stress levels and potential physical injuries due to crowding. Moreover, there is evidence to suggest that larger size can also increase catch rates (Meintzer, Walsh, and Favaro 2018; 2017). Some pots are designed to be collapsible on deck, for easy storage but also "collapse" when they are hauled to the surface, thereby increasing amount of and degree of fish to net contact. A suitable mechanism to prevent this could significantly improve catch welfare during retrieval.

Technology Readiness Level: 9; Technical risk: Low

15.3 Handling

Handling here refers to the process of removal of the catch from the gear, sorting operations onboard the vessel and potential containment of the catch. Research is currently focused on providing evidence that with proper handling, fishers can promote survival of unwanted catch (for high survivability exemption from landing obligation - European Commission 2016).

Innovation with a potential for transformative performance improvement

Improved handling practices: Handling of the catch by the fishers is one of the major determinants in the survival of any released animals (BMIS n.d.). Through simple, but well considered, improvements in handling practices (i.e. allowing the fish to swim freely from a purpose-made opening in the net) the survival of fish can be significantly increased. Survival is greatly enhanced by minimising the exposure fish have to emersion from the water. This simple principle could be generally applied to especially small-scale fisheries to improve the welfare of the captive animals, both targeted and unwanted catch, and thus improve the likelihood of any released animals (personal communication).

Unwanted catch should be identified with urgency and released into the water quickly and with care, via a route that promotes its escape from the surface and minimises likelihood of further injury and encounter with predators (e.g. through release pipe system). The handling practices and effects thereof are to some extent species-specific but e.g. for sharks and rays good handling practices can lead to a 15-20% improvement in survival rates (Restrepo *et al.* 2017). Good handling practices for sharks and rays have been compiled by Poisson (2014).

Technology Readiness Level: 9; Technical risk: Low

Innovation with a potential for incremental performance improvement

Barotrauma descender device: Barotrauma can lead to low survival rates after catch and release of deep-sea fish and as barotrauma may also affect fertility, it potentially has a wider impact on fisheries (M Breen and Nin 2017). High discard rates and post-release injury and mortality in the red snapper fishery Gulf of Mexico may impact rebuilding of this fishery. Texas A&M University researchers examined various strategies to reduce this discard mortality, including assisted recompression for animals suffering from physical barotrauma, with the use of fish descender devices that can reverse the complications resulting from barotrauma. Researchers tagged fish with an acoustic transmitter that monitored the levels of activity, depth, and fate after release. Tagged fish released at the seafloor using descender devices showed greater survival rates compared to fish released at the surface. Local recreational anglers helped test these devices on fishing trips. These descender devices are showing great promise for enhancing the survival of discarded reef fish and represent an effective tool for reducing discard mortality in recreational and commercial fisheries (Fisheries 2019). Also, the descenders could be made for commercial vessels in the form of large lifts (personal communication).

Technology Readiness Level: 3-5; Technical risk: Low

Post-release mortality prediction: Different fish species react differently to stress factors. Many sharks are vulnerable to fishing pressures and impacts of post-release mortality due to their slow growth rate and late maturity. Scientists at the Mote Marine laboratory have worked with commercial longline fishermen to tag sharks with data loggers. Data from those tags can show whether a shark survives after capture and release and provide additional information to estimate a recovery period after capture. Researchers have also been using a new accelerometer technology to look at the blood physiology of sharks at capture to predict post-release mortality. By also measuring blood stress values at the time of capture, researchers can correlate those stress values with data from the tags to see whether the shark survives after release. Researchers have assessed the post-release outcome of more than 200 sharks and nine species providing crucial data for stock assessments and fishery managers. In addition, the accelerometer technology dramatically reduces the costs associated with collecting data on the post-release mortality of sharks (Fisheries 2019).

Technology Readiness Level: 3-5; Technical risk: Low

Developing functional welfare metrics: For wild-caught fisheries there is little research describing observations in response to typical capture related stressors. In order to establish physiological, behavioural and quality baselines observation, monitoring of animals during commercial fishing operations are needed to evaluate the compound effects of the above-mentioned stressors on welfare. Developments in underwater video technology, such as the Deep Vision (Scantrol Deep Vision 2016) will enable behavioural observations to be made. Such behavioural observations are essential in the development of a welfare metrics and can take into account both the response to capture related environmental changes as well as response to subsequent release or slaughter. These insights are essential for identifying the most prevalent capture-related stressors (Anders, Breen, *et al.* 2019).

Technology Readiness Level: 3-5; Technical risk: Low

Environmental physiology in relation to welfare: There is a need to increase the overall knowledge base about marine fish environmental physiology, especially with regards to tolerance thresholds for major environmental stressors and how such stressors affect performance within their tolerated range. A particular application of such data would be to improve the reliability of models in order to gain a better understanding of what defines current fish distribution and abundance and, therefore, to increase confidence in projections of the effects of ongoing global change. But also, the development of physiological metrics would enable researchers to describe responses to capture related stressors, which in turn are important in determining subsequent effects on meat quality e.g. temperature change, oxygen and salinity. This directly links responses to capture related stressors i.e. welfare to product quality, which e.g. fishers and consumers can directly relate to (Breen *et al.* in press).

Technology Readiness Level: 3-5; Technical risk: Low

15.4 Slaughter

European legislation requires farmed fish to be stunned prior to slaughter (please refer to the chapter on Farmed animal health and welfare for further details of handling and slaughter of farmed animals). Thus, in aquaculture, fish killing methods such as using water saturated with CO_2, cutting of blood vessels (including gutting) or gills or gutting without stunning, rapid chilling or asphyxiation without prior stunning are considered highly aversive and therefore all deemed as inhumane ways of killing.

However, in aquaculture fish are typically killed using killing methods that are designed to kill fish individually. In e.g. the trawl industry, the smaller size of the species of fish captured, the larger numbers captured and the need to process the catch quickly, unstable conditions on board offshore fishing vessels (potentially reducing effectiveness of any automated stunning or killing technology) usually precludes the use of such individual fish killing techniques. In addition, prolonging the overall pre-killing (capture and sorting) process in an attempt to individually kill each fish may increase the overall stress of the captured population as a whole and compromise the quality of the seafood product.

Current slaughter practices on commercial fishing vessels vary with target species, fishing method, the vessel size and age, as well as the catch size and composition. Experts noted that generally the catch does not achieve optimal welfare standard with regards to killing and slaughtering (personal communications). For example, catches from trawl codends are typically deposited on deck for sorting or in hoppers (dry or with water), from where the fish are individually sorted, gutted and possibly bled. For larger catches, e.g. from purse seines, fish are typically transferred (potentially pumped) directly from the net into an ice slurry or chilled water, where most die from hypoxia. Where animals are removed individually from the fishing gear, e.g. pots and longlines, is it possible to use humane slaughtering methods.

Where there is a significant mark up on price for fish killed in ways that avoid a stressful death e.g. tuna, fishers have invested in using more optimal slaughtering methods (although it is debatable whether these are humane without first stunning the fish (‘Ikejime: A Humane Way to Kill Fish That Makes Them Tastier’ 2019)).

Innovation with a potential for transformative performance improvement

Keeping the catch alive: There are various improvements made to hoppers, or onboard containers of seawater, where the catch is held for sorting. The primary use of hoppers was initiated to improve the quality of retained catch, but hoppers can also improve the survival of discards under certain conditions (Norwood n.d.) and depending on species in question (Schram, and Molenaar 2018). New developments include live capture methods, where fish are caught using low-stress methods (e.g. Tiaki as described in the above section on Capture) and then held in welfare holding facilities until slaughtered. Nofima (Norwegian Institute of Food, Fisheries and Aquaculture Research) has been involved in trials with live storage of haddock, with very promising results. If haddock is caught alive and kept in tanks up to slaughter, high-quality products can be produced from the entire catch (Johnsen 2017). Previously, fish might have been kept alive for slaughter at a later time point, e.g. to manage short-term supply to market. In Norway’s coastal pelagic fleet, fishes are often transferred to cages and held there till a transfer boat comes along. If the captivity isn’t too stressful this can have benefits on fillet quality, as cumulated stress from the capture has time to subside – as well as providing a level of market supply and demand control for the fishers (personal communication). Such practices are sometimes referred to as capture-based aquaculture (Humborstad *et al.* in press), a technique not yet fully commercialised, although there have been attempts, e.g. with juvenile cod. Most established is likely the catch of juvenile tuna which are then ranched (Ellis and Kiessling 2016, 9).

Technology Readiness Level: 9; Technical risk: Low

Electrical Stunning: Research into using electrical stunning in wild-capture fisheries is still limited (Anders, Roth, *et al.* 2019) but with promising results. The electrical stunning protocol has been shown to be effective for slaughtering mackerel in a manner consistent with good welfare and without inducing quality defects. Further research is required to verify the unconscious condition (e.g. via electroencephalogram) but a few vessels (including SINTEF led research) have already used electrical stunning including stunning tables in order to address welfare issues (Digre 2012; Leschin-Hoar 2017).

Technology Readiness Level: 9; Technical risk: Low

Innovation with a potential for incremental performance improvement

Percussive: Humane slaughter methods to promote welfare in wild-capture fisheries may be easier to adapt for small-scale fishers and some are already employing them e.g. Alaskans Own[1] and Usan Salmon Fisheries[2] in Scotland. Fish are caught in traps as to not injure or damage the fish, which are manually stunned by percussive stunning, possibly followed by bleeding. The salmon is marketed on its high-quality and welfare.

Technology Readiness Level: 9; Technical risk: Low

For further information on novel stunning technologies, please refer to chapter 21 on ‘Primary processing technologies’.

Anaesthesia: There is limited research on using anaesthetics in commercial wild-capture fisheries but the use in aquaculture may pave the way for use in wild catch (albeit limited number of compounds due to strict regulations) (Matsche 2017). The potential use as a sedative in wild-capture fisheries may increase welfare but is unlikely to be acceptable due to food safety regulations.

Technology Readiness Level: 3-5; Technical risk: Moderate

15.5 Communication about welfare in wild-capture fisheries

Fish welfare in wild-capture marine fisheries has more recently been highlighted as not only an ethical consideration, but also as an enabler towards ensuring good product quality, longer shelf-live and promotion of the survival of unwanted catch, thereby directly contributing to reduced fishing mortality and promoting a more sustainable fishery (Breen *et al.* in press).

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[1] Alaskans Own: https://alaskansown.com/

[2] Usan Salmon Fisheries: http://www.usansalmon.com/

Innovation with a potential for disruptive performance improvement

Education and industry pull: Pamphlets on how to promote survival of unwanted catch and making the link between “Good welfare”, “Quality”, “Added-Value” and “Longer Shelf life”. This linking is beginning to gain wider traction amongst major suppliers of fresh seafood and as major supermarket chains start enquiring about welfare, the industry is sure to make the change (Leaflets Flyshoot Fishing 2019).

A “bottom-up” approach including key stakeholders including the fishers is likely to be more engaging. Fishers may be used to thinking they are being monitored in terms of how much they are throwing overboard (please refer to chapter 19 ‘Selectivity of gear and avoidance of unwanted catches’), and the discussion about also monitoring how this is done, how the fish are treated and gutted life etc. will need to be approached cautiously and constructively and not punitively. A promising move and a potential way to ensure good communication is the increase in Community Supported Fisheries (e.g., Skipper Otto[1]), with clear objectives to keep independent small-scale fishing alive, protecting their valuable ocean resources, and ensuring customers have direct access to wild, sustainable seafood.

The ethical concept of “good welfare” will promote confidence in consumers with respect both the quality of the product and sustainability of the fishery, which will inevitably give added value to the final product (Mood 2010). There is also a potential for welfare labels for seafood, following the trend for farmed agricultural animals (Leschin-Hoar 2017). As such, a premium market in better welfare may help bring better practice across the whole industry and placing the fishers as the conservationists promoting sustainable practices.

Technology Readiness Level: 9; Technical risk: Low

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[1] Skipper Otto: https://skipperotto.com/

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16 Ghost fishing and marine litter from fishing gear

Contents

<u>From the SIF Executive Board</u>

The method applied in this review has generated numerous examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently happening. It is recognised that there are existing innovations and research areas that are not included here, and new areas where future innovations may occur. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

16.1 Overview: ghost fishing and marine litter from fishing gear

What is the challenge in the UK?

Abandoned, lost or otherwise discarded fishing gear is a significant source of marine litter. Once lost, fishing gear has a disproportionate impact on marine wildlife compared to other forms of marine litter, primarily through the phenomenon of 'ghost fishing'. The economic cost to UK fisheries of lost landings due to ghost fishing is estimated to be between £10 million and £70 million, with further costs incurred through the value of gear and time lost.

What are the most promising innovation categories?

- Spatial or temporal zoning of fisheries to avoid gear loss and gear conflicts
- Implementation of fishing activity best practices to reduce risk of gear loss
- Ropeless fishing systems and acoustic release devices

Where are their important knowledge gaps?

- Economic and environmental costs and benefits of spatial/temporal zoning of fisheries with a focus on avoiding gear loss and gear conflicts

The increase in marine litter and its impacts on marine ecosystems has been a major concern amongst the scientific community for decades. In recent years public interest and awareness of the topic has increased significantly thanks to increased media attention on issues such as single use plastics and microplastics appearing in the marine environment. In the UK, the Blue Planet II documentary series also contributed significantly to public interest in the topic in 2017.

Whilst much of the attention has been on issues such as microplastics and general marine litter, the focus of this chapter is on the waste originating from the fisheries sector. The rationale for this focus is that, waste from the fisheries sector, particularly fishing gear litter, has a disproportionate impact on marine wildlife compared to other forms of marine litter, primarily through the phenomenon of 'ghost fishing' (Kelsey Richardson, Hardesty, and Wilcox 2019). 'Ghost fishing' can be defined as the mortality of fish and other species that takes place after all control of fishing gear is lost by a fisher (Brown and MacFadyen 2007).

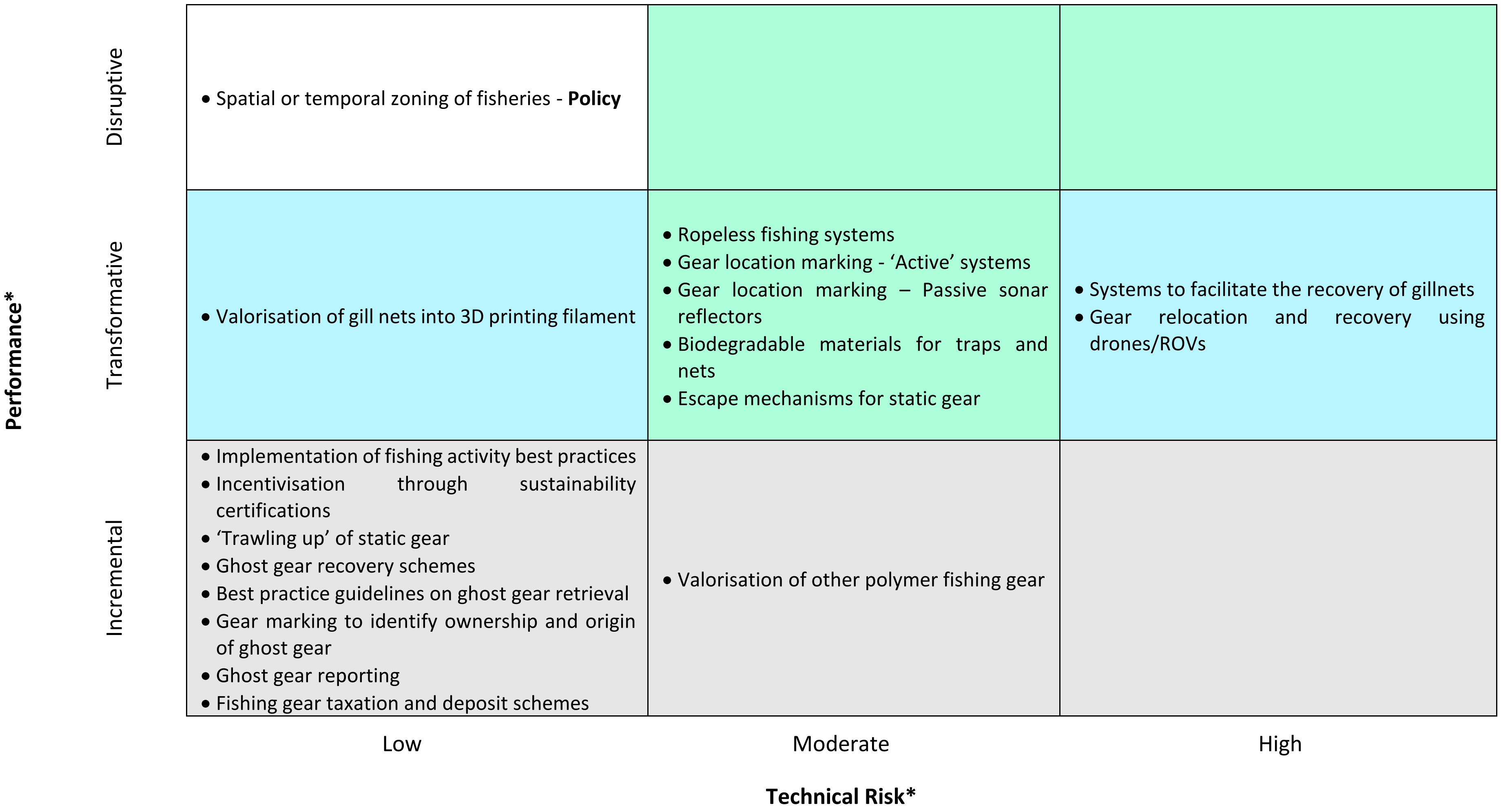
Ghost gear, otherwise known as 'Abandoned, Lost or otherwise Discarded Fishing Gear' (ALDFG) or 'derelict fishing gear' has negative impacts on fishing activities, such as potential to damage fishing gear, loss of catch or navigation at sea. In terms of the prevalence of ghost gear, researchers at CSIRO have estimated that 29% of fishing lines, along with 6% of all fishing nets and 9%of all traps are lost or discarded in the world's oceans each year (Kelsey Richardson, Hardesty, and Wilcox 2019). Bad weather, gear becoming ensnared on the seafloor, and gear interfering with other gear types are the most common reasons for commercial fishing gear being lost (Ibid.). In the UK, gear interactions with offshore oil and gas pipelines and other infrastructure are also a problem (Rouse, Hayes, and Wilding 2018). In terms of gear type, gillnets, traps and pots, fish aggregating devices (FADs), and long line fishing gear have been identified as some of the biggest contributors to ghost fishing (World Animal Protection International 2018; Huntington 2017a).

In terms of marine fauna and the marine ecosystem, ghost gear has a number of significant impacts including (FAO/UNEP 2016):

- Mortality of marine fauna that become trapped in the ghost gear.
- Disruption and damage to the benthic environment.
- Entanglement of cetaceans, pinnipeds and turtles.
- Release of microplastics and toxic compounds.
- Transportation of alien species.

Finally, in terms of the economic impact of ghost fishing, one estimate suggests that the equivalent of 1-7% of all landed catches in European and North America are lost to ghost fishing. Given the value of landings in the UK was £989 million in 2018, this equates to between £10 million and £70 million in potential landings lost to ghost fishing.

An overview of the potential performance improvement rating of recent (2015-2019) innovations for ghost fishing and marine litter from fishing gear are outlined in Figure 15-1.



Performance* \ Technical Risk*	Low	Moderate	High
Disruptive	• Spatial or temporal zoning of fisheries - **Policy**		
Transformative	• Valorisation of gill nets into 3D printing filament	• Ropeless fishing systems • Gear location marking - ‘Active’ systems • Gear location marking – Passive sonar reflectors • Biodegradable materials for traps and nets • Escape mechanisms for static gear	• Systems to facilitate the recovery of gillnets • Gear relocation and recovery using drones/ROVs
Incremental	• Implementation of fishing activity best practices • Incentivisation through sustainability certifications • ‘Trawling up’ of static gear • Ghost gear recovery schemes • Best practice guidelines on ghost gear retrieval • Gear marking to identify ownership and origin of ghost gear • Ghost gear reporting • Fishing gear taxation and deposit schemes	• Valorisation of other polymer fishing gear	

Figure 16-1: Performance and technical risk rating of innovations in ghost fishing and marine litter management.

**See section 4.4 for definitions of the performance and technical risk rating scales.*

16.2 Ghost fishing prevention

Ghost fishing prevention aims at understanding the reasons why fishing gear becomes abandoned, lost or discarded and implement measures to stop fishing gear becoming ghost gear. For fishers, lost or damaged fishing gear represents a significant financial loss and will therefore do their best to ensure that gear is not lost and make attempts to retrieve lost gear immediately when it is safe to do so. Despite these best efforts there are occasions when gear is lost and so it is important to understand why these gear loss events happen.

Richardson *et al.* (2018) has developed a fault tree based on interviews with fishers that attempts to identify the conditions and events that lead to fishing gear becoming ghost gear. Three primary types of event were identified: stowed gear is washed overboard; worn out nets are abandoned overboard; gear is lost or abandoned during the fishing operation. The first two of these events should, in theory[1], be less significant causes of ghost gear in the UK due to the health and safety policies regarding vessel design and net storage, the IMO International Convention for the Prevention of Pollution from Ships (MARPOL), which bans the dumping of waste at sea, and the EU Port waste reception facilities Directive, which requires Member States to ensure that every port provides waste reception facilities where fishers can safely dispose of waste[2], including fishing gear. The focus of this chapter is therefore on prevention. In the case of the UK of gear loss during the fishing operation.

Causes of ghost gear mentioned in the scientific literature include:

- Conflicts with other gear types (Yildiz and Karakulak 2016; K. Richardson *et al.* 2018; Dagtekin *et al.* 2019; Jawad 2016).
- Conflicts with cargo vessels (Yildiz and Karakulak 2016; Jawad 2016).
- 'Snagging of nets'/bottom structure hindrances (Yildiz and Karakulak 2016; K. Richardson *et al.* 2018; Jawad 2016).

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[1] In practice, the enforcement of fisheries waste policies is challenging and there is evidence to suggest that there are higher quantities of fisheries-related litter in areas arounds ports, suggesting that safe waste disposal is still an issue for UK fisheries (Unger and Harrison 2016).

[2] Again, in practice many small ports across the UK and EU do not have sufficient space to provide waste reception facilities and the cost of logistics in more remote locations can be a barrier to safe disposal of fisheries waste.

- Bad weather conditions (Yildiz and Karakulak 2016; K. Richardson *et al.* 2018; Dagtekin *et al.* 2019; Jawad 2016).

A focus on prevention of gear loss is generally considered preferable to either mitigation or remediation as it eliminates the risk of ecosystem impacts and is likely to be more cost-effective.

Innovations with a potential for disruptive performance improvement

Spatial or temporal zoning of fisheries to avoid gear loss and gear conflicts: The use of spatial and or temporal zoning has been identified as a potential management approach to reduce gear conflict (Goodman *et al.* 2019; FAO/UNEP 2016; Huntington 2017a; Gilman 2015). One widely implemented form of spatial zoning is the designation of areas in which certain types of gear are not allowed to be used. Gillman (2015) identified 10 inter-governmental organisations that had implemented this type of spatial zoning, most with a focus on gillnets and trammel nets.

Other forms of zoning include the separation of static and mobile gear types to avoid gear conflicts and restrictions on the use of certain types of gear based on the risk of gear loss due to submerged features (e.g. reefs or wrecks) or marine traffic. This model has been successfully applied in the Inshore Potting Agreement in South-West England. It comprises an area of 500 km^2 in which there are dedicated zones for static gear (mainly crab pots), and seasonal zones for static gear, which can also be fished by towed gear in periods when it is free from static gear (Blyth *et al.* 2002). This type of voluntary agreement, developed locally by discussion between fishers, has proven successful in the UK.

There may be opportunities to build on this success to further develop the application of zoning principles towards a risk-based approach that would take into account the risk of gear loss due to gear conflict, submerged features, marine traffic etc. Such an approach could be informed by the increasing dataset concerning the location and gear types in gear loss events, as well as geo-spatial data on fishing activities and gear type that it is now possible to collect through Vessel Monitoring System (VMS) and Automatic Identification System (AIS) data (Lee, South, and Jennings 2010; Egekvist, Mortensen, and Larsen 2017).

Interactions between fishing gear and other industries, such as oil and gas infrastructure and offshore wind farms, are being managed through a variety of measures in the UK, including the use of Fisheries Liaison Officers and the development of the FishSAFE unit[1] – a dedicated plotter that helps skippers to identify and avoid oil and gas infrastructure.

Zoning to avoid conflicts between static and mobile gear types appears to be particularly relevant to the UK fisheries sector given that shellfish and demersal species represent 37% and 36% of UK landings value (Marine Management Organisation 2019). However, there appears to be a lack of data concerning the economic and environmental costs and benefits of implementing zoning systems to reduce gear conflict. This represents a significant knowledge gap and will contribute to the overall risk of implementing this measure as policy-makers and fishers will need a full understanding of the potential costs and benefits before committing to this type of approach.

Technology Readiness Level: 9; Technical risk: Low

Innovations with a potential for transformative performance improvement

Ropeless fishing systems and acoustic release devices: Static gear such as crab and lobster traps normally feature an endline, which connects the final trap in a trawl to the surface, where a buoy marks the location of the gear. These endlines can be hundreds of metres long and cetacean entanglements with these lines are a major problem in many fisheries. The extent of the problem in UK waters is not clear, although significant cetacean entanglement and interaction with fishing gear off the coast of Ireland has been recorded (Lusher *et al.* 2018). The endlines can also be severed by passing vessels or storm action, resulting in the traps being lost and contributing to ghost fishing.

‘Ropeless’ fishing systems have been developed to address these issues by avoiding the need for endlines to be deployed until the fisher is ready to collect the gear. The system works by packing the endline and marker buoy into a bag, which is sunk to the seabed with the gear. The marker buoy and endline are held in the bag by an acoustic release device, meaning that the column of water above the trawl is free from any lines during the fishing operation.

When it is time for the fisher to retrieve the gear, they use GPS to find the approximate location of the gear and then use a transponder to emit an acoustic signal. When this signal is received by the acoustic release device, it triggers the device to release a mechanism, which is allows

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[1] FishSAFE unit: https://www.ukfltc.com/fish-safe/

the marker buoy and endline to rise to the surface, where it can be spotted and the gear retrieved.

Commercial systems are available from a variety of commercial suppliers including the ARC-1XD (Desert Star Systems LLC) and the 5112 Ropeless Fishing System (EdgeTech). The ARC-1XD system is claimed to have a 99% release effectiveness up to a maximum operating depth of 300m. The systems are compatible with standard fishing gear.

There are a number of barriers to the implementation of ropeless fishing systems. In many static gear fisheries, including the EU, USA and Canada, it is illegal to deploy traps without an endline marker buoy, although trials of ropeless systems have begun in several N. American static gear fisheries in an effort to reduce cetacean entanglements.

A key technical challenge is how to fulfil the location marking function when using a ropeless system. A number of stakeholder need to know the location of deployed fishing gear, including the fisher (to help relocate the gear when it is due to be retrieved), for other fishers and vessels (to avoid gear conflicts and navigation hazards) and enforcement bodies (to check the legality of fishing activities). Whilst the fisher can record the location of the deployed gear using GPS and their plotter system, the gear might be moved by storm action between deployment and retrieval, making it difficult for the fisher to relocate their gear. Fishers are also very reluctant to share the location of their deployed gear as it might result in gear/catch theft or alert other fishers to their favourite fishing spots. To overcome this issue, a combination of virtual gear marking and acoustic gear marking are being developed by commercial suppliers. The virtual gear marking uses GPS and a mobile phone application to mark the location of gear on a map. Crucially, the location of gear is only visible to users within a certain radius of its location (which might be set at 500m for example). This enables other vessels to avoid the gear whilst preventing the gear location from being broadcast too widely. Acoustic marking involves the use of small transponders, attached to the first and last traps in a trawl, which can be pinged by the control unit on board the vessel. The response signal from the transponder helps to give the range to the vessel to help relocate it.

No formal studies were identified in the review regarding the effectiveness of ropeless fishing systems in reducing ghost fishing or entanglement incidents, although researchers have called for the technology to be implemented urgently in fisheries with high rates of cetacean entanglements (Baumgartner, Werner, and Moore 2019). In terms of fishing performance, early results from trials being conducted by the Canadian Wildlife Federation and NOAA indicate a 100% success rate in recovery of traps and trawls using ropeless systems. The affordability and practicality of these systems may be a problem for the types of small open vessel used by UK inshore trap fishers.

Technology Readiness Level: 9; Technical risk: Moderate

Gear location marking - 'Active' systems: A number of technologies have been developed that allow the location of gear to be identified or calculated through the use of 'active' systems, which can transmit a signal over large distances to a receiver. A comprehensive overview of the these technologies has been produced by FAO (2016) and He and Suuronen (2018). Examples of active gear location marking systems include active radio-frequency identification (RFID) tags, AIS transponders and acoustic pinger/transponder systems (He and Suuronen 2018).

In tests by BIM in Ireland, a range of commercial, off the shelf active RFID technology was used to mark the location of buoys. A detection range of up to 240m was reported, although this was reduced in adverse weather conditions (BIM, 2007 cited in He and Suuronen, 2018).

Acoustic pinger/transponder systems have also shown promise. In these systems, a hydrophone is dropped in the water from the vessel which emits a coded ping. Any transponders within range will then emit a return signal. The time delay between the initial ping and the response enables the distance to the transponder to be calculated. Canadian company, Notus have commercialised this technology with the Gearfinder 700[1]. It has previously been used for the relocation of scientific equipment and can operate up to depths of 700 fathoms (1280m) and has a horizontal range of up to 2 NM.

The Nettag project is trying to make pinger/transponder hardware more affordable so that each piece of fishing equipment can be tagged with a transponder. The project is testing the use of low-cost transponders, which should cost less than £50 per unit to manufacture at commercial scale. The prototype units are the size of a matchbox and have a range of 3km. When transmitting data, the transponder produces a 1-Watt signal, which is designed to be sufficiently low power to minimise the negative impacts on the fauna in the area. The aim of the project is to test if the transponders. combined with the simple ROVs mentioned above, can enable fishers to recover lost gear independently, quickly and efficiently.

Technology Readiness Level: 9; Technical risk: Moderate

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[1] Gearfinder 700: https://www.notus.ca/gearfinder-700/

Gear location marking – passive sonar reflectors: Passive sonar reflectors support gear location marking by reflecting active sonar signals. The SonarBell produced by Subsea Asset Location Technologies Inc. (now in liquidation) is a spherical marker that utilise different materials in the shell and the core to generate constructive interference. This effectively amplifies the sonar ping and re-emits it, with a significantly stronger signal than would be possible with a solid sphere reflector. The technology was originally developed for defence-related applications and no field trials have been conducted for the application of this technology for fishing gear location marking. One potential risk is that biofouling could impact the effectiveness of the marker over time, although presumably this could be mitigated through the implementation of a cleaning regime after each retrieval.

Technology Readiness Level: 6-8; Technical risk: Moderate

Innovations with a potential for incremental performance improvement

Implementation of fishing activity best practices to reduce risk of gear loss: A wide variety of fishing best practices have been identified to reduce the risk of fishing gear becoming lost. A comprehensive summary of best practices has been compiled as part of the best practice framework produced by the Global Ghost Gear Initiative (Huntington 2017a). Suggested best practices include:

- Avoidance of high-risk areas (risk of snagging on reefs or wrecks) and situations (high seas, poor visibility).
- The use of well-maintained and set fishing gear.
- Minimising the amount of gear set.
- Adjust fishing methods to prevailing conditions to reduce the risk of gear loss eg shorter soak time, etc.
- Training and awareness-building of crew in good practice and responsible fishing.
- The clear marking and identification of fishing gear and its main components.
- The responsible disposal of redundant fishing gear and other potential marine litter.

The majority of UK fishers already implement many of these best practices, although there are still likely to be opportunities to increase knowledge and implementation of these best practices.

Technology Readiness Level: 9; Technical risk: Low

Incentivisation through sustainability certifications: Obtaining a sustainability certification for a fishery can require many years of effort and investment in data collection, gear modification/upgrades, training of fishers, and changes to fishing practices. Fishers, keen to obtain or maintain the certification of their fishery, take seriously any new requirements imposed by the certification schemes.

The MSC sustainability label has begun to consider ghost fishing impacts within the fisheries assessment process. In the Marine Stewardship Council (MSC) certified Normandy and Jersey lobster fisheries, all pots are tagged with boat registration and year. Fishers must report lost pots and only a limited number of replacement tags are available. This system motivates fishers not to lose their pots (Marine Stewardship Council 2018)

Ghost fishing mitigation measures are also being encouraged through the MSC label. When the Alaska Pacific cod fisheries became MSC certified, they were required to monitor gear loss to maintain their certification and have made technical modifications to their gear such as the introduction of biodegradable escape panels and escape rings.

Whilst the direct financial cost of lost gear and the potential decline of the fishery are likely to be the primary motivating factors for fishers to reduce ghost fishing, sustainability certification schemes are likely to be an influential partner in fisheries that hold or are seeking such certifications.

Technology Readiness Level: 9; Technical risk: Low

‘Trawling up’ of static gear: In some crab and lobster fisheries it is common practice to deploy single traps, where each trap has its own buoy line. This leads to a proliferation of vertical lines running through the water column, increasing the risk of entanglements and loss of gear due to accidental severing of the buoy line. ‘Trawling up’ involves connecting a two or more traps to form a ‘trawl’ with a single endline per trawl, which reduces the total number of endlines in the fishery and thereby reduces risk of gear being lost due to an endline being severed. Another benefit of this approach is that it also reduces the risk of entanglement for cetaceans – which is the primary driver for implementing this measure in some fisheries.

Technology Readiness Level: 9; Technical risk: Low

16.3 Ghost gear mitigation

Ghost gear mitigation are measures taken to reduce the fishing efficiency of ghost gear. In static gear fisheries, the natural fibre materials that were traditionally used in the construction of lobster and crab traps would naturally biodegrade over time if lost. However, the use of modern high-performance polymers means that such traps can now retain their integrity and fishing efficiency for extended periods e.g. several years. This problem can be exacerbated by the 'automated re-baiting' of these traps, whereby moribund and decomposing organisms caught in the derelict gear attract scavengers. Feeding by scavengers, in turn, releases odours that augment attraction to the ghost gear. Some of these scavengers become caught and eventually decompose, providing a continual source of 'bait' until the ghost gear eventually loses its fishing efficiency (FAO/UNEP 2016). Similar issues exist for gillnets whilst mobile gear has a somewhat reduced potential for ghost fishing due to the smaller mesh size and that fact that they do not retain their optimum geometry or fishing efficiency once lost to the seabed (Huntington 2017a).

Whilst a number of mitigation measures are being investigated and developed including biodegradable materials and escape panels/mechanisms, it would seem that there are potentially more aspects of gear design that could be investigated. For example, designing the gear such that it collapses after a short period unattended, minimising its size and fishing effectiveness (Wilcox and Hardesty 2016).

Innovations with a potential for disruptive performance improvement

Biodegradable materials: The use of biodegradable materials is being investigated for use in both static and mobile fishing gear. Within static gear, such as lobster and crab traps, escape hatches made of biodegradable materials have been tested

Kim et al (2016) have tested the use of a blend of 82% polybutylene succinate (PBS) and 18% polybutylene adipate-co-terephthalate (PBAT) as a biodegradable material for gillnet use in a yellow croaker fishery off the coast of South Korea. Mechanical performance of the material was similar to the current Nylon monofilament material and no significant difference in fishing performance was observed in sea trials. The material began to show significant signs of degradation after two years in seawater. However, other commentators have noted that 'effectiveness' of ghost gill nets decreases rapidly, with an 80% reduction in performance within 1-4 weeks of loss reported (Wilcox and Hardesty 2016).

The fishing efficiency of biodegradable gillnets has also been questioned within some studies. A study of Norwegian cod and saithe found that 27-50% fewer cod and 23-41% fewer saithe were caught over two seasons (Grimaldo *et al.* 2019). This level of performance would represent a major barrier to adoption of biodegradable gear for fishers who will almost certainly not be willing to compromise fishing efficiency in favour of potential ghost fishing reduction benefits.

As well as gillnets, biodegradable materials are also being tested for static gear types. Kim et al (2014) have tested the use of PBS/PBAT biodegradable materials for use in conger eel traps. Although the fishing performance was similar to conventional PE traps, some differences in the mechanical performance of the biodegradable traps suggested their performance might deteriorate over time.

Polyhydroxyalkanoates (PHAs) have been identified as a promising class of material for ghost gear mitigation use as the biodegradation process is performed by microbes commonly found in the marine environment. Furthermore, the microbes feeding on the PHA exhibit inhibited or delayed growth when exposed to UV meaning that the rate of degradation is very slow if retrieved regularly, where they are exposed to daylight, but will accelerate if the gear becomes lost (Huntington 2017a). A recent meta-study on the modelling of biodegradation of single use plastic items constructed from PHA materials found that the average rate of biodegradation of PHA in the marine environment is 0.04–0.09mg per day per cm^2 (Dilkes-Hoffman *et al.* 2019). Bilkovic et al (2012) performed field trials using PHA-based escape panels built into traps. Over two seasons in a blue crab fishery in the USA, legal catches were comparable in terms of abundance, biomass and size between the traps with biodegradable escape panels and standard traps. However, further field studies are required to validate the performance of PHA-based fishing gear in a wider range of fisheries and gear types.

A further consideration with respect to biodegradable fishing gear is the useful lifetime of the gear. If such gear offers a shorter useful lifetime than the current norms, the cost of more replacement is likely to be a significant financial barrier to adoption, particularly for small-scale coastal fisheries with limited financial capital.

Technology Readiness Level: 6-8; Technical risk: Moderate

Escape mechanisms for static gear: Due to its robust nature, static gear, such as crab and lobster traps, can continue ghost fishing for many years when lost and have therefore been identified as a high priority ghost fishing mitigation efforts (Huntington 2017b; World Animal Protection International 2018).

Trap designs have been modified over the years to reduce the level of bycatch (such as sub-legal size crabs/lobsters and non-target species), through the introduction of escape rings for example (Stearns *et al.* 2017). Whilst these measures may go some way to reduce ghost fishing, the traps will still be effective against the species and size of specimen targeted.

Rot cords, which are legally required in some static gear fisheries in N. America may not be effective as although the trap lid gapes open once the cord rots through, crabs struggle to escape through the top of the trap (Bilkovic *et al.* 2012). Other systems that rely on hinge mechanisms are susceptible to biofouling and may not be effective either (Bilkovic *et al.* 2012).

A patent has been filed in South Korea which uses a metallic element that corrodes and releases an elasticated mechanism to open the ends panels of a cylindrical fish trap (J. H. Lee *et al.* 2018). Whilst metal corrosion may or may not be a more reliable degradation mechanism than biodegradation of polymers or natural fibres, the release mechanism may still be susceptible to biofouling.

Technology Readiness Level: 6-8; Technical risk: Moderate

Systems to facilitate the recovery of gillnets: A patent filed in China describes a system of floats and self-disengaging weights (Zhang *et al.* 2017). If several of the floats are damaged the net will begin to sink. At a certain depth, a mechanical system ensures that the weights are released, allowing the net to float back to the surface. The inventors claim that this can help to reduce damage to the benthic environment and aid the recovery of the net.

Technology Readiness Level: 3-5; Technical risk: High

16.4 Ghost gear relocation, identification and recovery

European Council Regulation 1224/2009 requires that fishing vessels carry equipment for the retrieval of lost fishing gear and that when a vessel does lose control of their gear, they make an immediate attempt to recover the gear[1]. If they fail, they are required to provide details of the type of gear lost and its location to its flag Member State. However, there are suggestions that the enforcement of this regulation currently very limited (Dimitropoulos 2019).

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[1] Unless the gear is snagged on a cable or pipeline, in which case it must be sacrificed.

Advances in gear relocation and recovery technology should help to reduce the time and cost incurred in recovering lost gear. However, currently fishers are sometimes reluctant to attempt gear recovery, even when it is safe to do so, as the time and effort required is often higher than the value of the fishing gear, although this varies with the scale of the fishing operation and the type of gear (Huntington 2017a).

Innovations with a potential for transformative performance improvement

Gear relocation and recovery using drones/ROVs: As part of ghost gear recovery programmes, the use of drones and Remotely Operated Vehicles (ROVs) is being developed to assist the location and recovery of gear. Aerial drones can be used to quickly survey large areas for ghost gear, but may be limited to shallow water fisheries, such as river estuaries (Bloom *et al.* 2019). For other types of fishery, underwater ROVs are being developed. Deep Trekker have developed the DTG3 ROV[1], which they claim can be used for ghost gear identification and recovery. The unit feature high definition camera suitable for low light conditions and can be fitted with a grabber arm. The unit is also high portable, weighing just 8.5kg, and has a maximum operating depth of 200m. Prices start at $6,249 for the basic ROV with a 50m tether cable. Whilst this might be prohibitively expensive for small individual fishers to purchase, it might be possible for fishers co-operatives to invest in such technology so that the cost and equipment can be shared amongst a larger group of vessels.

To date, there does not appear to have been any scientific studies conducted into the feasibility or effectiveness of using ROVs for ghost gear recovery. This knowledge gap is now being addressed by the Nettag project[2], which is investigating the potential for simple ROVs to be used by fishers for immediate gear retrieval when gear is lost.

Technology Readiness Level: 6-8; Technical risk: High

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[1] DTG3 ROV: https://www.deeptrekker.com/products/underwater-rov/dtg3

[2] Nettag project: http://net-tag.eu/

Innovations with a potential for incremental performance improvement

Ghost gear recovery schemes: There are a variety of ghost gear recovery schemes in operation around the globe. Fishing for Litter (FFL)[1] is a vessel based programme where litter encountered at sea is voluntary retrieved from the ocean and returned for appropriate disposal. In the UK, there are projects in Scotland and South-West England, involving 31 harbours and 380 vessels, which have collected 1,632 tonnes of marine litter to date. There are further projects affiliated with FFL in Yorkshire, Northern Ireland and the Republic of Ireland.

Other global schemes include the Global Ghost Gear Initiative[2] and Dive Against Debris[3], both of which include a surveying and data reporting element as well as recovery of ghost gear.

Whilst many ghost gear recovery schemes rely on volunteers or the goodwill of fishers to participate in the scheme, the cost of running formal retrieval schemes can be high (NOAA Marine Debris Program 2015). Furthermore, the logistics and cost of final disposal of the collected waste can be challenging. This suggests it is important to implement ghost gear prevention measures alongside existing ghost gear retrieval projects.

Technology Readiness Level: 9; Technical risk: Low

Best practice guidelines on ghost gear retrieval: The Bay of Fundy fishers association conducted a major ghost gear recovery operation between 2008 and 2015. The scheme recovered 1000 lobster traps, almost 24km of rope, 692m of cable and 76 buoys, amongst other litter. As part of this programme, a best practice manual on ghost gear retrieval was produced and circulated to local fishers. The ghost gear retrieval manual is available online[4].

In the EU, the MARELITT project has produced a toolkit that aims to support the entire process of establishing a ghost gear retrieval programme, from planning and seeking funding through to technical details of retrieval operations. The toolkit is available online[5].

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[1] Fishing for Litter: http://www.fishingforlitter.org.uk/

[2] Global Ghost Gear Initiative: https://www.ghostgear.org/

[3] Dive Against Debris: https://www.projectaware.org/diveagainstdebris

[4] Ghost gear retrieval manual: https://www.fundynorth.org/ghost-gear.

[5] MARELITT toolkit: https://www.marelitt.eu/files/14259815070.pdf

Technology Readiness Level: 9; Technical risk: Low

Gear marking to identify ownership and origin of ghost gear: Gear marking to identify ownership and origin, does not reduce the incidences of ghost fishing in itself but it can be useful in addressing ghost fishing from several perspectives. First, it can support enforcement of capacity management and ghost fishing prevention policies by enabling authorities to trace the owner of ghost gear.

Secondly, it can be used to build datasets about when and where fishing gear is being lost. These datasets can then be analysed to identify fisheries or gear types that have a high probability of gear loss and can therefore be considered high risk from a ghost fishing perspective. Policy measures can then be implemented to manage these high-risk fisheries or gear types in order to reduce ghost fishing.

FAO’s Code of Conduct for Responsible Fisheries requires fishing gear to be marked and have produced details guidelines on the marking of fishing gear, including a risk-based approach to determining when gear marking should be mandated (FAO 2019).

A variety of technologies have been tested or implemented to help identify the origin and ownership of gear. These include colour coding of buoy lines, coded wire tags, and RFID tags. Passive RFID tags, for instance, are used in Scottish creel and pot fisheries for crabs and lobsters (He and Suuronen 2018). They have a read range of less than 3m but are significantly lower in cost than active RFID systems.

Coded wire tags are minute, magnetised steel tags that have a unique code printed on them that can be read under a microscope. Field tests conducted in 2009 found that implanting the tags in braided twines was the most successful approach, leading to 90% of tags being readable after a season of fishing (FAO 2016). However, there has been limited further testing since the 2009 field trials, perhaps due to the cost required to ensure satisfactory identification rates (He and Suuronen 2018).

Technology Readiness Level: 9; Technical risk: Low

Ghost gear reporting: The Global Ghost Gear Initiative have developed a mobile phone app that can be used to report ghost gear found or recovered, including time, location and details of the type of gear. There is also a freely accessible data portal[1] which enables researchers and industry to identify regions with increased instances of ghost gear.

Note that whilst ghost gear reporting initiatives do not directly contribute to reduction of ghost fishing, when combined with gear marking to identify ownership and origin of ghost gear, such measures can help to understand when and where fishing gear is lost and so inform policy measures.

Technology Readiness Level: 9; Technical risk: Low

16.5 Fishing gear recycling and valorisation

Currently, the majority of worn out fishing gear ends up in landfill, with only 1.5% of fishing gear being recycled in the EU (European Commission 2018). Valorisation of fishing gear is made more complicated by the fact that the polymer materials involved are likely to have degraded during use due to the harsh marine environment in which they are used. Furthermore, materials are often contaminated with biofouling, which must be removed in order to ensure the performance of the recycled. Recycling and valorisation of fishing gear is therefore complicated and has yet to become a mainstream method for managing worn out fishing gear. Whilst priority should be given to measures that prevent or mitigate ghost fishing, suitable waste valorisation technologies are required to deal with recovered ghost gear as well as worn out fishing gear.

Innovations with a potential for transformative performance improvement

Valorisation of gill nets into 3D printing filament: Fishy Filaments have commercialised a proprietary technology for the reprocessing of fishing nets into engineering grade filament for 3D printing. The technology works with monofilament trawl nets made from Nylon 6. When suitable nets are disposed of by fishers through the existing waste reception facilities within the port, Fishy Filaments collect the nets and take them to their reprocessing facility, very close to the port. A proprietary process is used to remove the biofouling, before they are ground and extruded into filament form. The filament can be used in a wide range of mid-range 3D printers, including Fused Deposition Modelling (FDM) printers. Whereas the disposal

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[1] Global Ghost Gear Initiative data portal: https://globalghostgearportal.net/

and management of discarded nets typically results in a cost to the local economy of £0.50 per kg, the Fishy Filaments generates added value of around £80 per kg. The reprocessing facility has been designed to fit in a standard shipping container and can therefore be located within, or very close to, a port facility, thereby minimising transportation impacts and cost.

Whilst the Fishy Filaments example represents a relatively small-scale operation for one specific gear type, the concept of converting worn out gear into a high-value product through scalable facilities located close to ports has the potential to have a transformative impact on the ghost fishing issue as it demonstrates the added value that can be achieved with focused innovation activities. It also helps to build the case for investment in the infrastructure and systems required to process worn out gear, making it simple for fishers to dispose of their nets in a sustainable manner rather than them ending up as litter in the marine environment. Achieving this potential within the limitations of the infrastructure and space available at small and medium-sized ports represents a significant innovation challenge.

Technology Readiness Level: 9, Technical risk: Low

Innovations with a potential for incremental performance improvement

Valorisation of other polymer fishing gear: In Europe there just two facilities that are able to recycle waste fishing gear at a significant scale. Aquafil's facility in Slovenia is able to recycle Nylon waste from fishing gear, along with other Nylon waste streams such as carpet material into yarn and textiles under the ECONYL® brand. Waste fishing gear is collected through partnerships with organisations and projects involved in ghost gear retrieval, such as the Healthy Seas programme[1]. Based on a life cycle assessment, Aquafil claim that the ECONYL product reduces the global warming impact of nylon production by around 80%[2].

Plastix, based in Denmark, produce recycled HDPE and PPC plastics made using input from waste fishing nets and sold under the brand name 'OceanIX'. Plastix have participated in small-scale projects funded by World Animal Protection in which around 50 tonnes of ghost gear was collected from the waters around several Scottish ports and was sent to the Plastix facility in Denmark for recycling (World Animal Protection International 2018).

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[1] Healthy Seas Programme: https://healthyseas.org/about-us/

[2] Life Cycle Assessment of ECONYL: https://www.econyl.com/the-process/

Many examples of the types of finished products that make use of materials produced from fishing gear waste can be found on the Circular Ocean project webpage[1]. A key challenge for the UK is that there are currently no large-scale facilities for waste fishing gear recycling. Shipment of waste gear to the existing facilities in Denmark or Slovenia is unlikely to be economically sustainable in the long term due to the transportation costs. There may therefore be an opportunity for small-scale facilities that can be located close to port facilities if they are able to reprocess a wide variety of fishing gear types.

Technology Readiness Level: 9, Technical risk: Moderate

Fishing gear taxation and deposit schemes: A number of financial measures have been identified as means to encourage proper disposal and valorisation of used fishing gear. In Iceland, fishers are required to pay a tax of between 11 and 30 Íkr (7-30 pence) per kg of fishing gear purchased. This is implemented as part of the Act on Processing Fees and the Recycling Fund (Úrvinnslusjóður 2017), which applies to a wide range of products beyond fishing gear. The taxes collected through this regulation are used to help fund recycling activities and the development of recycling infrastructure.

One concern that has been raised about financial measures is that they can inadvertently lead to increased illegal dumping of waste, for instance, if there is a fee to pay at the point of disposal. Deposit refund systems have been proposed as a financial measure that overcomes this type of behaviour as the deposit is paid at the point of purchase and is refunded only if the waste is returned to an appropriate waste disposal facility (Sherrington *et al.* 2016).

Technology Readiness Level: 9, Technical risk: Low

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[1] Circular Ocean: http://www.circularocean.eu/opportunities

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17 Habitat, environment and ecosystem impact

Contents

From the SIF Executive Board

The method applied in this review has generated numerous examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently happening. It is recognised that there are existing innovations and research areas that are not included here, and new areas where future innovations may occur. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

17.1 Overview: habitat, environment and ecosystem impact

What is the challenge in the UK?

The main challenges with regards to reducing habitat, environmental and ecosystem impacts from marine and diadromous fisheries are not new. The overarching challenge in the UK is understanding and agreeing on how to best minimise habitat damage from dredging, trawling and collateral impact of bycatch. Key aspects include a need for data e.g. the distribution of essential fish habitats such as cod nursery ground, of sensitive habitat and an understanding of the true footprint of damaging fisheries. Data-limited fisheries present a challenge as they only provide a limited basis for management decisions.

There is a focus on challenges around data gathering and ways to monitor and assess impact in a cost effective and time efficient manner. Also, challenges around engaging stakeholders in management decisions, particularly to address issues around stakeholder awareness, compliance with regulations and management and the use of stakeholder's information in the decision process.

What are the most promising innovation categories?

- Methodologies that allow for (big) data collection, processing and analysis
- Whole system modelling incl. marine protected areas
- Improved acoustic instruments for identification of catch and size (for fishing operations and scientific surveys to assess state of the stock)
- Better tools to assess impact of e.g. bottom trawling on the structure and functioning of benthic ecosystems

Where are their important knowledge gaps?

- Data collection, verification, processing and use
- Data on impacts of fisheries on open-ocean ecosystems of fisheries on sedimentary habitats in offshore waters

Many commercial fishing activities, especially in coastal areas, are known to lead to changes in the structure of marine habitats and impacting diversity, composition, biomass and productivity of the associated biota. The direct effects of fishing vary according to the gears used, target species, the intensity of the fisheries and the area where fishing takes place. The relative impact of marine fisheries on habitat, environment and ecosystems can be seen as determined by the magnitude of the disturbance. The direct effects of fishing including the effect on the population of the target species, bycatch species and on the infaunal and epifaunal communities (depending on fishing method).

As summarised by Sinclair *et al.* fishing can affect (i) Predator-prey relationships, which can lead to shifts in community structure that do not revert to the original condition even after the cessation of fishing pressure (known as alternative stable states). (ii) Fishing can alter the population size and body-size composition of species leading to a fauna composed of primarily small individual organisms (this can include the whole spectrum of organisms, from worms to whales). (iii) Fishing can lead to genetic selection for different body and reproductive traits and can extirpate distinct local stocks. (iv) Fishing can remove or reduce populations of non-target species (e.g. cetaceans, birds, reptiles and elasmobranch fishes) as a result of bycatches or ghost fishing. (v) Fishing can reduce habitat complexity and damage or remove seabed (benthic) communities (Sinclair and Valdimarsson 2003).

In sheltered areas where complex habitats develop at shallow depths, e.g. warm-water coral reefs, the direct effects of fishing may be marked and have profound effects on the ability of the habitat to sustain fish production. The long-term direct effects of fishing on reefs can be determined by the rate at which coral can regrow and offset any damage caused (personal communication). In some areas, including the tropics, small-scale and artisanal fishers may deploy very harmful techniques, such as drive-netting, pull-seining, poison and explosive fishing. However, the overall impact may still be relatively localised in comparison with those attributable to commercial fishing boats using towed gears.

Bycatch and discards (as defined in the chapter 19 ‘Selectivity of gear and avoidance of unwanted catches’) are the key focus areas in research on the impact of fisheries. A recent summary of globally reconstructed fisheries catches categorised by major gear categories for 1950-2014 showed that two industrial gear types, bottom trawling and purse seining, jointly account for over 53% of all catches, while bottom trawling alone dominated discarded fish catches (Cashion *et al.* 2018). Also, the impacts of pelagic trawling on e.g. common dolphins is being considered by the European Commission (Council of the European Union 2020).

In the small-scale sector, over 60% of catches were caught by gillnets, various line gear, and encircling nets. Small-scale fisheries were found to contribute most to the value of landed catches (primarily shellfish), while industrial bottom trawlers were responsible for discarding large amounts of potentially valuable catches. Catches by purse seines fluctuated over time, mainly due to variability of the underlying species, e.g., anchovies and sardines. The distribution and scale of use of different fishing gears, combined with knowledge of their divergent environmental impacts should allow a new wave of research into the global impacts of fisheries (Cashion *et al.* 2018).

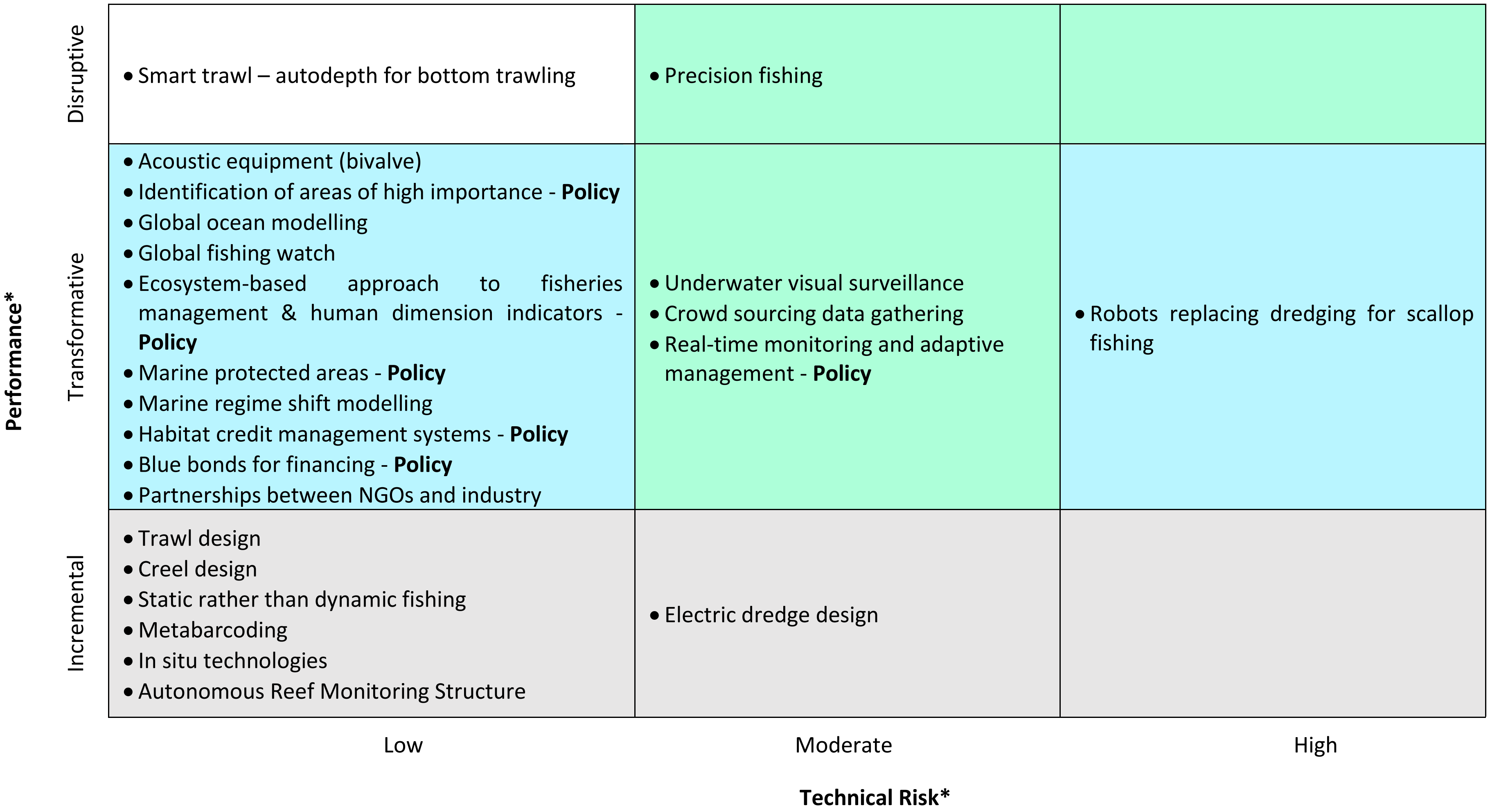
There are also numerous indirect effects of fishing such as the potential to interrupt trophic cascades. A well-documented example of top-down control in marine ecosystems is the effect of sea urchin populations and their over-grazing on reef and kelp habitats. Sea urchins, are in most places not an important target species but in instances where fishing has reduced the biomass of herbivorous, the urchins begin to dominate the grazing community. Also, once an urchin-dominated community is established it is difficult for herbivorous fishes to re-establish themselves (Schiel and Foster 2015; McClanahan and Kurtis 1991).

When a few species of predator, all of which may be fished, selectively feed upon one or two gracing organisms such as urchins and starfish, which dominate the herbivore community, those predator species have an unusual role as keystone species in a marine system.

There is a plethora of studies listing the different impacts that marine fisheries have on different habitats, environments and ecosystems. By damaging the seabed, fisheries can reduce the abundance and diversity of fauna in the marine environment. This loss also has a wider effect, including on commercial fish stocks, by reducing the supply of important prey species, the suitability of habitats for spawning etc, and by increasing predation risk for juvenile fish in those areas thereby undermining recruitment into the stock.

Overall, it is understood that fishing has a serious impact on the marine environment, habitats and the broader ecosystem and that some fisheries, such as scallop dredging and bottom trawling, are particularly damaging and impactful. However, the interplay between complex parts of the marine ecosystem remain largely unknown and poorly understood. This explains why most focus is in this area of research is still on assessing and monitoring to record various impacts and on developing methodologies. Monitoring helps ascertain the level of impact, where efforts to reduce this should be focused and also to determine which management measures are effective and which are not. The primary scope of this chapter is focused on novel innovations mitigating known / established impacts of fisheries, with a focus on fisheries relevant to the UK.

An overview of the potential performance improvement rating of recent innovations (2015-2019) in mitigating impact of fisheries on habitats, environments and ecosystems are outlined in Figure 17-1.



Performance*	Low	Moderate	High
Disruptive	• Smart trawl – autodepth for bottom trawling	• Precision fishing	
Transformative	• Acoustic equipment (bivalve) • Identification of areas of high importance - **Policy** • Global ocean modelling • Global fishing watch • Ecosystem-based approach to fisheries management & human dimension indicators - **Policy** • Marine protected areas - **Policy** • Marine regime shift modelling • Habitat credit management systems - **Policy** • Blue bonds for financing - **Policy** • Partnerships between NGOs and industry	• Underwater visual surveillance • Crowd sourcing data gathering • Real-time monitoring and adaptive management - **Policy**	• Robots replacing dredging for scallop fishing
Incremental	• Trawl design • Creel design • Static rather than dynamic fishing • Metabarcoding • In situ technologies • Autonomous Reef Monitoring Structure	• Electric dredge design	

Technical Risk*

Figure 17-1: Performance and technical risk rating of innovations in habitat, environment and ecosystem impact.

**See section 4.4 for definitions of the performance and technical risk rating scales.*

17.2 Pelagic and diadromous fisheries impact

Pelagic fisheries are those which aim to catch fish or shellfish when they are in the water column (i.e. not on the seafloor). Few shellfish fit into this category given most live on the seabed. Fish species which are caught in this way include tuna, mackerel, herring and anchovies.

Many fishing gears have direct effects on habitat structure, but less so in pelagic fisheries. Here the fishing has a number of direct effects on marine ecosystems because it is responsible for increasing the mortality of target and bycatch species. Also, the direct effects of fishing have many indirect implications for other species. Indirect effects occur when fishing initiates shifts in the relationships between those organisms responsible for habitat development and degradation and thus, pelagic fisheries have more of an indirect effect on habitats.

The diadromous fisheries of relevance to the UK, namely European eel, salmon and trout, are highly regulated and neither of the three species are currently fished on a commercially scale anywhere in the UK (BBC News 2019; Britishseafishing.co.uk n.d.). The authorisations for commercial yellow and silver eel fishing are limited to those already licensed to fish (Environment Agency 2017) which gives an estimated total catch per annum of approximately 26 tonnes, which is less than 1% of the total European catch (Pisces Conservation 2012). Thus, the impact of these fisheries is negligible, and no innovations were found in relation to diadromous fisheries with regards to reducing impact on habitat, environment and ecosystems.

Innovation with a potential for disruptive performance improvement

Reduction of bycatch: There is a number of developments to reduce bycatch. Bycatch is here referring to discarded catch plus incidental catch. Bycatch is when a fish or other marine species are caught unintentionally while targeting certain species and sizes of fish or shellfish. It including the incidental take of undesirable size or age classes of the target species (e.g. juveniles or large females), and the incidental take of other non-target species including protected species such as sharks, seabirds, cetaceans and sea turtles. Globally, a significant part of the bycatch is discarded and unobserved (AlphaFilm/DTU n.d.). According to some estimates, global bycatch may amount to 40% of the world’s catch, totalling 63 billion pounds per year (Keledjian *et al.* 2014).

Bycatch is an issue that affects both the ecosystems as well as the economy of wild-capture fisheries. Most fish that are discarded often die and cannot reproduce, impacting marine ecosystems. Bycatch can contribute to over-fishing and slow efforts to rebuild fish stocks by slowing the rebuilding of overfished stocks. It has also been shown to place protected species such as whales and sea turtles at further risk directly through death due to bycatch and entanglement and indirectly due to reduced availability of prey, which again affects marine ecosystems and the productivity of fisheries overall. An example of a negative economic impact from bycatch is that fishers may have to stop fishing ‘early’ because of high bycatch of a non-target species (Keledjian *et al.* 2014).

There are various developments with disruptive technologies including remote electronic monitoring, vision systems for fish identification, measurement and sorting (trawl), pre-catch characterisation by vision systems and echo sounders (purse seine) and LED lighting (gillnet) or pre-catch characterisation by physical sampling (purse seine).

For innovations on how to avoid or reduce bycatch please refer to the chapter on Gear selectivity and bycatch reduction for further information.

For innovation with regards to ghost fishing please refer to the chapter on Marine litter.

For marine mammal protection and deterrent technologies, please refer to the chapters on Aquaculture Habitat, environment and ecosystem impact and Selectivity of gear and avoidance of unwanted catches.

17.3 Demersal and benthic fisheries impact

Demersal fisheries are fisheries which target fish or shellfish when they are on the seafloor. All bivalve shellfish fisheries fall into this category with some, such as scallops, even requiring that the fishery extract the scallops from within the seafloor. Most cod, haddock, flat fish and *Nephrops* (aka scampi or langoustine) are caught in this way.

Unlike pelagic fisheries, these necessarily come into contact with marine habitats. The direct effects of fishing change the structure of fish and benthic communities and such changes may affect the growth of those organisms which are responsible for structuring habitats. The resuspension, transport and subsequent deposition of sediment may affect the settlement and feeding of the biota in other areas. Chronic fishing disturbance of the benthos leads to the fundamental changes to the seabed ecosystem, including the removal of high-biomass species that are composed mostly of emergent seabed organisms (Rijnsdorp *et al.* 2017). These organisms increase the topographic complexity of the seabed and have been shown to have a key role in numerous habitats e.g. providing shelter for juvenile fishes, reducing their vulnerability to predation. Heavily fished areas on the other hand are dominated by small-bodied organisms, such as polychaete worms and scavengers e.g. starfish. Such a change in habitat may lead to changes in the composition of the resident fish fauna. Fishing also has indirect effects on habitat through the removal of predators that control bio-engineering organisms such as algal-grazing urchins (Kaiser 2003).

Trawling and dredging are known to have a significant and lasting impact on seabed ecosystems. They can be responsible for resuspending a large proportion of the sediment load in some marine environments. Those parts of the trawl net that come into contact with the sea bed will flatten and damage any benthic ecology and cause bottom sediments to be resuspended but the turbulence created by the trawl doors suspends most material and plays a key role in herding fishes towards the net. The magnitude of the impact is determined by the speed of towing, physical dimensions and weight of the gear, type of substratum and strength of currents or tides in the area fished (Rijnsdorp *et al.* 2017; Juan, Demestre, and Sánchez 2011). The effects of resuspension may persist for a few hours in shallow waters with strong tides or for decades in the deep-sea, depending on sediment type (Rijnsdorp *et al.* 2017; Juan, Demestre, and Sánchez 2011). The effects of damage to the ecosystem may last from several months to several decades. If observations of trawl marks are to be used to provide an index of fishing intensity then some knowledge of their persistence, as determined from experimental studies, is required.

The effect on the infaunal and epifaunal communities, tends to increase with depth and the stability of the substrate (Blaxter, Southward, and Tyler 1998). Dredging is primarily used in bivalve fisheries and, following long-term declines in fish stocks, scallop dredging has become a major fishery in the UK. One interviewee suggested that mitigation of the amount of damage caused by scallop dredging could be an area innovation given that it would both address key sustainability concerns about the scallop fishery, and improve the conditions for the recovery of other fish stocks which are currently limited by degraded essential fish habitat (personal communications).

One of the recent European Union policy objectives have committed to support small-scale coastal fisheries, but the characteristics and sustainability of these are poorly understood. In the UK, there is currently no clear definition of ‘small-scale’ beyond a 10-m length threshold used for fishing vessel administration (University of York 2018; Seafish 2019). Very few of them would be suitable for MSC certification due to poor stock health and/or stock uncertainty (Davies *et al.* 2018). However, the Shetland scallop fishery using traditional dredging is MSC certified (Carrell 2018). MSC certification in scallop fishing is somewhat controversial as the method has a significant impact on the seabed (Scottish Fishermen's Federation 2015; personal communication).

Aquaculture offers a more sustainable bivalve supply, and already provides 89% of the total annual global production (Wijsman *et al.* 2019). China and Japan still account for the majority of bivalve production (Smaal *et al.* 2018) but scallop aquaculture in the West is slowly on the rise (Bever 2018). This is also supported by the spreading 'green' consumer perception of farmed mussels (The Fish Site 2019).

For more information on bivalves of relevance to the UK, please refer to the chapter on Species diversification.

Another example of a fishery with impact on the benthic environment is the cockle fishery. The effects of cockle harvesting in terms of disturbance on the cockle population as well as on the intertidal benthic community in places along the coast of Scotland are obvious. Overharvesting caused a drastic reduction in the abundance of individuals, which ultimately led to a crash of the cockle stock and year on year harvesting bans (Marine Scotland Science 2015; Scottish Government 2014). There are however, now four MSC certified cockle fisheries in the UK (FIS 2019).

For innovations regarding monitoring and assessing the benthic environment, please refer to the chapter Aquaculture Environment and ecosystem monitoring and impacts.

Innovation with a potential for disruptive performance improvement

Precision fishing: Certain fisheries, such as bottom trawling for *Nephrops*, are currently indiscriminate – they impact seabed and capture relatively high proportions of non-target species. It may be possible to address this by providing skippers with live feeds from the gear to allow them to target only those areas where *Nephrops* are present and to avoid areas where there are high levels of non-target species. Being targeted in this way has the potential to reduce benthic disturbance by up to 50% (personal communication). The technology is developed for precision farming and there are likely some technical and engineering challenges to overcome, but no 'hard problems' as such. For more information on camera systems for catch monitoring and selective release (trawl) please refer to the chapter on Gear selectivity and bycatch reduction.

Technology Readiness Level: 6-8; Technical risk: Moderate

MLD Trawl Steering System™: The MLD Trawl Steering System[1] was originally developed for pelagic fishing but it now ready to accept orders for bottom and semi-pelagic trawl steering systems. These systems have the ability to keep a constant distance from the seabed and hence not impact the seabed at all (Miljøstyrelsen 2018).

The system uses an innovative and patented mechanical flapfoil solution based system as part of the trawl doors' hydrodynamic design with a dependable electromechanical system where the movement and control of each of the MLD Trawl Door's two flaps is enabled by hydraulic systems. The system also consists of a computer and several sensors, enabling the MLD Trawl Door to operate independently. The communication between the trawler and the MLD Trawl Doors is enabled by using acoustic modems. The Advanced Software systems comprise of the control software which is the user's interface with the MLD Trawl Steering System, allowing the skipper or operator to decide exactly where the MLD Trawl Doors shall be positioned to locate the trawl in the perfect depth and shape. And the subsea software controls the MLD Trawl Door, receiving instructions from the trawlers acoustic modem and the software sends status information back to the trawler from its acoustic modem. The MLD subsea software has the AUTODEPTH function, which enables automatic operation of the MLD Trawl Door to ensure a constant door depth.

Other benefits include increased efficiency of the trawler, as the MLD Trawl Steering System enables "on the fly" changes, which will result in faster catch and better quality of the fish. The system also reduces costs for the trawler, as fuel economy (drag) is constantly optimised to what is really needed to have a perfect shape of the trawl, less days at sea or more catch due to the increased efficiency.

Technology Readiness Level: 9; Technical risk: Low

Innovations with a potential for Transformative performance improvement

Robotics: As well as being highly damaging, dredging for scallops is relatively inefficient, requiring as many as four passes with a dredge before all scallops are caught. Divers are far more discriminating because they can see the scallops and they do not need to damage the entirety of an area to collect them (personal communication). However, diving for scallops currently constitutes only 5% of the scallop fishery in the UK and is highly location specific due to potential interactions i.e. it is not safe for divers if trawls and other fishing gear is being

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[1] MLD Trawl Steering System: http://mld.one/

deployed in the same area. As an alternative to dredging and diving for scallops, scallop collecting remotely operated vehicles[1] are still in development for scallop harvesting (James and Siikavuopio 2012). These are also used for rapid surveying of new fishing areas e.g. in relation to sea urchins fisheries (James *et al.* 2016). These are technically very challenging but offer an opportunity to address concerns of sustainability and economic pressures (such as rising fuel prices) in the dredge fleet, as well as making new areas accessible to the scallop fishery.

Technology Readiness Level: 3-5; Technical risk: High

Acoustic equipment: Bivalve fisheries such as the blue mussel fishery can significantly reduce their footprint by deploying acoustic equipment to detect mussel concentrations. This allows the fishers to more precisely target the mussel beds and hence reduce fishing in areas with low mussel density (Kozarek 2018). Whilst not being a novel technology, hydro-acoustic equipment keeps being further improved and developed (HTI 2015; ICES 2018).

Technology Readiness Level: 9; Technical risk: Low

Novel advances for acoustic equipment use include examples of real-time receivers that can detect signals from transmitters on tagged (endangered) fish passing by, which relays information on fish identity and time of detection to a website, where information can be viewed on either a computer or mobile telephone. This system is currently used on research scale e.g. for detecting the arrival of migrating winter-run Chinook salmon near a water diversion and alerting regulatory biologists to keep the diversion closed to increase the migratory success (Klimley *et al.* 2017).

Technology Readiness Level: 6-8; Technical risk: Moderate

Real-time monitoring and adaptive management: With advances in remote electronic sensors, satellite surveillance, automated underwater vehicles and video technology, real-time monitoring is increasingly used to inform management of fisheries, resource management and conservation decisions. Traditional ways of real-time monitoring and adaptive management include for example the Icelandic cod fisheries where a fishery areas will be shut if a certain proportion of the catch is below a particular size (Björnsson, Sólmundsson, and Pálsson 2015).

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[1] ROV development example: https://www.youtube.com/watch?v=1Jpp9NN5k2Q

The I-Fish North Sea system is an example of a system that is developed to provide accurate marine fisheries data to provide value-added services to fisheries stakeholders for improved sustainability of fisheries. It is based on a central hub capable of SatCom-enabled information interchange (receiving, processing and forwarding messages including GNSS-derived vessel position, market and catch data). Selected data can be securely transferred between and made available for value-added services for various stakeholders such as fisheries authorities and compliance agencies, vessel agents, auction houses, wholesalers and fish markets (stock availability and market demand information) and fishermen (event data, vessel position, catch, fishing operation, changes, area closures) (European Space Agency n.d.).

Technology Readiness Level: 6-8; Technical risk: Moderate

Innovation with a potential for incremental performance improvement

Moving towards static rather than dynamic fishing: There is continuous developments of fishing traps, for catching demersal fish that are typically caught with dynamic fishing gear. Between 2008 and 2015, a higher proportion of 10m-and-under landings of demersal fish species were caught using passive fishing gears, with a lower environmental impact compared to larger vessels (Davies *et al.* 2018). An example includes the gillnet-fishing in German Baltic Sea waters where local fishermen have been engaged in the development and testing of environmentally friendly fish traps. This is paving the way for sustainable fisheries along its coast in a wider context of adding value to the local catch (Bouker 2018). Another example includes Atlantic cod fishery in Newfoundland, where the most commonly used fishing gear is still bottom-set gillnets (Rouxel and Montevecchi 2018). Catch-related advantages (efficiency, size selectivity) for bottom-set gillnets are not adapted to “the new” quality-based fishery. Restriction of gillnet-fishing and promotion of complementary hand-lining and pot fishing would support a best practices and more sustainable approach (Rouxel and Montevecchi 2018).

Technology Readiness Level: 9; Technical risk: Low

Dredge design for sea cucumber fishing: Sustainable harvesting and protection of the marine ecosystem are key concerns for the Icelandic fishing industry - one of the most modern and competitive seafood industries in the world. Aurora Seafood has initiated the project Topbalat to achieve a more productive and environmentally respectful value chain for the fishing and processing of sea cucumbers. Part of this involved the build of a new sea cucumber dredge. The design is built on previous development with a few more implementations such as rubber sleeve on the mouthpiece and a sensor bracket. The dredge is currently being tested alongside standard dredges for comparison e.g. with the traditional ski dredges (Topbalat 2017). The Aurora Seafood team is measuring impact of the dredges on the seabed, recording possible difference in catch rate and if and what type of damages the dredges have to the catch. So far it has only been reported that the new dredges allow for higher fishing rates and better quality of the catch.

Technology Readiness Level: 9; Technical risk: Low

Electric dredging design for razor clam fishery: Electric dredging for razor clams is a promising development (Marine Scotland Science 2014; Breen, Howell, and Copland 2011). It involves probes being pulled slowly over the sea bed from an inshore fishing vessel, this causes the clams to emerge from their burrows and they are collected by divers. Research has shown that the methodology is highly selective, produces high-quality product with zero bycatch and is less intrusive than traditional methods like dredging (Scottish Government 2016).

There seems to be a growing interest in electrical fishing in the United States (personal communication). However, all forms of electric fishing remain controversial, one key problem being that the power may be altered on individual vessels, with the potential to have a negative impact on the benthic environment. For electric fishing to be a viable and more sustainable technique, there needs to be a way to lock the power settings to be within a certain range and to tightly control the fisheries where the technique is being used. It is known that whole fisheries in Asia have been wiped out due to electric fishing (personal communication).

Technology Readiness Level: 9; Technical risk: Moderate

Trawl design: As part of the Benthic Ecosystem Fisheries Impact Study (BENTHIS), a pan-European research project to study the impact of bottom trawling, it was shown that the use of (semi-) pelagic otter doors reduced bottom impact and the fuel cost without affecting the catch rate of the target species (Rijnsdorp *et al.* 2017). It was also shown that replacing mechanical stimulation by tickler chains with electrical stimulation e.g. in the beam trawl fishery for sole can reduced footprint and penetration depth as well as the fuel cost. However, this sole fishery is incredibly controversial and is in the process of being shut down (Fortuna 2019). Electrical stimulation has been identified as a promising innovation to reduce the bycatch and bottom contact in the beam trawl fishery for brown shrimps (Rijnsdorp *et al.* 2017).

Technology Readiness Level: 9; Technical risk: Low

New creel designs: Creel has less of an impact on habitat and environment than trawl in the *Nephrops* fishery (Frandsen *et al.* 2015) and hence the method gaining popularity (Marine Scotland Directorate 2017). Special creel designs with mounted escape gaps will further ensure low rates of bycatch and should be considered in favour of trawl for a more sustainable Neophrops fishery (Fishing News 2017).

Technology Readiness Level: 9; Technical risk: Low

17.4 Fisheries impact monitoring

Various approaches and related innovations have been developed over the past five years, monitoring the impact on fisheries on coastal and open-ocean systems.

It has been argued that one reason it has taken so long to identify impacts of fisheries on open-ocean ecosystems is the limited number of complete and reliable long-term multi-species catch datasets from multiple ecosystem components (Ortuño Crespo and Dunn 2017). Ortuño Crespo and Dunn recently demonstrated the importance of long-term multi-species catch datasets and stock assessments for understanding not just population-level impacts on target and non-target taxa, but also to parameterise community-level mass-balance models to demonstrate community and ecosystem-level impacts of fishing on the open-ocean.

However, such datasets are based on observer monitoring programs which are still absent in many regional fisheries management organisations. It is argued that if long-term multi-species monitoring programs are not established, understanding the broader ecological impacts of fisheries on open-ocean ecosystems will be difficult and fisheries will be at risk of failing to recognise early warning signals of trophic cascades or fisheries-induced regime shifts. To ensure the sustainability of open-ocean fisheries, the extent and thematic coverage of observer programmes should be increased and include non-target species, as well as other forms of monitoring such as community-level modelling efforts and genetic sampling.

Such activities are on the increase in Europe due to the implementation of the Marine Strategy Framework Directive, which dictates that European Member States are required to improve marine monitoring and design monitoring networks. This is partly achieved by developing and testing innovative and cost-effective monitoring systems, as well as indicators of environmental status. There are also various international agreements that require the monitoring of protected species bycatch. This section focusses on recent developments or new innovations over the past five years only.

Innovation with a potential for transformative performance improvement

Identification of areas of high importance: Data is currently lacking to help define and map ecologically important areas in the UK. These areas including essential fish habitats e.g. nursery areas for cods or whiting and knowing where they are will enable better protection of the full life cycle of the fish stocks. Such areas also including e.g. herring spawning areas, with a certain type of gravel seabed type, where scallops are also often found. Understanding where these herring spawning areas are will allow for better regulation of scallop harvesting to avoid dredging during herring spawning periods (Fey *et al.* 2014).

Currently, little of the European seabed has been mapped using modern methods. A direct consequence of such data deficiency is that 76% of seabed habitats are in unknown status (EEA 2015) and there are no systematic habitat mapping programmes in place at national or pan-European scales.

In the absence of adequate seabed data, the urgent need to define seabed habitats for management resulted in the construction of modelled seabed data such as UKSeaMap (Connor *et al.*, 2006). These maps contain errors due to data deficiencies and generalisations but high-resolution data only existing as a localised patchwork and does not address needs to define biogeographical limits of species or overall habitat distribution at a regional scale. To overcome this difficulty and make best use of existing resources, the novel strategy of continuously logging high-resolution multibeam data during existing monitoring cruises has been adopted on the RV Cefas Endeavour (BODC 2019) using the Olex software programme.

Technology Readiness Level: 9; Technical risk: Low

Underwater visual surveillance: Marine observatories allow the collection of long-term time-series of environmental parameters but have yet not been commonly used. It is widely recognised that underwater technology could open new and interesting opportunities to ensure continuous, long-term, execution of monitoring. In particular, during the last decades, underwater video technologies have gained considerable importance in all fields of marine science. They represent a powerful, non-destructive and useful tool to study the dynamics and the interactions between benthic organisms as a potential indicator of fisheries impact monitoring, especially on hard-bottom sediments where traditional grab methods are ineffective. The use of underwater visual surveillance is becoming increasingly accessible for monitoring activities since it is versatile, serving as an “underwater eye” for researchers. The recently developed technology CLEAN SEA (Continuous Long-term Environmental and Asset iNtegrity monitoring at SEA), uses a commercially available Automated Underwater Vehicle, which has been upgraded with technologies enabling offshore monitoring of seafloor integrity and pollution. The Clean Sea system was launched by Eni E&P and its subsidiary Eni Norge, in co-operation with Tecnomare. The vehicle is characterised by a set of sensors able to measure both physical and chemical parameters and carry out in situ analysis of trace pollutants. The CLEAN SEA system can also collect discrete water samples in situ. It is developed to perform acoustic surveys of the seabed and pipelines/flowlines as well as to detect hydrocarbon leakage. The CLEAN SEA system can also perform benthic community survey with detailed photographic/video coverage of the investigated area in order to determine the abundance and biodiversity of benthic assemblages and their temporal variations. CLEAN SEA is characterised by wireless underwater communication for mission data downloading and wireless power recharge for increased autonomy. This may enable a “permanent” operation subsea independently of support from surface.

Technology Readiness Level: 9; Technical risk: Moderate

Innovation with a potential for incremental performance improvement

Metabarcoding: This refers to large-scale analyses of biodiversity through the amplification and sequencing of marker genes. The development of high-throughput sequencing technologies and of standardised procedures is allowing metabarcoding analyses to be included in routine monitoring programmes (Zaiko *et al.* 2015). Metabarcoding alone is unlikely to be able to confirm any changes seen are the result of fishing unless combined with other collected parameters (personal communication).

Technology Readiness Level: 6-8; Technical risk: Low

In situ technologies: Some of the best approaches to meet current demands in fisheries impact monitoring are represented by novel in situ technologies, which provide high-frequency (continuous or semi-continuous) observations. So far, most of in situ instruments have been developed to monitor marine hydrological and physico- chemical variables, whereas the monitoring of the biotic variables is still mostly dependent on non-remote or automatic devices.

An example is the system of SmartBuoys[1] from Cefas, which house a range of instruments for measuring salinity, temperature, turbidity, chlorophyll fluorescence, oxygen saturation and nitrate concentration. Such instruments enable the creation of wide-scale international networks of environmental data acquisition and sharing. Nonetheless, technological limitations are at the base of the presently scarce modelling capacity regarding population/stock and biodiversity assessments as well as ecosystem functioning. The physical environmental parameters measured by the SmartBuoys can be used in models to predict the distribution of species and / or habitats, provided that observational data for these are available too, which could then inform fisheries management.

Technology Readiness Level: 9; Technical risk: Low

Autonomous reef monitoring structure: As a means to monitoring impact on reefs the National Oceanic and Atmospheric Administration (NOAA) has developed a standardised biodiversity assessment tool called an “Autonomous Reef Monitoring Structure”. This device consists of nine 23 × 23 cm grey, Type I PVC plates stacked in an alternating series of layers that are either open to the current or obstructed, which are intended to mimic the three-dimensional structure of the reef environment. They should be deployed for 1–3 years and colonized by bacteria, algae and sessile and mobile fauna, including cryptic species, of different size ranges (meiofauna, 20–500 μm; macrofauna, >500 μm; large macrofauna, >2000 μm). After recovery, both sides of each plate are photographed, and then surfaces are scraped, homogenized and analysed using barcoding and metabarcoding techniques. The Autonomous Reef Monitoring Structure processing protocol applies a combination of morphology (for organisms >2000 μm) and molecular-based (all components) identification approaches to assess species richness (Leray and Knowlton 2015).

Technology Readiness Level: 9; Technical risk: Low

Crowd sourcing: Large sets of data are collected by e.g. recreational fishermen and volunteers undertaking beach cleans or shore watches for marine mammals and seabirds. The Ocean Sampling Day is a simultaneous sampling campaign of the world's coastal oceans which took place for the first time on the summer solstice (June 21st) in the year 2014 and was repeated in 2015 and 2016 (Kopf *et al.* 2015). Collected samples related in time, space and environmental parameters, provide new insights regarding microbial diversity and function and contribute to the blue economy through the identification of novel, ocean-derived

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[1] SmartBuoys: https://www.cefas.co.uk/data-and-publications/smartbuoys/

biotechnologies. The standardised procedure including a centralised hub for laboratory work and data processing via the Micro B3 Information System, ensuring the collection and the processing of sea water samples with a high level of interoperability and consistency between data points worldwide. All Ocean Sampling Day data (i.e., sequences and contextual data) are archived and immediately made openly accessible without an embargo period. The aim is to create an Ocean Sampling Day time-series indicators to assess environmental vulnerability and resilience of ecosystems and climatic impacts. In the long term such indicators may be incorporated into the Ocean Health Index (OHI) (Halpern *et al.*, 2012), which currently does not include microorganisms due to the lack of reliable data. OSD has the potential to close that gap expanding oceanic monitoring toward microbes. This could lead to a global system of harmonised observations to inform scientists and policy-makers, but also to raise public awareness for the major, unseen component of world's oceans (Danovaro *et al.* 2016).

Technology Readiness Level: 9; Technical risk: Low

17.5 Fisheries management

This section is included as most of the research on fisheries impact on habitats, environments and ecosystems is focused on modelling and management. The innovations are typically not of technical nature and may be less relevant to SIF but included here for completeness in terms of giving an overview of current activities in the field.

‘Peak’ fish from wild catches came around the mid-1990s and it is estimated that today there are 70% less large fish, marine mammals, turtles and birds than before the industrialisation of fishing (Greenpeace International 2019). Landings have declined significantly since then and there is a need for improved monitoring of all fisheries with the goal that what is caught on quota systems match what is landed (Pauly and Zeller 2016).

Fish stocks generally have a high, but not unlimited, reproductive capacity. If fishing is not controlled, stocks may collapse or fishing may cease to be economically viable. It is therefore in everyone's interest to have a fisheries management system in place to safeguard stock reproduction for sustainable long-term yield to ensure a profitable industry and to share out fishing opportunities fairly, and conserve marine resources.

Fishing is the most widespread human exploitative activity in the marine environment and the estimated primary production that is required to sustain fisheries in many intensively fished coastal ecosystems has been revised over the past 20 years (Kaiser 2003; Pauly and Christensen 1995; Pauly and Zeller 2016). Estimates from the 80s and 90s of the primary production required were much lower and led to the conclusion that fishing had few fundamental effects on the structure or function of marine ecosystems apart from those on fished species. These views were widely accepted at the time since they were in accordance with the overriding philosophy of many fisheries scientists who based their assessment and management actions upon the short-term dynamics of target fish populations. However, studies in the 1990s such as those of Pauly and Christensen (Pauly and Christensen 1995), coupled with empirical evidence for shifts in marine ecosystems, implied that the actions of fishers indeed had important effects on ecosystem function. As a result, the emphasis of marine fisheries research shifted from population to ecosystem-based concerns with research describing the effects of fishing on ecosystem structure and processes. However, the lack of clear necessity kept the ecosystems perspective from advancing in a field whose historically, pragmatic concern is the mechanics of short-term fishery management.

Since the 1990s fisheries management has slowly moved from traditional single-species management to operationalisation of ecosystem-based fisheries management, primarily based on various extant ecological indicators (Hornborg *et al.* 2019).

Experts have commented that for various current fisheries policies, the weight of evidence supporting environmental effectiveness is poor and it has been suggested that governments should promote policies that define an end goal rather than the methods to achieve a particular goal. *“This might encourage the industry to take greater responsibility and adopt the adaptive management strategies”* (personal communications).

17.5.1 Ocean data collection

Collection of big data including the needed methodologies of how to measure things without interrupting daily activities, sending data via satellites, how to harness, process and use the data is an area of rapid development. The aim is to mobilise the industry to be able to provide that data.

Ocean data collection in collaboration with fishing vessels offers a range of opportunities including active involvement in stock assessments, protected species monitoring and a cost-effective hydrographic data collection in the data coverage gaps of coastal and shelf seas. Today the collection of oceanographic data, especially subsurface data, is expensive. The high costs of data collection make longer-term monitoring not viable. This resulting data shortage holds back advances in a wide range of sciences and industries. Furthermore, this data is beneficial not just for oceanography, but also for fishing industry and fisheries science. There are a variety of programs collecting ocean data with fishing vessel, involving both scientists and fishing industry.

Innovation with a potential for transformative performance improvement

Global ocean modelling: There is an increasing number of marine focused modelling systems, making use of big data and machine learning with a focus on informing and developing ecosystem-based management, through aquatic ecosystem modelling. A major part of the work is focused on developing a spatial model of the global ocean in order to evaluate alternative future scenarios. Topics including climate, earth system, food web, fisheries, ecological, economic, social, and governance researcher.

Technology Readiness Level: 6-8; Technical risk: Low

Global Fishing Watch: Electronic monitoring systems have helped to build shared trust between industry and regulators. Programmes like Global Fishing Watch[1] are revolutionising the ability to monitor the global commercial fishing fleet, offering near real-time tracking of fishing activity. Anyone can use it, for free, to track fishing boats and download data about their past and present activities. The platform is helping enable scientific research, advocate for better policies to support marine protection, tackle over-fishing and improve the way fishing is managed. However, it relies on AIS technology. It is a legal requirement for vessels greater than >15m to have their AIS devices permanently enabled. It is widely understood that fishing vessels will sometimes switch theirs off. This is a particular issue in Scotland, where many boats habitually and permanently leave the devices off (personal communications).

Most fishing nations also collect Vessel Monitoring System data to track commercial fishing activity in their nation’s waters but typically do not make that information public. This data is owned by the national government and includes information on the country’s commercial fishing fleet and foreign vessels registered to fish in their waters.

Global Fishing Watch are committed to processing and publishing Vessel Monitoring System data from any nation committed to taking this bold step toward transparency. Global Fishing Watch aims to partner with 20 countries within the next 5 years to make their Vessel Monitoring

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[1] Global Fishing Watch: https://globalfishingwatch.org

System data public. Going “transparent” will mean for those governments that monitoring becomes cheaper, more effective, and that responsible fishing is rewarded, will non-responsible fishing will stand out more clearly and can be penalised appropriately. One expert noted that one objective of data collection should be to enable traceability within the quota system *“and this should be made available to the public so consumers are aware of what is going on”* (personal communication).

Technology Readiness Level: 9; Technical risk: Low

Ecosystem-based approach to fisheries management (EBM): Ecosystem-based fisheries management is not a new concept but continuously being developed. An example includes ICES, which provides three main outputs to support EBM: advice on fishing opportunities, fisheries overviews, and ecosystem overviews. These products are continually developing to address new information as well as changes in the ecosystem, legislation, and the drivers of fisheries. Spatial management and regional priorities are addressed as all of the advice is given by ecoregion (ICES 2014). Another example is MareFrame, an EC-funded project consisting of numerous case studies across Europe, with the aim to remove barriers preventing more widespread use of the ecosystem-based approach to fisheries management. The project entailed development of new tools and technologies, development and extension of ecosystem models and assessment methods, and development of a decision support framework that can highlight alternatives and consequences. The work is undertaken in a way to ensure that close integration and co-creation with stakeholders lead to the ownership lying with them and hence, increase the chance of acceptance and uptake of the project outcomes. The vision of MareFrame is to significantly increase the use of ecosystem-based approach to fisheries management (EAFM) when providing advice relating to European fish stocks.

Technology Readiness Level: 9; Technical risk: Low

Berring Data Collective: The Berring Data Collective is an incentive to collect data for improved fisheries management. Commercial fishing gear is a cost-effective platform for collecting oceanographic data. Fishing gear offers a free ride for sensors, so fishermen are fishing for data and fish at the same time. The objectives are to enable fishing vessels to collect data and to engage fishing fleets and scientific programs who are already collecting data to get their data to those who need it. The Berring Data Collective offers a flexible database with data and meta-data standards, custom-tailored APIs to query and deliver data specific to the users’ needs and an additional source of income for fishers.

Technology Readiness Level: 9; Technical risk: Low

17.5.2 Marine spatial planning

Marine spatial planning is a process that aims to organise the use of the ocean space, as well as the interactions among human uses (e.g., fisheries, aquaculture, shipping, tourism, renewable energy production) and between users and the marine environment (Santos 2019). Full protection of areas has been shown to maximise the reproductive subsidy to fishing grounds and this subsidy is much bigger than the increase in biomass (Marshall *et al.* 2019). During the United Nations (UN) Ocean Conference in June 2017 it was highlighted that environmental managers and scientists need to find a better approach to the selection of natural areas that might be suppressed or modified by coastal development. The United Nations needs to review their indicators, assessing the quality of achievements, real protection and ecosystem representativeness with an end goal of effectively conserve threatened and highly biodiverse regions, ecosystems, and species (Pinheiro 2018).

Innovations with a potential for Transformative performance improvement

Guild of Coastal Fishermen: The Danish “Ocean in Balance” is an example of a cooperative community quota company, set up by a social enterprise, with a focus on sustainable coastal fishing (Højrup 2018). Such co-operatives are not novel thinking, but they are gaining ground and continuously improved, with increasing consumer awareness and corporate responsibility generating a consumer pull.

The overall aim of Ocean in Balance is to promote increased sustainability within fishing in order to preserve the marine environment and the biodiversity in the local sea. The overall aim is sought to be secured through providing financing to independent fishermen, groups of fishermen and associations of fishermen, who exercise fishing within the frames of the company’s aim. The financing includes the construction of new small-scale fishing boats with the latest technologies for sustainable fishing, leasing of small-scale fishing boats, acquisition of fishing quotas for low-impact fishing, the development of knowledge and ways of organising and administrating this type of fishery. There are several positive aspects to this approach including that fishing quotas are bought, paid off, owned and managed by the fishing families’ cooperative quota guild, Thorupstrand Guild of Coastal Fishermen. The culture of owning in common gives the local fishing families an incentive to make use of the local sea in a sustainable way as this secures a balance between fishing and ecology for the fishermen themselves, as well as for the new generations of their community. In addition, the cooperative access to the natural resources make way for a constant generational handover, where fishermen, boats and gear are continuously replaced by new generations without a loss of value in the cooperative. Every generation contributes to the building up of the local community's common quotas by using these to create a business that pay off the loans of the guild.

Technology Readiness Level: 9; Technical risk: Low

Marine protected areas: MPAs are nothing new but the ways they are being selected and managed is continuously being developed and refined (Humphreys and Clark 2019). In 2016 a ambition was articulated by IUCN, calling on nations to set aside at least 30% of the world's oceans as "highly protected" areas by 2030. Common objectives for MPAs globally are almost never met with MPA coverage in single percentage figures. Thus, it has been argued that a 10% coverage is not enough to secure the main objectives of MPAs whereas the 30% by 2030 MPA target is supported by scientific research (O'Leary *et al.* 2016). Experts have however pointed out that the management put in place for the MPA has far more significant role than the area of coverage.

Using MPAs to build resilience to climate change requires high levels of coverage and protection (Roberts *et al.* 2017). It has been shown that fully protected MPAs had 7x more fish by weight than unprotected areas, while partial protection only doubled biomass (Sala and Giakoumi 2017). Furthermore, fully protected MPAs have been shown to lead to a population increase of 5-10x, an increase in reproduction by 10-100x, an export of offspring and young to other protected areas and surrounding fisheries (natural corridors) and an increasing extent and complexity of biogenic habitats. Strategically placed, MPAs offer stepping stones, corridors and refuges of last resort with benefits that scale with the area protected (Marshall *et al.* 2019; O'Leary *et al.* 2016; Sala and Giakoumi 2017; Elliott *et al.* 2016). However, most UK MPAs have no fisheries management measures in place at all.

There is currently ongoing research and collaboration to develop a participatory approach to the management of fishing activity within UK offshore MPAs (Solandt *et al.* 2020). By bringing together the fishing sector, NGOs, regulators, scientific advisors and academic researchers the aim is to build stakeholder stewardship to develop and trial a consistent approach for managing sedimentary habitats in MPAs in light of scientific uncertainty. A positive trend in seabed biodiversity if trawling / fishing / dumping is prevented has been shown for some of these MPAs.

Technology Readiness Level: 9; Technical risk: Low

Marine regime shifts: The concept of regime shift in marine ecosystems has arisen over the past 10-15 years. Marine ecosystems can experience regime shifts, in which they shift from being organised around one set of mutually reinforcing structures and processes to another (Rocha 2015). The origin, scientific meaning and key driving forces of marine ecosystem regime shifts are still debated. Some of the key driving forces include climate-ocean oscillation, fishing, introduced species, river flow, eutrophication, disease and pollution (Möllmann 2012, 4). It is challenging to separate many of the driving forces e.g. impact of fisheries, and to determine whether the impacts of ecosystem regime shift are necessarily always bad.

Various methods used to model regime shifts in ecosystems have been developed over the years and with new methods being researched. One recent example (Smoliński 2017) is the use of sclerochronological studies, based on hard structures of marine organisms, which can be used both for reconstructing past climate conditions and for predicting future impacts of environmental changes on marine resources. This approach can make use of existing archives, which house e.g. millions of fish otoliths (ear stones), and such archives seem to remain under-utilised (Smoliński 2017).

The implications of regime shift in fisheries are obvious including direct impacts, consequences of not considering regime shift, and difficulties in incorporating regime shift into the current stock assessment models which in turns has implications for strategy development for fisheries management.

Technology Readiness Level: 6-8; Technical risk: Low

Human dimension indicators in ecosystem-based fisheries management: Efforts to collate indicators of potential use for future ecosystem-based fisheries management research on the human dimension have highlighted that there is a wide range of human indicators that are linked to ecological status (Breslow *et al.* 2016). Traditional fisheries management is well-founded in one topic of the human dimension: fisheries exploitation. A recent meta-study found that less attention has historically been given to both broader ecological considerations (e.g. maintaining ecosystem structure and function); and broader objectives of the human dimension, such as community wellbeing and institutional aspects – this is where ecosystem-based fisheries management principles intend to improve current practice (Hornborg *et al.* 2019). It was found that fishing economy has been given disproportionate attention in ecosystem-based fisheries management research and suggested that future research efforts should ideally be channelled to understudied components of ecosystem-based fisheries management. Increased effort on collecting data and developing indicators related to, in particular, social-cultural and institutional dimensions of ecosystem-based fisheries management, is vital for ecosystem-based fisheries management to go forward (Hornborg *et al.* 2019). Some understudied objectives, such as indicators belonging to 'Responsible and profitable trade' and 'Safe, healthy, fair working conditions', are more easily included due to their quantitative nature – whereas the objective 'Community wellbeing' may comprise of more qualitative indicators that are difficult to both manage and develop objectives and appropriate performance indicators for.

Technology Readiness Level: 6-8; Technical risk: Low

Habitat credit management systems: Following implementation in a range of other resource sectors, a number of credit-like systems have been proposed for fisheries, where the credit systems can be distinguished as 'mitigation' and 'behavioural' fishery credits (Riel *et al.* 2015). Mitigation credits require resource users to compensate for unsustainable catches of target species, by-catch species or damaging practices on the marine environment by investing in conservation in a biologically equivalent habitat or resource. Behavioural credit systems incentivise fishers to gradually change their fishing behaviour to more sustainable fishing methods by rewarding them with, for instance, extra fishing effort to compensate for less efficient but more sustainable fishing methods (Riel *et al.* 2015). It has been shown that implementing a habitat credit management system can provide incentives to reduce fishing in peripheral areas at minimal cost (Rijnsdorp *et al.* 2017). Fishers typically concentrate their activities in only a part of their total fishing area. These core fishing grounds are characterised by a relative low status (high impact). Thus, additional fishing in these core grounds have only a small impact. In the peripheral areas where fishing intensity is low, additional fishing will have a much larger impact. Hence, shifting trawling activities from the core fishing grounds to the peripheral areas will increase the overall impact. Shifting activities from the peripheral grounds to the core will reduce the overall impact. This asymmetry provides the possibility to reduce the impact at a minimal cost.

Technology Readiness Level: 9; Technical risk: Low

Blue bonds for financing: Blue bonds offer an opportunity for private sector capital to be mobilised to support the blue economy. Capital markets have a key role to play in environmental stewardship and more specifically, the protection of the oceans and coasts. Blue bonds are seen as an innovative ocean financing instrument whereby funds raised are earmarked exclusively for projects deemed ocean-friendly (IntraFish 2019b).

A few recent examples include: (1) The Republic of Seychelles last year, launched the world's first sovereign blue bond raising a total of $15 million to advance the small island state's blue economy. The World Bank helped design the bond and vice president and treasurer Arunma Oteh said the blue bond was "yet another example of the powerful role of capital markets in connecting investors to projects that support better stewardship of the planet" (IntraFish 2017). (2) The international not-for-profit group The Nature Conservancy (TNC) recently unveiled plans to mobilise $1.6 billion of funding for global ocean conservation efforts through blue bonds under a scheme dubbed "blue bonds for conservation". An innovative finance model using philanthropy to save the world's oceans by providing upfront capital (The Nature Conservancy 2019). (3) Last year the Nordic Investment Bank, the international financial institution of the Nordic and Baltic countries, launched a "Nordic-Baltic Blue Bond" in January raising SEK2 billion for projects such as wastewater treatment, prevention of water pollution and water-related climate change adaptation (Nordic Investment 2019).

Partnerships between NGOs and industry: Partnerships between NGOs and industry are growing in numbers, partly due to a consumer push and a want / increasing need for transparency and trust from the industry side (personal communication). Here the example of Greenpeace and Aker BioMarine is provided. What started off as a soft partnership between the Norwegian krill producer Aker BioMarine and non-governmental organisation Greenpeace has transformed into a new level of collaboration between the NGO and the industry operating in the Antarctic Ocean. In 2018, Greenpeace launched a campaign to protect the Antarctic, which received support from 94% of the krill fishing companies that operate in the waters (IntraFish 2019a).

Technology Readiness Level: 9; Technical risk: Low

Communication: The traffic light ratings for wild-caught and farmed seafood in terms of environmental and ecosystem impact is steadily growing and becoming more and more used by consumers globally. Marine Stewardship Council is just starting to introduce GFG ratings based on fishing in MPAs and byers and consumers are encourage to get familiar with their seafood sources, and start asking for evidence on whether seafood is being caught inside MPAs, and then ask the question of suppliers as to why. For other certification schemes and innovation in this area please refer to the chapter on Sustainability and accreditation labels.

Technology Readiness Level: 9; Technical risk: Low

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18 Illegal, unreported and unregulated fishing and vessel monitoring

Contents

From the SIF Executive Board

The method applied in this review has generated numerous examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently happening. It is recognised that there are existing innovations and research areas that are not included here, and new areas where future innovations may occur. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

18.1 Overview: IUU fishing and vessel monitoring

What is the challenge in the UK?

Within the EU it is estimated that EUR 1.1 bn worth of IUU fish enters the EU market every year and some of this will end up in the UK.

What are the most promising innovation categories?

The most important innovations advancing the combat of IUU fishing activities are advances within IT systems for observation: these include improved image recognition systems and artificial intelligence and lower hurdles (cost and availability) of vessel observation either from space via satellites or via drones:

- Existing vessel monitoring systems (VMS) and vessel's automatic identification systems (AIS) are constantly improved in terms of data analysis
- VMS and AIS data can be combined with data gathered by satellites, particularly using optical images and SAR (synthetic aperture radar)
- Data can be more readily shared between jurisdictions about ship movements
- Progress is being made in rapid species detection, which will allow officials to certify what type of species has been caught

Where are important knowledge gaps?

- The key to stopping IUU fishing activities are improved monitoring of vessels and improved control on trade. For both – monitoring vessels and monitoring trade – the key to success will lie in rapid data analysis technologies, including AI/machine learning techniques
- The introduction of new monitoring technologies will need to go hand in hand with regulatory mechanisms and legislation

Illegal, unreported and unregulated (IUU) fishing is estimated to cause losses between US \$10 billion and US \$23.5 billion annually – between 10 and 22% of total global fisheries production (Seafish 2016). In 2005 it was estimated that approximate EUR 1.1 bn of illegal fish products enter the EU each year (data from 2005) (IUUwatch.eu 2016).

In the combat against IUU fishing governments need to:

- Minimise IUU fishing activities in waters under their control.
- Avoid the entrance of products which resulted from IUU fishing activities entering their supply chains.

The "IUU fishing index", as published by the Global Initiative Against Transnational Organized Crime and Poseidon – Aquatic Resource Management Ltd, scored the UK 5th best performing country for general state responsibility with regards to combatting IUU fishing activities (Macfadyen, *et al.* 2019). Nevertheless, operators of smaller vessels are less strictly controlled and the Buyers and Sellers regulations do not cover small amounts. Recreational activities are both unreported and largely unregulated. There have been recent reports of IUU fishing activities in UK waters, particularly regarding fishing in protected areas (Greenpeace 2019; BBC 2018). A snapshot of the extent of the trade in illegally caught fish in Europe was seen two years ago, when police in Spain arrested 79 people involved in illegally smuggling bluefin tuna from Italy and Malta into Spain – an operation that had been taking in an estimated EUR 12.5 million annually (White 2018).

It is known that globally, vessel operators engaging in IUU activities frequently

- Flag ships with states with convenient laws which allow them to declare low or no income tax, access to cheap labour, and the ability to obscure the true ownership of a vessel (Heffernan 2019).
- Switch off the ships Automatic Identification System (AIS) and possibly other vessel monitoring systems when engaging in illegal activities.
- Use transhipments to hide illegal catch (e.g. moving fish from a fishing vessel onto a refrigerated container ship in international waters).

In recent years some progress was achieved combatting IUU fishing. The FAO's Agreement on Port State Measures (PSMA) prevents vessels engaged in IUU fishing from using ports and landing their catches. In this way, the PSMA reduces the incentive of such vessels to continue to operate while it also blocks fishery products derived from IUU fishing from reaching national and international markets. One example of a country which successfully reduced IUU fishing activities in its own waters is Indonesia, whose authorities were able to clamp down on illegal fishing by introducing measures such as sinking illegal fishing boats and therefore strengthening their own fishing industry (Gokkon 2019; Cohen 2018).

The UN's "Goal 14 Initiative" aims to eradicated IUU by 2020 (UN 2019, 14).

Technologies to mitigate against IUU fishing activities are mainly focused on tracking vessels and monitoring their activities. Data from these systems can then be compared with logbooks entries to verify the catch. Still it is not always possible to monitor all fishing activities, for example it is very difficult monitor and verify the exact species being fished and the weight of the catch at a given time or to monitor discard.

There are several systems which are already available and in use by monitoring control and surveillance (MCS) programs at national and international levels:

- *AIS (Automatic Identification System)* - An AIS system is based on VHF radio. It can be regarded as a Vessel Monitoring System (VMS), but the term VMS shall be used for satellite-based systems in this chapter. Vessels carry a transmitter whose signal is picked up by coastal based AIS base stations. It was developed primarily as a tool for maritime safety to avoid vessel collision by Vessel Traffic Services (VTS). Using AIS can be made mandatory by countries inside their EEZ for all ships which exploit their resources. The system is relatively cheap to operate. Commercial companies offer monitoring services, and GFW (Global Fishing Watch) offers a free basic monitoring service to countries willing to participate. As the basic system is purely based on VHF radio its range is limited by the curvature of the earth to approximately 40 nautical miles, depending on the ground station height. Beyond this range, satellites can be used to detect AIS signature and the term **Satellite-AIS (S-AIS)** is used. AIS information supplements marine radar, which continues to be the primary method of collision avoidance for water transport. AIS is required to be fitted aboard all ships of 300 gross tonnage and upwards engaged on international voyages cargo ships of 500 gross tonnage and upwards not engaged on international voyages and all passenger ships irrespective of size (IMO 2019). In the EU All EU member-country-flagged fishing vessels greater than 15 metres are required to operate AIS. Some nations, such as Canada, don't insist on fishing vessel owners using an AIS at all, and most small boats (for example 90 % of the Indonesian artisanal fleet) aren't required to carry AIS (Heffernan 2019).
- *VMS (Vessel Monitoring System)* - This is a term frequently used for satellite-based monitoring system which at regular intervals provides data to the fisheries authorities on the location, course and speed of vessels (European Commission 2016). Strictly

speaking, AIS is also a Vessel Monitoring System, but shall be referred to as AIS, rather than VMS in this chapter. Within the EU VMS is compulsory for fishing vessels longer than 12 m (EU 2016). V MS are typically more expensive than the basic AIS systems and can range from very simple systems with “black box transceivers” (no user interface on board) to more complicated systems. The systems report the vessels location once every two hours (but most devices record the location at more frequent intervals). In the UK the introduction of the Inshore Vessel Monitoring Systems (I-VMS) for fishing vessels under 12 metres operating in English waters has recently been delayed (Marine Management Organisation 2019).

- *Electronic Recording and Reporting System (ERS)* - also commonly referred to as E-Logbook, contribute to better management of fish stocks by keeping track of catches (origin and volume) and gear used. As part of the EU VMS system an Electronic Reporting System (ERS) is also implemented which automates collection of catch data, and exchange of data between EU states. On-board logbooks are mandatory requirements for high sea fishing vessels in some RFMOs such as the Indian Ocean Tuna Commission (Girard and Du Payrat 2017).

The development and proliferation of these digital MCS (monitoring, control and surveillance) technologies over the last decade has opened up opportunities for private actors, including non-governmental organisations (NGOs), to voluntarily support states to (1) survey their territorial waters, (2) close the (perceived) regulatory gaps in the high and/or (3) proactively demonstrate the traceability of fish products and/or ‘good’ fishing practice (Toonen and Bush 2018). Examples of such organisations include for example the International MCS Network[1], whose overarching goal is to improve the efficiency and effectiveness of fisheries-related MCS activities through enhanced co-operation, coordination, information collection and exchange among national organisations and institutions responsible for fisheries-related monitoring, control and surveillance or Global Fishing Watch[2], as well as work of many other international charities and trusts.

Apart from technologies, procedures need to be in place to avoid the trade of IUU fish. Therefore, within the EU the catch certification scheme was established to protect the EU market against products stemming from illegal fishing. Certificates are required for each

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[1] International MCS Network: https://imcsnet.org

[2] Global Fishing Watch: https://globalfishingwatch.org/

consignment of fishery products entering the EU territory, ensuring that fishery products from third countries come from legal sources. As until the middle of 2019 this was paper-based and could be tampered with - copies of the same catch certificate could have been used to import multiple consignments through multiple entry points into EU member states. Due to absence of a centralised database, under the old paper-based system authorities in one EU member state were unable to conduct cross-checks of catch certificates and related documents submitted to other member states. In May 2019 a new digital system ("CATCH") was introduced and is expected to be compulsory by 2021 (Godfrey 2019; Ganapathiraju 2019; European Commission 2019).

An overview of the potential performance improvement rating of recent (2015-2019) innovations for IUU fishing and vessel monitoring are outlined in Figure 17-1.

		Technical Risk	
Performance	Low	Moderate	High
Disruptive	• Global Fishing Watch – data analytics to combat IUU • OceanMind	• Using AI and predictive analytics on satellite AIS data (Spire Global) • Synthetic aperture radar (SAR) for high-resolution vessel monitoring from satellites • Radarsat Constellation	
Transformative	• Trade data analytics (Detect-IT) • Advances in regulations of using electronic monitoring on board • Reef Cubes – physical barriers to prevent IUU • Handheld DNA scanner (Nanopore) to identify fish species	• Solar powered ultra-light vessel tracking system (Pelagic) • Acoustic detection systems • Drone systems combining drones and AI • FishFace – image recognition system for fish species • Handheld DNA scanner (Conservation X Labs) to identify fish species	• EM system for longline vessels, with AI for weight and species detection
Incremental	• Sensors for picking up vibration from trawling activity or other on-board activity • Improvement in unmanned surface vehicles for maritime operations (hardware) • Coastal surveillance using UAVs • Handheld DNA scanner (Nanopore) to identify fish species	• Use of smartphones for VMS applications	• Using tagged marine animals to detect IUU activities

Figure 18-1: Performance and technical risk rating of innovations in combatting IUU fishing activities.

**See section 4.4 for definitions of the performance and technical risk rating scales.*

18.2 Advances in vessel monitoring systems

The basic technologies for vessel monitoring systems and AIS have been known for a long time and they have been used in monitoring fishing vessels. However, constant improvements are being made for better observational capabilities. As originally AIS was implemented as a safety precautions for marine vessels, the system can be switched off – a feature which creates “dark vessels” and can hide IUU activities.

Further the technology of VMS as well as the operation of such a system can be costly and therefore not suitable for poorer nations.

Advances in these systems include:

- Advances in satellite technologies: In recent years image resolution of optical images and also radar images have improved, and cost of those images has reduced significantly due to new private operators in this sector (“NewSpace”). The increase in the number of operating satellites means that satellites can be used to monitor vessel movements from space. These data can be combined with data from satellite AIS and VMS systems, creating a more complete picture of vessel movements and potentially their activities. The key to making the information collated from these sources actionable is high-speed data access and timely analysis.
- Advances in image recognition / artificial intelligence: Advances in data handling, including artificial intelligence algorithms make it faster to analyse and more feasible to combine data from various sources.
- Advances in hardware to make VMS more cost-effective.

Innovations with a potential for disruptive performance improvement

Using AI and predictive analytics on satellite AIS data: Spire Global is a company that operates a fleet of more than 80 small satellites (“CubeSats”) which observe the earth using “GPS radio occultation” - monitoring the bend in GPS radio signals. Thus, data including profiles for temperature, pressure and humidity can be acquired as well as signals which originate from AIS systems. In August 2017, Spire Global Inc. released an API (Spire Sense Cloud) that delivers satellite-AIS data enhanced with machine learning. The platform allows access to cleansed AIS data and delivers predictive analytics (Spire Global n.d.; Etherington 2017). In February 2019 Spire Global announced the launch of a new business unit, Spire Maritime, to be specifically dedicated to developing satellite data and analytics solutions for the Maritime industry (Spire Global 2019). The technology platform has been patented (Platzer and Vaujour 2019)

Technology Readiness Level: 6-8; Technical risk: Moderate

Synthetic aperture radar (SAR) for high-resolution vessel monitoring from satellites: Iceye, is a Polish and Finnish microsatellite manufacturer, founded in 2014. The company developed a synthetic aperture radar (SAR) systems which can deliver images down to 1 m resolution. One of the targeted applications of their technology are advanced monitoring solutions for maritime authorities, organisations and industries (Iceye 2019b). In 2019 Iceye started a collaboration with Spire Global to enable the detection of “dark vessels” (vessels which have switched off their AIS system) and illegal activities at sea. The new product from this collaboration will assist in the detection of illegal transhipments and enable countries with a never before available level of visibility and awareness of vessels within exclusive economic zones. (Iceye 2019a)

Technology Readiness Level: 6-8; Technical risk: Moderate

Satellite imaging: RADARSAT Constellation Mission is a 3-spacecraft fleet of earth observation satellites operated by the Canadian space agency. The satellites are capable of SAR imaging, similar to Iceye, and will be used to detect IUU fishing activities (Chase 2019).

Technology Readiness Level: 6-8; Technical risk: Moderate

Innovation with a potential for transformative performance improvement

Solar powered ultra-light vessel tracking system: Pelagic Data Systems created an ultra-light Vessel Tracking System which is solar powered and is suitable for the “autonomous tracking of vessels of any size, including those not large enough to be well-suited for AIS or VMS systems”. In contrast to some existing VMS, the position of the vessel is recorded every few seconds and a year’s worth of data can be stored directly on board. The devices are also very cost-effective with EUR 300 per device and EUR 300 for one year of data service. (Kouvelis and Deligianni 2018; SeaWeb 2018).

Technology Readiness Level: 6-8; Technical risk: Low

Innovations with a potential for incremental performance improvement

Use of smartphones for VMS applications: Smartphones can be used to collect VMS data, so that monitoring of fishing vessels can be enabled on a handheld device. Satellite operators can provide software which shows vessel location, estimated time of arrival or the course over the last 24 hours, and these data can be send using a 3G or 4G connection to the device owner (Girard and Du Payrat 2017).

Technology Readiness Level: 6-8; Technical risk: Low

18.3 Acoustic observation technologies

Acoustic systems are already widely used for mammal and fish activity measurements and ocean ambient noise control applications, with acoustic autonomous recorders being the most popular tool. These devices could also be used to detect IUU fishing activities. Acoustic sensors are particularly effective in situations where silent, undetectable monitoring of IUU activity is required. The IUU fishers would be unaware of the surveillance, and therefore not inclined to modify their behaviour, as would happen with visible forms of surveillance. Data collected could also be used in connection with Vessel Monitoring System (VMS) information to identify non-VMS equipped ships, which could indicate IUU fishermen who typically do not use VMS or automatic identification system information on larger vessels (Salloum, Sutin, and Pollara 2018).

Innovation with a potential for transformative performance improvement

Deploying of hydrophones to investigate fishing: The US-based Stevens Institute of Technology developed the Stevens Passive Acoustic Detection System (SPADES). SPADES consists of two - or potentially more - moorings, each of which has four highly sensitive wideband hydrophones deployed on a collapsible frame. A data acquisition system that captures the signals with a frequency content up to 100 kHz is installed at the centre of the mooring. SPADES can detect, track, and classify surface vessels. Utilising this technology, the Stevens Institute of Technology has developed the Stevens also developed and built the Portable Acoustic Recorder System (PARS), which is designed to digitally record precisely time-stamped signals acquired by interchangeable sensors, like hydrophones or microphones. The advantage of these systems is that they are relatively low in cost and are simple to use. The disadvantages include potential for theft and concerns about false positive detections. Further development work is necessary to prove the concept of automated methods of vessel detection, tracking, and classification so that IUU fishing can be alleviated (Salloum, Sutin, and Pollara 2018), see also (Salloum *et al.* 2017).

Technology Readiness Level: 3-5; Technical risk: Moderate

Innovation with a potential for incremental performance improvement

Trawl monitoring by picking up vibrations from trawling activity: Russian Space Systems holds a patent on using an acoustic method to monitor trawling (Method and device for monitoring fishing operations using trawl when monitoring fishing vessels 2017). The patent describes the use of acoustic metrology to measure vibration which occur during trawling. Hence this monitoring system can be used to control at when a vessel is undertaking trawling. The device would be placed on board of the vessel and would address the current lack of data on the actual operation of fishing gear.

Other similar sensors monitoring the operation of fishing gear already exist and can be used by electronic monitoring (EM) systems.

Technology Readiness Level: 6-8; Technical risk: Low

Using tagged marine animals: Marine animals, such as e.g. sharks, are frequently tagged with acoustic devices (including GPS trackers) in order to study their behaviour. During an event in 2014 marine scientists suddenly detected a near simultaneous loss of 15 tags, which could be traced to illegal fishing activity in the area. It has now been speculated whether the tagging of animals can be used to detect illegal fishing. The tracing of sharks could also lead to finding fish – information the fisherman may have but not the coastguards (Manson 2019; Tickler *et al.* 2019).

Technology Readiness Level: 1-2; Technical risk: High

18.4 Drones

Drones are ‘unmanned aerial vehicles/systems’ (UAS, also named RPAS “remotely piloted aircraft systems” or UAV “unmanned aerial vehicles”) operating under radiofrequencies and pre-programmed GPS-guided flight scripts that provide near-real-time data on the people, processes and landscapes they survey (Clarke 2014). It has already been demonstrated that camera-equipped drones can:

- Detect fishing vessels and identify if they are registered in a given jurisdiction.
- Observe the use of fishing gears deployed from both vessels and land.
- Can relay near-real-time data on location and movement of vessels.

For example, in response to EU sanctions for IUU fishing banning export to the European market, the government of Belize deployed ‘quadcopter’ drones with live video streaming to extend the MCS capacity of their 70 personnel strong fishing enforcement department responsible for patrolling 390 km of coastline and more than 200 islands. Similar technologies are also being adopted by Palau, Jamaica and Costa Rica to detect and prosecute illegal fishing, and by NGOs like Sea Shepherd, Black Fish and Earthrace Conservation ‘to detect, record, and in some cases intercept vessels undertaking illegal activity, or provide enforcement departments with robust information to aid in prosecution’. However, questions have been raised over the capacity of drones to make the oceans legible as the drones’ overall coverage may be extensive, but they are only able to give a snapshot of the ocean at any given moment, and provide limited insight on specific behaviours related to non-compliance. (Toonen and Bush 2018).

In the UK the main barrier to implementation is regulatory, such as the requirement for a license from the Civil Aviation Authority to operate in some areas of the UK, and the consent to operate drones over the sea (personal communication).

Innovation with a potential for transformative performance improvement

Drone systems combining drones and AI: FishGuard is a partnership between North African company ATLAN Space, Grid-Arendal and Trygg Mat Tracking. The partnership was recently awarded $150,000 by the National Geographic Society in its Competition to Combat Illegal Fishing, a search for innovative solutions and technologies that protect and sustain fisheries in coastal communities. FishGuard’s aim is to use drones to identify and reduce illegal fishing in the Republic of Seychelles. The drone system will register the type of ships that are present on the water, and if recognised as a fishing vessel will establish whether the boat is authorised. The system could use with any type of drone. It was noted that a small drone with a combustion engine could offer an operational range of up to 800 km (Stop Illegal Fishing 2018). Programmes to use drones to combat illegal fishing have also started operating in other countries, e.g. Costa Rica (personal communication).

Technology Readiness Level: 6-8; Technical risk: Moderate

Innovation with a potential for incremental performance improvement

Unmanned surface vehicles: Maritime Robotics[1] is a Norwegian company dealing in unmanned vehicles (surface vehicles, e.g. boats, as well as moored balloons) for maritime operations. One of the applications listed for this company is combatting IUU fishing.

Technology Readiness Level: 9; Technical risk: Low

Coastal surveillance using UAVs: UK company Martek[2] has recently developed a service supporting coastguard operations using remotely piloted unmanned aerial vehicles (UAVs) for applications including pollution detection, law enforcement, but also fishery control. The unique service involves flying remotely piloted aircraft systems and unmanned aircraft systems up to 100 km 'beyond visual line of sight' at sea to provide vessel detection, identification, behaviour monitoring & tracking.

Technology Readiness Level: 9; Technical risk: Low

18.5 Blockchain

The blockchain algorithm became prominent when used in cryptocurrencies such as bitcoin. The algorithm has applications in supply chain monitoring, as entries cannot be falsified and are therefore traceable as the product(s) move from one link in the chain to another (see chapter on Sustainability and Accreditation Labels). This should make it impossible to mix illegal catch with legal catch. However, monitoring and verifying the first entry is essential for the system to work.

Please refer to chapter 23 on ‘Sustainability and Accreditation Labels’.

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[1] Maritime Robotics: https://www.maritimerobotics.com/wave-glider

[2] Martek: https://www.martek-marine.com/maritime-surveillance-and-detection

18.6 Trade data analysis

Analysis of available trade data provide an important tool in combatting IUU fishing as irregularities can lead to detection of IUU activities.

Innovation with a potential for transformative performance improvement

DETECT-IT: Is a data analytics tool[1] which was developed by TRAFFIC, World Wildlife Fund (WWF) and Hewlett Packard Enterprise. It can be used by businesses, non-governmental organisations, Customs officers, law enforcement and fisheries officials to search quickly through fish trade data to identify potential illegally caught and traded fish products around the world. The tool enables users to visualise the data in a variety of ways, highlighting major discrepancies in trade data as a red flag and a starting point for researchers, policy-makers and fishery officials to investigate further (Traffic 2017)**.**

Technology Readiness Level: 9; Technical risk: Low

18.7 On board electronic monitoring (EM)

Onboard electronic monitoring systems allows fishing activities on board to be monitored remotely, without there being observers onboard of a vessel. The systems - usually a central computer attached to gear sensors and video cameras - allow authorities to monitor and record a vessel's activity in real-time. It has been demonstrated that installing and using EM systems that cover all fishing activities is considerably cheaper than placing observers on vessels. While savings estimates vary based on fishery size and type, a 2018 study in Peru estimated that an EM system cost half that of human observers; for pot cod vessels out of Alaska, costs were estimated at 27 % to 41 % less than observers; and for commercial gillnet vessels out of Denmark, they were estimated at 15 % less (Pew Trusts 2019). Other benefits of EM systems include: building shared trust in fisheries, operational benefits, seafood market benefits (Michelin, Elliott, and Bucher 2018). It is estimated that up-to-date 1,000 EM system have been installed over the last two decades, and in a conservative scenario of the future

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[1] DETECT-IT: https://www.worldwildlife.org/projects/detect-it-building-a-better-way-to-detect-illegal-fish-trade

another 5,000 vessels will be fitted with EM systems in the coming decade. In more favourable scenarios, with the right regulatory environments and user incentives this number however can be increased to up to 50,000 vessels (Michelin, Elliott, and Bucher 2018).

Technology used for electronic onboard monitoring include:

- Video cameras (specific uses such as gear settings and gear hauling as well as general observation of on-board activities).
- Hydraulic and drum rotation sensors to monitor gear usage.
- VMS (vessel monitoring systems) which track the vessel's route and pinpoint fishing times and locations.

Data from above systems can be combined for best monitoring practices. The limits of EM systems are that they cannot collect biological data and may not capture compliance with mitigation measures (e.g. steps to reduce bycatch and discard). They also require basic maintenance from the crew.

EM systems have been in operation for a while, but improvements are still ongoing. In the UK the "Catch quota project" was initiated in 2011 and has helped to eliminate discards at sea helped fishermen verify quotas, eliminate waste, and encourage selective fishing practices (Tisot n.d.).

Innovation with a potential for transformative performance improvement

Advances in regulations of using EM: While many EM systems exists and/or are in developments, standards, specifications and procedures need to be in place as well as funds to enable implementation of EM (Pew Trusts 2019).

Technology Readiness Level: 9; Technical risk: Low

EM system for longline vessels: In 2018, the North Pacific Fishery Management Council and NOAA Fisheries implemented an electronic monitoring program to provide a monitoring alternative for longline vessels, where accommodating an observer can be logistically difficult. The system uses two cameras that pair images, allowing for highly precise measurements - even of flopping fish being hauled onboard. Currently work is ongoing on incorporating AI into the systems, so that the system will eventually be able to automatically process length measurements and highly accurate species identification for most common species (NOAA 2019).

Technology Readiness Level: 3-5; Technical risk: High

18.8 Integrated platforms

Shipping vessels can be tracked via the “traditional” terrestrial systems (AIS and VMS), as well as by newly emerging “NewSpace” satellite observation technologies (either tracking AIS systems or observing vessels using images from space and/or radar). In order to combat IUU efficiently data from these sources need to be collated and analysed in a time efficient manner. Data sharing between jurisdictions of different countries and different observation technologies has in the past been a major obstacle in combatting IUU activities. Integrated platforms try and overcome these hurdles by providing rapid data analysis for nearly real-time information on fishing vessels and their activities.

Innovations with disruptive performance improvement

Global Fishing Watch (GFW): Is a technology platform developed by Google, SkyTruth, and Oceana that uses satellite Automated Information Systems (AIS) data to monitor fishing activity around the world in near real-time. The non-profit institution which developed this platform was set up in 2016. GFW tracks the activity of about 60,000 commercial fishing vessels in near-real-time using AIS. GFW is also collaborating with a growing number of countries to include data from other sources, such as government-operated VMS (Global Fishing Watch n.d.). The GFW platform can also be used by academic institutions to mine data. One example is University of Santa Barbara’s Sustainable Fisheries Group (SFG) which uses GFW in projects such as “Tracking the global footprint of fisheries”, “Understanding the global network of transnational fisheries” and “Can IUU measures provide an alternative pathway to recovering global fisheries”? (Sustainable Fisheries Group UCSB n.d.). Notably countries which made vessel tracking data publicly available through the GFW platform include Indonesia, Chile, Costa Rica, Panama and Namibia (Craze 2019). In total, GFW reports to now be tracking about 65,000 fishing vessels, most of which are more than 15 metres in length and likely account for the majority of fishing activity on the high seas (Huffman 2019).

Technology Readiness Level: 9; Technical risk: Low

OceanMind: is a UK-based not-for-profit organisation that describes itself as empowering and enforcement and compliance to protect the world’s fisheries. OceanMind[1] provide insights and

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[1] OceanMind: https://www.oceanmind.global/about/

intelligence into fishing compliance to those who can most effectively use it. OceanMind began in 2014 as “Project Eyes on the Seas”, a collaboration between the UK Satellite Applications Catapult and The Pew Charitable Trusts. Initially, a collaboration to develop technology fusing satellite data and artificial intelligence to detect illegal, unreported and unregulated (IUU) fishing, it soon developed into a suite of services to help governments and the seafood supply chain to understand the compliance of fishing activities. OceanMind uses an AI-based system to analyse satellite data on pinpoint vessel locations as well as predicting next steps (Satellite Applications Catapult 2018).

Technology Readiness Level: 9; Technical risk: Low

18.9 Fish identification systems

One of the issues in the identification of IUU fishing activities is the exact identification of species. This is necessary for fisherman, but also for officials and authorities to rapidly proof that fish and parts of fish are from protected species.

Innovations with transformative performance improvement

Handheld DNA scanner – Nanopore: UK company Oxford Nanopore Technologies have developed a handheld DNA scanner[1] (MinION) for DNA sequencing “in the field”. The scanner requires a small tissue sample, from which to extract DNA, and a laptop. No internet is necessary, as long as the genetic databases are already downloaded. It may take up to 48 hours to get a good chunk of genome sequence, but the device can reveal a species in an average of three or four hours—and sometimes in just a few minutes. The MinION gives more information than traditional barcoding, which identifies a species using a short, standardized fragment of DNA, and it can sequence a large section of a genome more cheaply than companies like Illumina, which currently full sequencing in a lab. The scanner has been successfully used in a field study on sharks. (Learn 2019; Johri *et al.* 2019)

Technology Readiness Level: 9; Technical risk: Low

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[1] MinION: https://nanoporetech.com/products/minion

Handheld DNA scanner - Conservation X Labs: US company Conservation X Labs is in the process of developing a DNA barcode scanner[1], a "low-cost, handheld, field-ready automated tool to validate the identity of a wildlife or food product, anywhere in the world, without specialised training, equipment, reagents, or even continuous power". Prototypes of the device have been developed and have been piloted with customs enforcement officials in Washington. Fish samples are ground up and solutions are added to free the DNA from cells. The device then analyses the DNA in the sample and compares it to the Barcode of Life DNA library to make an identification. It can be pre-programmed to indicate whether or not the sample matches the DNA of a protected species, and a built-in camera takes a screenshot to serve as evidence. Currently, each test takes about 30 minutes and each sample costs about $15 to process with the scanner (Fujita *et al.* 2018; Baisch, Holmes, and Bohringer 2019).

Technology Readiness Level: 6-8; Technical risk: Moderate

FishFace: Is a project funded by The Nature Conservancy. The project is photographing thousands of fish, recording lengths and weights, and collecting further information in order to create an image recognition system which can spot fish species. Since 2016, when this project won the "Google Impact Challenge" the relevant hardware has been built, the machine learning phase has been accomplished, and device accuracy during fishing trip in Kupang (Indonesia) was shown to be 90-95%. It is hoped that this platform can be used more broadly to e.g. monitor transhipments (Nature Conservancy Australia n.d.).

Swedish company Refind Technologies who are part of FishFace developed a product, the Speciegrade[2] which can be "used both as a standalone unit as well as integrated with an existing processing line. It features a camera inside a tunnel with controlled illumination, feeding its images to a piece of deep learning software, optimised to distinguish between fish species".

Technology Readiness Level: 6-8; Technical risk: Moderate

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[1] DNA barcode scanner: https://conservationxlabs.com/dna-barcode-scanner

[2] Speciegrade: https://www.refind.se/speciegrade

18.10 Physical barriers to IUU

It has been suggested that artificial structures deployed on the seabed could prevent towed fishing gear being used in certain areas

Innovations with transformative performance improvement

Reef cubes: Reef Cubes® by UK company ARC Marine are artificial manmade blocks which can be deployed on the seabed where they can interlock to create physical barriers to towed fishing gear, but also could protect subsea assets such as monopiles, cables, foundations and pipelines. The blocks are made from a marine friendly material and have a surface texture which replicates natural reef features and niches which enhances biological growth (ARC Marine n.d.; Envirotec 2017; Thomas and James 2019). The structures were tested by the University of Plymouth (2019)

Technology Readiness Level: 9; Technical risk: Low

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19 Onboard processing

Contents

From the SIF Executive Board

The method applied in this review has generated numerous examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently happening. It is recognised that there are existing innovations and research areas that are not included here, and new areas where future innovations may occur. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

19.1 Overview: onboard processing

What is the challenge in the UK?

To date, the adoption of, and R&D activity surrounding novel processing technologies onboard UK fishing vessels has been minimal. Due to high costs, state-of-the-art onboard processing is primarily the domain of larger, vertically integrated companies overseeing everything from harvest to processing and trade, such as the case with Dutch, Icelandic and Russian fisheries.

What are the most promising innovation categories?

- **Big data integration –** Real-time communication between various stakeholders of data from harvest to market, for best utilisation and profit
- **Grading and sorting –** Computer vision helps sort fish by size, weight, and species, eliminating a major bottleneck
- **Automation –** Faster and safer slaughter, cutting and end of line processing, with improved quality and utilisation
- **Chilling –** Lightweight, automated and sustainable solutions lead to significant improvement in product quality from point of harvest

Where are important knowledge gaps?

- Onboard automation of bleeding, gutting and heading
- Cost-effective solutions for smaller and medium-sized players

In the past decade, there has been great progress in raw material management, efficiency and quality promotion in fisheries processing. This progress has extended to the modernisation of fishing vessel operations, where processing fish closer to the source has led to better fuel efficiency, safer working conditions, greater automation (and thus less reliance on labour) and catch utilisation - all potentially contributing to a more robust bottom line.

Onboard processing can lead to reductions in processing times of fresh or frozen seafood by up to several days. Such improvements to quality and freshness alone have convinced numerous interviewees of the need to expand processing on vessels. Secondary processing capabilities have also been brought on board, allowing harvesters the flexibility to create value-added products according to real-time market demand. From fillets to by-product processing, creating new product forms even using parts that otherwise would be wasted, all contribute to maximising return on harvests.

The seafood processing sector has undergone various waves of investment throughout the years. While primary processing in salmon facilities has been the main focus onboard processing of whitefish in particular has enjoyed significant growth, with a number of vessels under construction worldwide, especially in Scandinavia and Russia. In the latter a fishing vessel construction boom is underway after the government offered additional fishing quota to companies that built new ships. Those willing to invest in these technologies take the "quantum leap" and seek full automation (IntraFish 2017). The trend for larger-scale operations is to combine a variety of technologies encompassing slaughter, cutting and end of line processing including by-product processing. New vessels also possess the foresight to set aside space and capacity for additional equipment to allow further automation and diversification into other consumer-ready products (personal communication).

The figures present a tantalising proposition – in 2018, the Faroese fishing vessel *Nordborg* may have been the world's most profitable pelagic fishing vessel, earning double the standard price value for herring it hauled onboard in 2017. Almost 45% of the £24 million total delivered catch value was the result of value-adding via onboard production of fillets, fishmeal and fish oil from offcuts. However, while Norwegian vessels were the first to start up with onboard production of fishmeal and fish oil, Nordborg currently is the only vessel thought to be using the technology on a large scale (IntraFish 2018b).

On a technical level, in addition to size, onboard processing equipment face numerous challenges, such as unsteady seas, vessel vibration, short-interval peak volumes and lack of speedy technical support (Optimar 2018). On a practical level, restrictions placed by regulations, quotas and the diverse needs of a fleet have hindered renewal efforts worldwide (personal communication).

However, the greatest barrier to widespread adoption of these technologies remain their cost, which is prohibitively beyond reach for most small and medium-sized enterprises. A Russian fishing company has recently commenced construction of groundfish freezing trawlers that produce headed-and-gutted and value-added products, including frozen-at-sea fish fillets, mince, liquid fish waste and fish meal. The cost of each trawler is around £34 million (IntraFish 2019).

With even basic water-jet cutting and portion grading equipment costing as much as £425,000, a healthy return-on-investment was said to only be possible from harvesters and processors achieving volumes of 15 to 20 tonnes per day (personal communication). Coupled with high satisfaction with the status quo, upgrading remains a tough sell for a historically conservative industry (personal communication).

In addition to capital expenditures, operating and labour costs must also be considered. In the case of early adopter Norway, although today there are eight vessels that fillet whitefish on board, many harvesters continue to opt for headed-and-gutted (H&G) fish, which are still more profitable because H&G factories on vessels are easier to operate and require fewer staff (IntraFish 2018a). One interviewee also confirmed the continued profitability of these simpler operations (personal communication).

Indeed, numerous interviewees commented that due to high costs, state-of-the-art onboard processing is primarily the domain of larger, vertically-integrated companies overseeing everything from harvest to processing and trade, such as the case with Dutch, Icelandic and Russian fisheries. These players, backed by capital investment to experiment and upgrade, can derive the most benefit from reduced labour through automation, as well as big data to maximise efficiency and profit throughout the value chain (personal communication). Furthermore, one interviewee mentioned that onboard processing also tends to negatively affect coastal communities when the work is moved out to sea and that it can be more challenging to enforce regulations in fisheries where secondary processing is carried out onboard.

In the UK as well as many northern Atlantic countries, adoption of novel fish processing technologies as a whole has been “conservative and incremental”, even amongst large farmed salmon and trout operations (personal communication). For one equipment manufacturer, sales of onboard processing equipment in the UK was deemed a “low priority” due to lack of market demand (personal communication). Low adoption was also confirmed in the USA, where small and medium-sized operations dominate (personal communication).

Modularity, flexibility and retrofitting on the other hand may appeal to smaller harvesters, who can start with basic automation, then freeze catches and by-products for further processing on land. Flexibility in terms of containerized solutions (e.g. fish protein hydrolysate reactors) that can be loaned out seasonally can make innovations more affordable (personal communication). However, for purchased equipment, another interviewee warned that due to the high cost of equipment and fitting, vessels must be able to operate for an additional 10 to 15 years to justify the investment. Regardless of the size of the operation, modernisation of fleets will require step-wise cost-benefit analyses weighing equipment expenditures against reduced labour costs (personal communication).

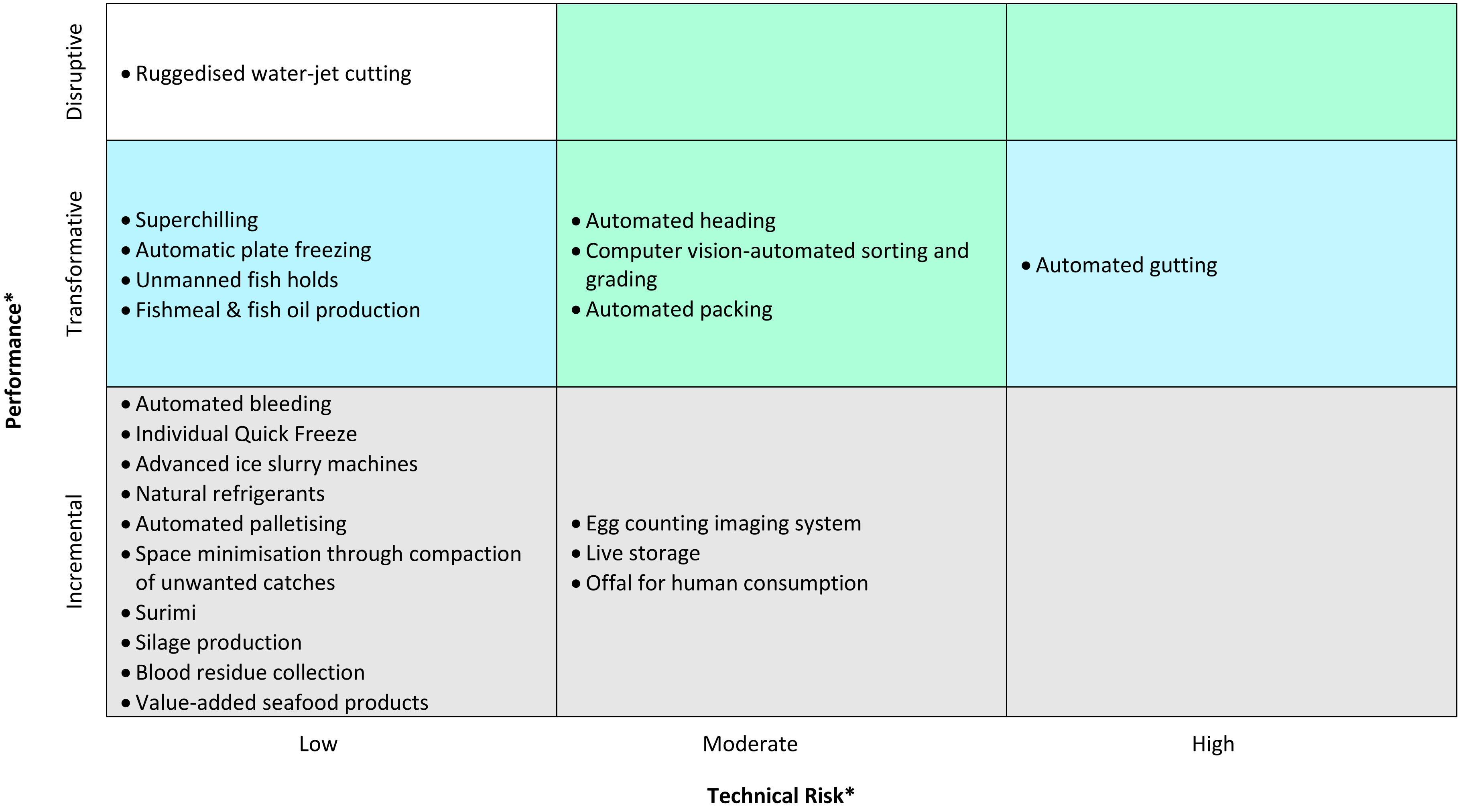
Since 2015, innovations in the area of onboard processing have primarily been driven by industry, particularly in Western Europe and Scandinavia. Patent activity is strongest in China, although for species and value-added products with little relevance to the UK. Furthermore, as technologies tend to be adapted from their onshore counterparts, recent innovation activity within the timeframe of this study is limited.

Looking ahead, the use of disruptive technologies such as big data and AI in fisheries and aquaculture, although not widespread now, may offer immense opportunities to enhance the technical and financial efficiency and sustainability of the sector, to improve sustainability, to create new work opportunities and to improve food security and livelihoods (FAO 2018).

Please note: the focus of this chapter is on innovations that make desirable, physical changes to seafood products onboard via primary and secondary processing. A fuller description of primary processing technologies may be found in chapter 21 ‘Primary processing technologies’.

Those pertaining to the improvement of the quality, and mitigation of deterioration of seafood products are covered in the chapter 22 ‘Quality and food safety management systems and accreditations’.

An overview of the potential performance improvement rating of recent (2015-2019) innovations in onboard processing in marine and diadromous fisheries are outlined in Figure 19-1.



Performance*	Low	Moderate	High
Disruptive	• Ruggedised water-jet cutting		
Transformative	• Superchilling • Automatic plate freezing • Unmanned fish holds • Fishmeal & fish oil production	• Automated heading • Computer vision-automated sorting and grading • Automated packing	• Automated gutting
Incremental	• Automated bleeding • Individual Quick Freeze • Advanced ice slurry machines • Natural refrigerants • Automated palletising • Space minimisation through compaction of unwanted catches • Surimi • Silage production • Blood residue collection • Value-added seafood products	• Egg counting imaging system • Live storage • Offal for human consumption	

Technical Risk*

Figure 19-1: Performance and technical risk rating of innovations in onboard processing.

**See section 4.4 for definitions of the performance and technical risk rating scales.*

19.2 Primary processing

In this first section, examples of R&D efforts relating to specific primary processing steps (from slaughter to cutting) will be presented, concerning species relevant to the UK, where applicable.

19.2.1 Grading and sorting

The need for fast and accurate onboard grading is apparent, as onboard processing often forms a bottleneck with traditional manual or semi-automatic grading. This bottleneck often means that product quality suffers, with otherwise viable product being discarded. Alternatively, grading accuracy is sometimes sacrificed to curtail processing delays, but this creates its own problems down the line. Either way, this dilemma results in substantial losses for the industry (Skaginn 3X 2019).

Innovations with a potential for transformative performance improvement

Computer vision-automated sorting and grading: Several companies are developing onboard sorting and grading systems that make use of computer vision systems. Norwegian processing technology provider Optimar is developing a system that can detect and sort whitefish, distinguishing between cod, haddock and saithe (with more species planned) based on image technology. The goal is to separate the fish by size and weight, enabling the operator to work more efficiently and at a higher capacity (IntraFish 2018a).

Icelandic processing equipment manufacturer Valka recently installed a vision-based system for recognising different fish species on seven new Icelandic fishing boats. The system uses learnable evolutionary algorithms to analyse the catch, distinguish between the species and automatically sorts it (Fishermen’s News 2019).

SEASCANN is an EC Horizon 2020-funded project of Icelandic processing manufacturer Skaginn 3X to develop an onboard solution which creates a digital record of a vessel’s catch as an integrated part of the grading process. The solution has currently been integrated onboard five vessels in Iceland as part of a pilot project. As well as sorting species and grading on size, this system can grade on colour and quality. A particular focus of the Skaginn 3X system is on the capture and sharing of catch data across the value chain. As fish are sorted, the system creates a digital record, stored in a cloud-based communication system, making real-time data available to a number of interested parties at once, including fisheries, land operators, processors, consumers and the authorities. Such a pipeline of live data enables real-time assessment of value and better planning for market placement and processing. The system is anticipated to launch in August 2020 (Skaginn 3X 2019).

Solutions based on data integration along the value chain are more suited to larger, vertically-integrated companies where harvest, processing and sales are conducted by one company (personal communication).

Technology Readiness Level: 6-8; Technical risk: Moderate

Innovations with a potential for incremental performance improvement

Egg counting: Developed by a group of French researchers, ZooCAM is a novel, in-flow imaging system allowing for fast and accurate onboard counting, sizing and classification of staged anchovy and sardine eggs in almost real-time after collection. When used in line with Continuous Underway Fish Egg Sampler (CUFES), it provided high-resolution maps of eggs (Colas *et al.* 2018).

Technology Readiness Level: 3-5; Technical risk: Moderate

19.2.2 Slaughter

Once fish are landed, slaughter encompasses the steps from stunning/bleeding to gutting, cleaning and heading fish. Weighing, grading and sorting may occur during this process.

An area with innovation potential lies in onboard bleeding, which is still largely carried out manually, even in early adopter countries like Iceland. Precise equipment that can accommodate a wide range of sizes is still required, so much so that some new vessels have left space to fit these in the future (personal communication). However, one fish processor commented that while vast improvements can be made to animal welfare and product quality (that can then be sold onto consumers at a premium), most capture fisheries continue to place little importance on this area. Furthermore, additional staff may be required to monitor compliance, the cost of which will be a deterrent (personal communication).

Innovations with a potential for incremental performance improvement

Automated bleeding: Skaginn 3X's FIFO Bleeding Wheel can be fitted into any type of workflow on land or at sea, wild or farmed as well as white or oily fish processing.

The Skaginn 3X FIFO Bleeding Wheel uses the first-in, first-out process, which ensures that the first fish that enter the bleeding wheel will also be the first to leave, thus ensuring traceability. Gentle back-and-forth tumbling action of the drum combined with a mechanically generated current replicate the natural movement of the fish through water, expelling the blood from the tissue (Skaginn 3X 2017a).

Technology Readiness Level: 9; Technical risk: Low

Norwegian fish handling company Optimar has recently received funding from Norway's Fisheries and Aquaculture Industry Research Fund (FHF) to develop technology for automated bleeding on board. It is anticipated that "this development will take a few years" (IntraFish 2018a).

Technology Readiness Level: 3-5; Technical risk: Moderate

Swim-in technology: In recent years, Optimar has invested in automated technology that stuns and kills fish onboard and in processing facilities, including a "swim-in" system that works by creating a flow of water allowing the fish to orient themselves to swim head-first into an electric stunner, as required by regulations (Fishermen's News 2019).

Technology Readiness Level: 9; Technical risk: Low

Please also refer to chapter 14 'Fish welfare in wild-capture marine fisheries'.

19.2.3 Heading and gutting

Innovations with a potential for transformative performance improvement

Automated gutting: Automated gutting was highlighted by an interviewee as an area with room for improvement, as it is still largely carried out manually, even in early adopter countries like Iceland. Precise equipment that can accommodate a wide range of sizes is still required, so much so that some new vessels have left space to fit these in the future (personal communication).

Technology Readiness Level: 3-5; Technical risk: High

Innovations with a potential for incremental performance improvement

Automated heading: Cost-effective automated heading solutions are also in demand (personal communication). Today there are five autoline vessels and three factory trawlers that fillet whitefish on board in Norway. Several vessels have licenses, but do not use them as it is more profitable to produce headed-and-gutted (H&G) fish, because factories on H&G vessels are easier to operate and require fewer staff (IntraFish 2018a).

Technology Readiness Level: 9; Technical risk: Low.

19.2.4 Cutting

Loosely speaking, cutting involves all the physical and mechanical steps taken to prepare fish prior to landing and may include: filleting, trimming, pin bone removal, skinning and portioning. One of the challenges that processors face is that customers are continually requesting narrower product specifications, requiring flexible and precise technologies.

Innovations with a potential for disruptive performance improvement

Ruggedised water-jet cutting: Iceland’s Valka has introduced the Valka Cutter to optimise the cutting and portioning of each fillet to match their customer orders, to reduce food waste and achieve a better overall price mix. The device automatically removes pin-bones and cuts to the desired portions: the machine uses a combination of an X-Ray and 3D image processing system along with robot-controlled water jets to locate and cut pin bone and portions. Valka offers a marine version, with a more compact and sturdier construction to withstand onboard vibrations. Cabinetry and compartments are temperature-controlled to prevent condensation (Valka 2019).

Technology Readiness Level: 9; Technical risk: Low

19.2.5 End of line

End of line involves finishing steps that may include quality control, chilling/freezing and packaging.

N.B. For innovations related to quality control and traceability please refer to the chapter 22 ‘Quality and food safety management systems and accreditations’.

Innovations with a potential for transformative performance improvement

Superchilling: A method that makes ice (accounting for up to 20% transport weight) redundant in cooling and storing fish by using a new technology to cool fish to -1° to -2°C, on the borderline of being frozen, but cooling it beyond what can be achieved with ice. A Norwegian study on farmed salmon confirmed superchilled salmon holds its water content better throughout the production and storage processes, and has a better culinary yield, e.g. when poached. The qualities and the firmness of the fish remain for longer, maintaining quality more effectively through production. Microbiological analysis has also confirmed that the fish stays fresher for longer than conventionally chilled fish, also confirming that superchilling can extend the shelf life of the finished product by as much as a week (Nordic Innovation 2016). Skaginn 3X's SUB-CHILLING™ Onboard[1] superchilling solution offers similar results in groundfish. Superchilling technologies are being widely fitted into new Icelandic fresh fish trawlers (personal communication) .

Technology Readiness Level: 9; Technical risk: Low

Automatic plate freezing: Skaginn 3X's automatic, onboard plate freezer can be used for bulk production of both small and big packs. Product quality is maintained by using patented non-pressure technology that ensures quality equal to that of blast freezing, but requiring only a quarter of freezing time and energy of a traditional blast freezer (Fishermen's News 2019).

Technology Readiness Level: 9; Technical risk: Low

Innovations with a potential for incremental performance improvement

Individual quick freezing (IQF): Products are frozen individually and rapidly on a conveyor system, with low temperature air being forced upon it, thus giving a naturally shaped product of high-quality. This technology was highlighted by one interviewee (personal communication).

Technology Readiness Level: 9; Technical risk: Low

Advanced ice slurry machines: Icelandic company Thor Ice offers Chilling Solutions, its new line of energy-efficient ice slurry machines to fishing and aquaculture, requiring a very modest amount of on-board space. Additionally, their patented IceGun system can shoot semi-dried ice slurry onto fish fillets. "Ice-on-Demand" capability is possible with the production capacity of the machine co-ordinated against the supply and demand of power produced on board. The

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[1] SUB-CHILLING™ Onboard: https://www.skaginn3x.com/products/sub-chilling-onboard

portfolio ranges from compact units of as little as 50 litres/hour, up to industrial ammonia-based systems with a daily production capacity of several hundred tonnes (World Fishing & Aquaculture 2019b).

Technology Readiness Level: 9; Technical risk: Low

Natural refrigerants: Refrigerant solutions based on natural refrigerants such as ammonia and CO_2 can improve the efficiency and sustainability of onboard processing. Norwegian company Therma Industri provides refrigerated seawater (RSW) solutions using seawater-cooled condensers, as well as evaporative and air-cooled capacitors. Seafood investor Broodstock Capital has acquired four-fifths of the company's shares (World Fishing & Aquaculture 2019a).

Technology Readiness Level: 9; Technical risk: Low

Innovations with a potential for transformative performance improvement

Automated packing: Norwegian processing technology provider Optimar is developing a new tool for packing fillets onboard, with funding from Norway's Fisheries and Aquaculture Industry Research Fund (FHF). Oftentimes, the area in the factory requiring the most people is the packing table, where fillets are placed into cartons one-by-one. Optimar is convinced an automated packing line that determines the location, weight class and destined carton would increase profitability during fillet production. It plans to have a prototype ready by around 2020 (IntraFish 2018a).

Technology Readiness Level: 3-5; Technical risk: Moderate

Innovations with a potential for incremental performance improvement

Compact palletiser: Optipall compact[1] is Optimar's automatic operated palletising system for a variety of cartons / block transporting pallets to cargo lift or to front cargo hold.

Technology Readiness Level: 9; Technical risk: Low

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[1] Optipall compact: https://optimar.no/solutions/onboard-fish-handling/products.html

19.2.6 Storage

Innovations with a potential for transformative performance improvement

Unmanned fish hold: Icelandic company Skaginn 3X have fitted a trawler, with what is claimed to be the world's first automatic tub transportation and storage system. Its Onboard Fish-hold Robotics system will allow tubs to be filled on the processing deck, transported to and stored in the fish holding deck automatically. In addition to faster processing, workers are no longer required in the hold during fishing or catch landing, providing a safer working environment (Skaginn 3X 2017b).

Technology Readiness Level: 9; Technical risk: Low

Innovations with a potential for incremental performance improvement

Live storage: Norwegian shipbuilder VARD has recently secured a contract to build a new state-of-the-art stern trawler for a Faroese fishery. The trawler will feature VARD's innovative catch handling systems, including a live fish tank to keep catches healthy until processing (Energy Industry Review 2020). One interviewee cautioned however, that while the technology would be suitable for increasingly remote trips, the cost of a new, redesigned vessel would be prohibitive for most fisheries. Instead, they recommended retrofitting primary processing equipment as a cost-effective alternative (personal communication).

Technology Readiness Level: 9; Technical risk: Moderate

Space minimisation: Compaction was proposed by an international team of researchers to circumvent the space and refrigeration challenges of unwanted catches, while still complying with EU zero discards policy. A pilot hydraulic press was tested to achieve maximum volume reduction while keeping liquid effluent pollution at a minimum. Cost savings are proposed from volume reduction and the recovery of added-value compounds from the press cake and liquor (Pérez-Gálvez *et al.* 2016).

Technology Readiness Level: 3-5; Technical risk: Low

19.3 Secondary processing

Advancements in on-board processing technology have created value-added opportunities that further increase the value proposition of especially new-builds. The main innovations concern ancillary products as the potential for onboard secondary processing to create added-value products, such as breading and fillets with butter, remains limited (personal communication).

Innovations with a potential for transformative performance improvement

Fishmeal and fish oil: With the price for fishmeal and fish oil at least doubling since 2000, there is much more interest for having fishmeal and fish oil processing on board trawlers. The recent boom in building has meant a rethink of how vessels are designed, with many seeing fishmeal and oil production as a necessity. Vessels originally built without meal and oil processing equipment are also seeking conversions and retrofits at costs ranging from £1.3 million to £2.1 million. However, sufficient volume throughput is crucial for good return-on-investment. Volumes under 40 metric tons per day of bycatch or offcuts should be frozen and brought onshore (IntraFish 2016).

Technology Readiness Level: 9; Technical risk: Low

Innovations with a potential for incremental performance improvement

Surimi: There are some “floating surimi factories” in operation worldwide, however, they remain few due to their considerable expense. According to surimi turnkey plant provider Optimar, a surimi boat fitted with sanitary, food-grade equipment (including reverse osmosis water purification systems) may cost upwards of £90 million. Alfa Laval assisted in refitting a used, 90m long, 2,400T French trawler with two surimi lines producing up to 50MT of blue whiting surimi per day, the only one of its kind in Europe. Production runs around the clock over two, 12-hour shifts. On board is a crew of 60 people, including kitchen and other staff. The cost of the refit was almost £8 million (Alfa Laval 2017).

Technology Readiness Level: 9; Technical risk: Low

Onboard silage system: Norwegian company PG Flow Solutions has developed a silage system that claims to produce high-quality fish protein concentrate (FPC) that can generate a market value of NOK 12-15 per kilogram, compared to the standard NOK 2 per kilogram. The solution, called PG Silage, is suitable for long-distance fishing vessels, typically 70-100 metres long, with quotas allowing for long trips. The PG Silage method manages to reduce 1,700 m3 of fish waste (equivalent to the waste generated from 1,000 m3 of fish fillets) to approximately 310 m3 of fish oil and 530 m3 concentrated FPC. The concentrated product can be stored up to two months (Johansen 2017). Danish company Landia has also developed an onboard silage systems for trawlers (Williams 2018).

Technology Readiness Level: 9; Technical risk: Low

Offal for human consumption: The US-based cod longliner F/V Blue North was specifically built to retain and market ancillary products for human consumption such as livers, collars, stomachs, skins, and frames that it is now selling in Japan, South Korea, and China (Seafood Source 2019).

Technology Readiness Level: 9; Technical risk: Moderate

Blood residue collection: Norwegian company Sandtorv Maskin have recently presented a prototype of their onboard Desline machine, in which salmon blood residue is removed from bleeding out water. Contaminated water is collected from bleeding tanks and removed of proteins, blood cells, enzymes and large amounts of mucus. This material turns into a soap, which can then be used in applications such as biogas or fertiliser production. The water is then fed through a double filtration process and sterilised, which can then be re-used or returned to the sea (Tekfisk 2019).

Technology Readiness Level: 6-8; Technical risk: Low

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20 Selectivity of gear and avoidance of unwanted catches

Contents

From the SIF Executive Board

The method applied in this review has generated numerous examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently happening. It is recognised that there are existing innovations and research areas that are not included here, and new areas where future innovations may occur. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

20.1 Overview: selectivity of gear and avoidance of unwanted catches

What is the challenge in the UK?

There are several key drivers for improved gear selectivity and bycatch reduction. The UK has obligations under national and international laws to reduce bycatch of protected species, including whales, dolphins, seals and seabirds. The long-term health and productivity of fisheries also requires overall biomass extraction rates to remain within sustainable levels whilst maximising the quantity and value of marketable seafood. Commercial drivers include the cost of wasted fishing effort and landing unwanted catches under the EU Landing Obligation, consumer demand for products that are not associated with significant bycatch, and the bycatch reduction requirements under the USA's Marine Mammal Protection Act.

What are the most promising innovation categories?

- Vision systems for fish identification, measurement and sorting in trawls
- LED lighting
- Pre-catch characterisation for purse seine

Where are their important knowledge gaps?

- Approaches for pinniped depredation management
- Ability for cost-effective data capture on actual levels of bycatch and discards within UK fleet

The avoidance of unwanted catches through reduction of discards and bycatch has been a long-standing concern for the fisheries sector. From a sustainability perspective, bycatch can cause stress on fish, marine mammal and seabird populations that threatens their survival. This in turn can have major economic implications as fisheries become less productive and efficient. These challenges have driven research and innovation into the development of bycatch mitigation technology as well as improvements to the selectivity of fishing gear.

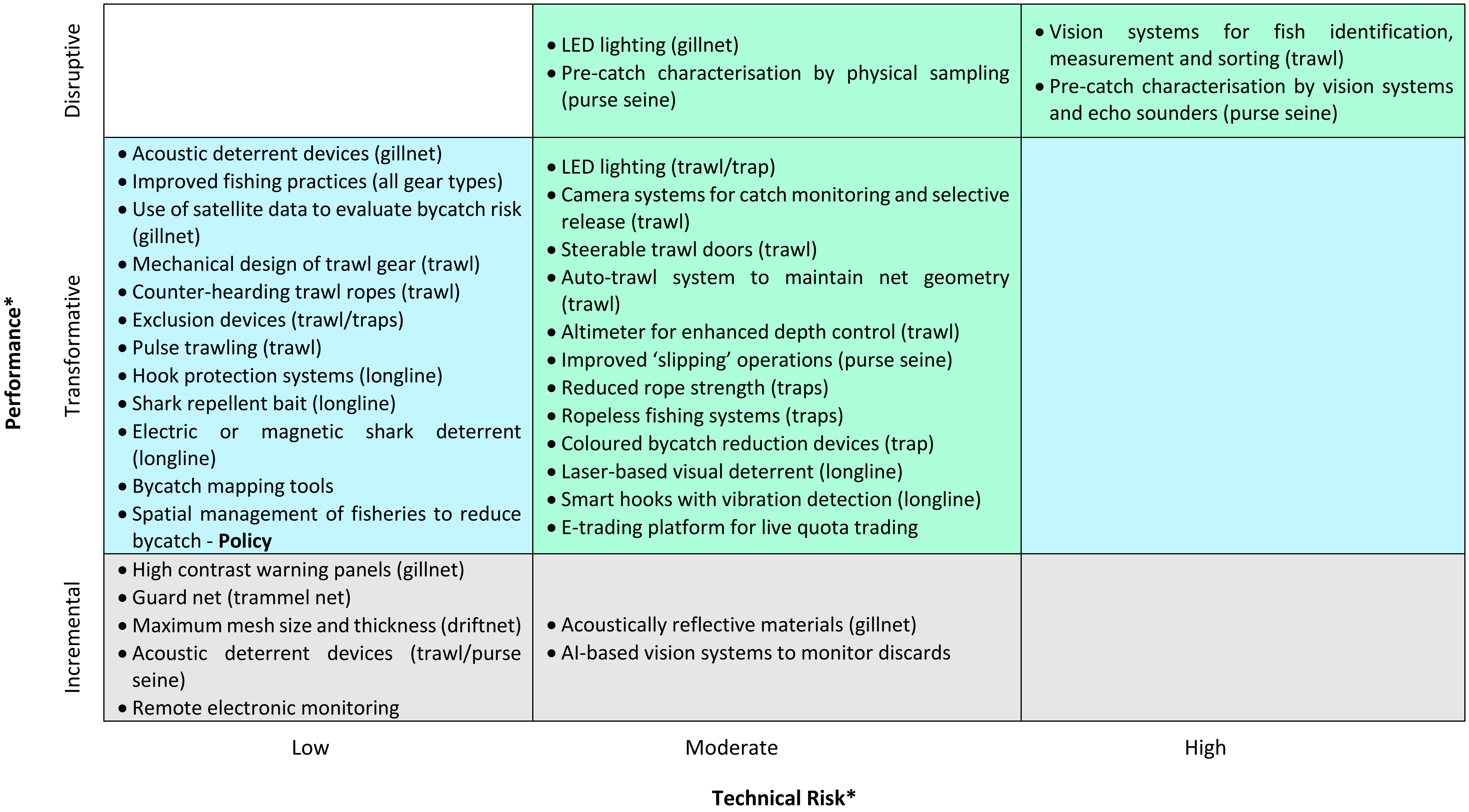
The following chapter presents the latest innovations in gear selectivity and bycatch mitigation approaches. The chapter is organised primarily by gear type, as although much of the academic research has focused on single taxon bycatch mitigation, there is potential for mitigation measures that are effective in reducing bycatch in one taxon to increase bycatch in other taxa (Gilman *et al.* 2019).

Some general principles that should be considered when trying to identify suitable bycatch mitigation measures have been described by Gilman (2011). Gilman suggests that mitigation measures need to provide fishery-specific solutions as the effectiveness of measures depend on a wide variety of factors including the target species, the typical bycatch species, the gear type, fishing practices etc. More recently, the increasingly complex and nature of quota systems and the increasing practice of quota trading means that individual vessels might need to customise the selectivity of their gear to match the profile of their available quota. Ultimately, bycatch measures may need to be adjusted on a trawl-by-trawl or trip-by-trip basis. This will create demand for fishing gear with selectivity performance that can be customised quickly and easily through the addition, combination or removal of bycatch reduction measures (Melli *et al.* 2020).

Early and significant involvement of fishing industry stakeholders including fishers and gear producers is considered essential as mitigation measures that are not practical, cost-effective or have a significant negative impact on target species catch will not be adopted. The involvement of fishing industry stakeholders is a point emphasised by other authors (Feekings *et al.* 2019).

Concerning this final point, Seafish have produced practice guidance for the financial assessment of fishing gear that can help when considering new or modified gear types Seafish have produced best practice guidance for the financial assessment of fishing gear (Seafish n.d.).

An overview of the potential performance improvement rating of recent (2015-2019) innovations for gear selectivity and bycatch reduction are outlined in Figure 15-1.



Performance* \ Technical Risk*	Low	Moderate	High
Disruptive		- LED lighting (gillnet) - Pre-catch characterisation by physical sampling (purse seine)	- Vision systems for fish identification, measurement and sorting (trawl) - Pre-catch characterisation by vision systems and echo sounders (purse seine)
Transformative	- Acoustic deterrent devices (gillnet) - Improved fishing practices (all gear types) - Use of satellite data to evaluate bycatch risk (gillnet) - Mechanical design of trawl gear (trawl) - Counter-hearding trawl ropes (trawl) - Exclusion devices (trawl/traps) - Pulse trawling (trawl) - Hook protection systems (longline) - Shark repellent bait (longline) - Electric or magnetic shark deterrent (longline) - Bycatch mapping tools - Spatial management of fisheries to reduce bycatch - **Policy**	- LED lighting (trawl/trap) - Camera systems for catch monitoring and selective release (trawl) - Steerable trawl doors (trawl) - Auto-trawl system to maintain net geometry (trawl) - Altimeter for enhanced depth control (trawl) - Improved ‘slipping’ operations (purse seine) - Reduced rope strength (traps) - Ropeless fishing systems (traps) - Coloured bycatch reduction devices (trap) - Laser-based visual deterrent (longline) - Smart hooks with vibration detection (longline) - E-trading platform for live quota trading	
Incremental	- High contrast warning panels (gillnet) - Guard net (trammel net) - Maximum mesh size and thickness (driftnet) - Acoustic deterrent devices (trawl/purse seine) - Remote electronic monitoring	- Acoustically reflective materials (gillnet) - AI-based vision systems to monitor discards	

Figure 20-1: Performance and technical risk rating of innovations in gear selectivity and bycatch reduction.

**See section 4.4 for definitions of the performance and technical risk rating scales.*

20.2 Bycatch from gillnets, driftnets and trammel nets

Bycatch is a significant concern for a variety of passive gear types, including gillnets, driftnets and trammel nets. Whilst the design of these gear types plus regulations on minimum mesh sizes has led to improve size selectivity for the target species, bycatch of non-target species and protected species remains a problem.

A number of factors have been identified that influence the prevalence of protected species bycatch in gillnets. Water depth, net height, mesh size and floatline type have a marked influence on bycatch across mammals birds and turtles (Northridge *et al.* 2017). Small cetaceans and pinnipeds bycatch is particularly problematic in gillnets as they are attracted to the gear by the opportunities for depredation of the catch and are not deterred by some of the commercially available solutions (Hamilton and Baker 2019). Harbour porpoise are one particular species that have been significantly impacted through gillnet interactions (Kindt-Larsen *et al.* 2019).

Innovation with a potential for disruptive performance improvement

LED lights: In a study of small cetacean and turtle bycatch in a Peruvian gillnet fishery, the fitting of green LED lights on the gillnets resulted in a decrease in the expected bycatch probability per set for small cetaceans of 67% in illuminated bottom set nets and 71% in illuminated surface driftnets (Bielli *et al.* 2019). Green LED lights have also proven successful in seabird bycatch reduction, specifically for guanay cormorants (Phalacrocorax bougainvillii) in a Peruvian gillnet fishery (Mangel *et al.* 2018). A number of other studies, mainly focused on sea turtle bycatch in Mexico and Peru but also including one study of elasmobranchs and finfish have reported bycatch reductions of between 40% and 100% (Coulter 2019). The evidence base from UK and European studies is currently limited although the success of LED lighting in gillnet bycatch reduction across multiple taxa is a significant positive for this technology.

Technology Readiness Level: 6-8; Technical risk: Moderate

Innovation with a potential for transformative performance improvement

Acoustic deterrent devices (pingers): The effectiveness of acoustic deterrents is largely species and fishery dependent (Clay *et al.* 2019). The use of pingers is required by EU Council

Regulation 812/2004 for all >12 metre vessels setting static nets in the Celtic Sea, the English Channel and some parts of the North Sea.

The use of acoustic deterrent devices have produced significant reductions in interactions and bycatch of marine mammals in various studies around the world. For example, a study of Burmeister's porpoise in Peru found that the use of pingers lead to an 86% reduction in porpoise activity around nets (Clay *et al.* 2019).

In the UK, a sea trial has been conducted with the Banana pinger, produced by Fishtek Marine, across a number of Welsh gillnet, trammel net and tangle net fisheries. No cetacean bycatch was recorded by the six vessels involved in the trial over the course of the summer fishing season (Woolmer 2015). Trials of an AQUAmark100 pinger conducted in Scotland found significant reductions in porpoise activity within 400m of the pinger array with no signs of habituation (Kindt-Larsen *et al.* 2019). However, trials in Denmark within the same study found a less pronounced reduction in activity and signs of habituation (Kindt-Larsen *et al.* 2019)

Similar concerns about pinger habituation have been raised for pinnipeds. It is suggested that over time the pinger could be associated with a food source (fish caught in static nets) – leading to a 'dinner bell' effect. However, a UK trial with Atlantic grey seals (Halichoerus grypus) at a seal sanctuary found that the seals were not attracted to or affected by the pinger (Cornwall Wildlife Trust 2013).

There are some concerns about the widespread and persistent use of acoustic deterrent devices in terms of the noise pollution generated, and the potential impacts on a range of species, such as habitat exclusion (Gotz and Janik 2015).

Technology Readiness Level: 9; Technical risk: Low

Improved fishing practices: Zollet and Swimmer (2019) have reviewed and summarised some general principles for reducing bycatch mortalities that are relevant for multiple taxa and several gear types, including gillnets. A recent expert workshop focused on cetacean bycatch reduction identified some of the gillnet-fishing practices being used to reduce cetacean bycatch (Cefas 2019).

Technology Readiness Level: 9; Technical risk: Low

Use of satellite data to evaluate bycatch risk: Halhlbeck et al (2017) have analysed oceanographic data in conjunction with bycatch records to identify the types of conditions that give rise to higher levels of ocean sunfish (*Mola mola*) and bluefin tuna (*Thunnus orientalis*) bycatch patterns in the California large mesh drift gillnet fishery. Their proposed model suggests that sunfish bycatch is linked to coastal upwelling conditions whilst tuna bycatch is linked to upwelling-derived fronts. They suggest that using the near-real time data on sea surface temperatures available from satellite observations can be used to identify upwelling conditions and hence increased risk of sunfish and tuna bycatch.

Technology Readiness Level: 3-5; Technical risk: High

Innovations with a potential for incremental performance improvement

High contrast warning panels in gillnets: The use of high contrast warning panels 60cm by 60cm, featuring a black and white chequerboard design, have been proposed as a visual warning of the presence of fishing gear that might help to reduce bycatch, particularly for seabirds (Martin and Crawford 2015). The proposal is based on an in-depth understanding of the visual capability of seabirds and other bycatch taxa, and the authors suggest that the proposed warning panel would be visible to seabirds at a distance of at least 2m in a variety of lower naturally occurring light levels (twilight to starlight) and at least 20m in daylight conditions. However, there appears to be limited empirical evidence to validate the efficacy of warning panels for gilnet bycatch reduction.

In fact, counter evidence comes from sea trials conducted in the Baltic sea. There it was found that both high contrast monochrome net panels and LED lights (constant green light or flashing white light) attached to the nets failed to reduce seabird bycatch amongst the two most commonly caught species: Long-tailed Ducks (*Clangula hyemalis*) and Velvet Scoters (*Melanitta fusca*) (Field *et al.* 2019).

Technology Readiness Level: 9; Technical risk: Low

Use of acoustically reflective materials in gillnets: Several trials have been conducted with gillnets that incorporate metal oxides in the filament to make them acoustically reflective with the aim of reducing cetacean bycatch. However, the results have been mixed and where reductions did occur, they may have been due to increased stiffness of the material rather than the acoustically reflective properties of the nets (Hamilton and Baker 2019). Furthermore, cetacean may encounter gillnets when they are not echolocating, which would reduce the effectiveness of the approach.

Technology Readiness Level: 6-8; Technical risk: Moderate

Trammel net with guard net: In a study of a Portuguese trammel net fishery focused on sole and cuttlefish, the addition of a 140mm stretched mesh guard net led to a reduction in commercial discards biomass of 68% by mass, including a 62% reduction in longfin gunards bycatch and 33% fewer greater weever. However, the commercial catch was also reduced by 38-46%. The authors concluded that the modified nets were unlikely to be commercially adopted in the form trialled due to the higher cost of the nets and the reduction in commercial catch.

Technology Readiness Level: 6-8; Technical risk: Low

Maximum mesh size and thickness for driftnets: Based on a review of the driftnet designs commonly used in European fisheries, Sala *et al.* (2018) propose a maximum mesh size and twine thickness of 90mm and 0.6mm respectively in order to reduce gillnet bycatch of marine mammals and protected species. They go on to suggest that additional restrictions on the types and overall dimensions of driftnets may be necessary to manage driftnet fisheries.

Technology Readiness Level: 9; Technical risk: Low

20.3 Bycatch from trawl gear

Demersal trawl gear accounted for almost two-thirds of the UK wild catch value in 2018 (Marine Management Organisation 2019) and is therefore a high priority for improved gear selectivity and bycatch reduction. Bycatch problems include the capture of juvenile fish of the target species and the capture of non-target fish species. There are a number of significant recent and ongoing European collaborative projects that are addressing the challenges of selectivity within trawl gear, including DiscardLess[1], FTL-Fish (European Commission 2019), SELUX (SafetNet Technologies 2018) and SMARTFISH H2020[2]. These projects have been funded as a response to new policy measures to minimise discards of commercial species, which remains a key challenge and management priority.

Capture of small cetaceans and pinnipeds is also a concern for trawl gear. This issue is made more complex by that fact that small cetaceans and pinnipeds will often deliberately enter the

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[1] DiscardLess: http://www.discardless.eu/

[2] SMARTFISH H2020: http://smartfishh2020.eu/

trawl to depredate the caught fish (Santana-Garcon *et al.* 2018). No reliably effective technical solutions to reduce small cetacean bycatch in trawl nets are available according to Hamilton and Baker (2019).

Innovation with a potential for disruptive performance improvement

Vision systems for fish identification, measurement and sorting: Deep Vision is a subsea vision system for identifying and measuring fish under water (Scantrol Deep Vision 2016). The device consists of stereo cameras mounted to a frame that is installed in the extension of a trawl. An image of each specimen that enters the trawl is captured by the cameras and is then analysed to identify the species and estimate the size. These data can be transmitted live to the vessel, along with location data. This enables live feedback for the crew on the composition of the catch. The system is currently only available as a tool for research, where it is being used to support stock assessment activities. The company aims to release a version suitable for commercial use in 2020. The ultimate aim is to integrate this technology with active sorting, although no details of how this system might work are provided.

Technology Readiness Level: 6-8; Technical risk: High

Innovation with a potential for transformative performance improvement

Mechanical design of trawl gear: For demersal trawl gear, there are a wide range of gear design parameters that can be adjusted to improve selectivity. These design parameters are extensively discussed in guidance documents produced by Marine Scotland Science and the DiscardLess project (O’Neill and Mutch 2017). Gear design aspects covered in the guidance include:

- Semi-pelagic trawl doors to reduce sediment disturbance.
- Shortened sweeps and bridles to reduce the swept area.
- Use of dropper chains to raise the fishing line and allow escape under the fishing line.
- Reduce headline height or cut-away headline to allow escape over the headline.
- Larger mesh sizes in the front end of the trawl to allow escape through the wings.
- Horizontal separator to differentiate species based on trawl response behaviour.
- Guide grids and escape panels in the tapered section to allow escape of sub-legal size specimens.
- Large, square mesh (which remains open under tension) rather than diamond mesh in the extension.

- Alternative mesh sizes, mesh shape, thinner twine and reduced number of twines (single vs double) have all been investigated in the design of the codend.

No single ideal trawl gear is proposed as the authors note that, “not only will the preferred selective performance differ at a fishery by fishery level, it may also vary at a vessel by vessel level, as individual fishermen may wish to tailor their gears to the specific catch and quota restrictions they may face and/or to optimise their response to the prevailing market forces.” (Ibid.). Based on the experiences of a UK bycatch reduction initiative, one of the keys to successful gear design modifications to improve selectivity is early engagement with both fishers and netmakers (Project 50% 2010).

Technology Readiness Level: 9; Technical risk: Low

Counter-hearding trawl ropes: The trawl ropes typically have a hearding effect on demersal fish that can increase bycatch. To reduce this effect, small-scale trials were conducted in the Danish nephrops trawl fishery with the trawl ropes in a ‘counter-hearding’ arrangement (Feekings *et al.* 2019). This consisted of two additional ropes that cross ahead of the trawl mouth with the aim of directing fish away from the trawl. This counter-hearding arrangement of trawl ropes resulted in significant reductions in cod, plaice and saithe bycatch whilst increasing catches of nephrops.

Technology Readiness Level: 9; Technical risk: Low

Camera systems for catch monitoring and selective release: SmartCatch, a US-based company, have developed a suite of products intended to help reduce bycatch. DigiCatch is a high definition camera that is installed in the trawl that provides real-time video to the wheelhouse of the fish entering the trawl. SmartNet, is a smart release system that allows fishers to release bycatch in their trawl nets without pulling the net aboard. The combination of the DigiCatch and SmartNet technologies enables the skipper to identify when a trawl contains a high percentage of bycatch and release it without having to haul the net in. No formal, independent studies of the effectiveness of this technology were identified.

Technology Readiness Level: 9; Technical risk: Moderate

Exclusion devices: Exclusion devices include various types of grid that are placed ahead of the codend and are used to mechanically guide non-target species towards escape panels. Examples include the Nordmøre grid, which is long-established as an effective measure to reduce fish bycatch in shrimp fisheries (Isaksen *et al.* 1992).

The effectiveness of exclusion devices varies by fishery and species and research continues to refine the design of devices for different applications. A recent example is FRESWIND, which is a rigid escape window that can be installed ahead of the codend in trawls in order to enable flatfish to escape demersal trawls targeting roundfish (Santos *et al.* 2016). Trials in the Baltic cod fishery found up to 68% flatfish bycatch and 30% reduction in undersized cod whilst marketable cod loss was only 7%.

Exclusion devices and escape panels have had mixed results for marine mammals. They have been shown to reduce pinniped bycatch but are less effective for dolphins, with some suggestions that to be effective for dolphins exclusion devices should be placed further forward in the trawl (Hamilton and Baker 2019).

Overall, whilst exclusion devices are a proven approach to bycatch reduction in trawl gear, their performance varies by fishery, species and application meaning that there is still potential for innovation in their design and implementation.

Technology Readiness Level: 9; Technical risk: Low

LED lighting: The use of LED lights, either to repel non-target species away from trawl gear or to attract towards escape panels, is being investigated in a number of fisheries. For example, in the Pacific hake mid-water trawl fishery the use of LED lights to guide Chinook salmon towards escape panels resulted in a 70% reduction in salmon bycatch (NOAA 2015).

A key aspect of LED lighting research is the impact on bycatch reduction of the position of the lighting system within the gear. In a study of ocean shrimp (*Pandalus jordani*), green or blue LED lights installed around a rigid gate bycatch reduction device actually led to a significant increase in bycatch of eulachon (*Thaleichthyspacificus*) and slender sole (*Lyopsetta exilis*), whilst installing the same lights across the fishing line fishing line dramatically reduced the bycatch of a wide variety of fishes with no effect on ocean shrimp catch (Hannah, Lomeli, and Jones 2015). Continuous lines of lighting on the leading edge of a separator panel and on the fishing line have been found to alter the height at which species such as haddock, whiting, plaice, common dab and gunnards enter the trawl – offering potential for increased selectivity (O’Neill and Summerbell 2019).

In the UK SafetyNet Technologies are developing a variety of LED lighting device for use in trawl gear. Their PISCES device can programmed to emit different light frequencies depending on the species to be influenced and the devices can be retrofitted to nets. They claim that the device has enabled cross-taxa bycatch reduction of 60-90%. The PISCES device is currently undergoing sea trials as part of the FTL-Fish (European Commission 2019), SELUX (SafetNet Technologies 2018) and SMARTFISH H2020[1] projects.

Technology Readiness Level: 6-8; Technical risk: Moderate

Steerable trawl doors: A number of companies have recently launched steerable trawl doors. These include the Poseidon range from Polar Fishing Gear[2] and the Trawl Steering System from MLD[3]. These systems allow the skipper to control the horizontal and vertical position of each of the trawl doors through a system of electromechanically controlled flaps. The height of the trawl above the seabed can be adjusted with the aid of inbuild altimeters and the geometry of the trawl can be maintained by adjusting the spread and relative position of the doors. Whilst there has not been any formal study of the potential for bycatch reduction, the increased control that the skipper has over the trawl when using steerable trawl doors, particularly the ability to control the altitude of the trawl above the seabed, is likely to enable reductions in bycatch.

Technology Readiness Level: 9; Technical risk: Moderate

Auto-trawl systems: Auto-trawl systems, such as iSYM Trawl Control (Scantrol 2016), help to manage and automate key aspects of the trawl operation such as vessel speed, direction and winch power in order to ensure that the trawl gear maintains optimum symmetry and geometry throughout the trawl with minimum fuel consumption and gear wear. There is some evidence to suggest that maintaining the geometry of the trawl can help to reduce dolphin bycatch in trawl gear and is more effective than acoustic pingers (Santana-Garcon *et al.* 2018).

Technology Readiness Level: 9; Technical risk: Moderate

Pulse trawling: Pulse trawling has been identified as a potential means to improve selectivity in shrimp and flatfish fisheries but was banned in the EU in 1998 due to concerns about the very high fishing efficiency of the gear and its impact on other demersal and benthic species. Partial exemptions to the EU ban were introduced in 2009, which enabled some further development of the gear, but these licences have subsequently been withdrawn.

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[1] SMARTFISH H2020: http://smartfishh2020.eu/

[2] Polar Fishing Gear: https://polardoors.com/

[3] MLD: http://mld.one/

In the North Sea brown shrimp (*Crangon crangon*) fishery, a comparison between a traditional 36 bobbin trawl and a 11 bobbin pulse trawl, the pulse trawl resulted in a discard reduction of small shrimp of up to 35% and a reduction of benthos and fish discards of up to 76%, with no loss of commercial shrimp (Verschueren *et al.* 2019). The pulse trawl also results in reduced contact with the seabed, resulting in less mechanical disturbance of the benthic environment. Further research is required to understand the full impacts of pulse trawling on benthos and the benthic ecosystem.

Technology Readiness Level: 9; Technical risk: Low

Innovations with a potential for incremental performance improvement

Acoustic deterrent devices (pingers): Acoustic deterrent devices can be attached to trawl gear and emit a loud ping to scare off small cetaceans and pinnipeds. Whilst a variety of devices have been tested, the results have been mixed according to a review by Hamilton and Baker (2019). This likely to reflect the potential for different behavioural responses between species and even between populations. High power (145dB) deterrent devices, such as the Aquatec 2446 pinger and the Banana pinger, have been found to be effective in reducing harbour porpoise activity up to 400m from the device (Friis 2017).

Technology Readiness Level: 9; Technical risk: Low

20.4 Bycatch from purse seine gear

Fishing effort using purse seine gear is limited within the UK fleet, but contributes significantly to the global wild catch. Bycatch and discards from this gear type are therefore significant at a global level. Much of the international research and development concerning purse seine bycatch reduction has focused on tuna fisheries, whereas in the UK purse seine is mainly used within herring, mackerel and sardine fisheries.

Innovations with a potential for disruptive performance improvement

Pre-catch characterisation by physical sampling. Purse seine is generally considered a non-selective fishing gear. However, the capture process can be highly selective when the fishers have sufficient information about the catch to decide whether to take or not in the early part of the fishing process (Breen *et al.*, 2012). For example, very low bycatches have been reported for a purse seine fishery targeting sardine and anchovy in the north Aegean Sea. This fishery uses multiple floating lights to attract the sardine and anchovy and, during the collection of these lights by a rowing boat, if it can be seen that the proportion of bycatch species is too high, the catch is abandoned before the net is set (M. Costantini, pers. com.).

More recently, a Norwegian team have developed an air powered sampling device that enables fishers to check the contents of the net during the early stages of fishing (WWF 2015). The system uses an air cannon to launch a sampling tube containing a mini-trawl into the net. The mini-trawl collects a sample of the fish, which is then hauled in for inspection. If the sampled fish are deemed unwanted catch, the seine is opened up to release them

Technology Readiness Level: 6-8; Technical risk: Moderate

Pre-catch characterisation by vision systems and echo sounders: SeinePrecog is a system for pre-catch characterisation that utilises a combination of 3D cameras, 2D cameras and echo sounders (FIS 2019). The technology is intended to support more accurate identification of species within the trawl before hauling to enable release of bycatch. The technology is currently being developed and tested within the SMARTFISH H2020 project.

Technology Readiness Level: 6-8; Technical risk: High

Innovations with a potential for transformative performance improvement

Improved fishing practices to reduce cetacean mortalities: A number of good practices for reducing small cetacean bycatch have been identified from the tuna purse seine fisheries of the Pacific Ocean. Not setting gear in the presence of whales and dolphins is the most simple, preventative measure. The ‘backdown manoeuvre with Medina panels’ is a manoeuvre that can allow dolphins to escape after they have been encircled by the purse seine net. This type of manoeuvre, combined with other good fishing practices, enabled a 98% reduction in dolphin mortality in Pacific Ocean tuna purse seine fisheries (Hall, Alverson, and Metuzals 2000).

A Code of Practice for mitigating interactions with wildlife has been developed by the South Australian Sardine Industry Association (SASIA 2019). The code provides guidance on good practices from crew induction and training, interaction monitoring and recording, through to setting the nets and ensuring safe release of any dolphins caught. The observed mortality rate of dolphins in the fishery dropped from 39 per hundred net-sets in 2004–05 to 2 in 2014–15 –

a 95% reduction (Ward, Ivey, and Carroll 2018).The code is regularly reviewed and updated to ensure its ongoing relevance.

Technology Readiness Level: 9; Technical risk: Low

Improved ‘slipping’ practices: ‘Slipping’ is the operation of controlled release from a purse seine trawl to reduce bycatch or when the sine is overloaded. A best practice slipping procedure was developed with the Norwegian Fisheries Directorate that has been shown to improve the welfare of discarded herring and mackerel (Uhlmann, Ulrich, and Kennelly 2019). Further details of these slipping practices are provided in chapter 14 ‘Fish welfare in wild-capture marine fisheries’.

Technology Readiness Level: 9; Technical risk: Moderate

20.5 Bycatch from pots and traps

Pots and traps contribute to bycatch in two main ways. First, through non-target species becoming caught in the trap itself. Secondly, large cetaceans can become entangled in the buoy lines. In some fisheries, the entanglement issue has become a critical concern (Hamilton and Baker 2019) and is now subject to significant research and innovation efforts.

Innovations with a potential for transformative performance improvement

Reduced rope strength: Pots and traps normally feature an endline, which connects the final trap in a trawl to the surface, where a buoy marks the location of the gear. These endlines can be hundreds of metres long and cetacean entanglements with these lines are a major problem in many fisheries. A study of ropes recovered from entangled whales led the authors to propose that ropes should be manufactured with a tensile strength of less than 7.56 kN (Knowlton *et al.* 2016). They suggest that this could result in a 72% reduction in life-threatening entanglements for large whales, whilst still providing sufficient strength and durability for hauling and general fishing operations.

Technology Readiness Level: 6-8; Technical risk: Moderate.

Ropeless fishing systems and acoustic release devices: An alternative approach to the issue of whale entanglement in endlines are ‘ropeless’ fishing systems. These avoid the need for endlines to be deployed until the fisher is ready to collect the gear. The system works by packing the endline and marker buoy into a bag, which is sunk to the seabed with the gear.

The marker buoy and endline are held in the bag by an acoustic release device, meaning that the column of water above the trawl is free from any lines during the fishing operation.

When it is time for the fisher to retrieve the gear, they use GPS to find the approximate location of the gear and then use a transponder to emit an acoustic signal. When this signal is received by the acoustic release device, it triggers the device to release a mechanism, which is allows the marker buoy and endline to rise to the surface, where it can be spotted and the gear retrieved.

Further discussion of ropeless fishing systems is presented in chapter 15 ‘Ghost fishing and marine litter from fishing gear’.

Technology Readiness Level: 9; Technical risk: Moderate

Exclusion devices for pinnipeds and cetaceans: In a trial in the Baltic Sea, cod pots fitted with seal exclusion devices were able to reduce seal bycatch to zero, without negatively impact the fishing performance of the gear (Königson *et al.* 2015). Oval shaped pot entrances or rectangular entrances with a central divider were recommended as having the best catch performance whilst still preventing seal depredation. Similar success bycatch reduction success has been reported for exclusion devices with bottlenose dolphins and crab pots, seals and salmon traps, sea otters and crab traps and sea lions pups and lobster traps (Hamilton and Baker 2019).

Technology Readiness Level: 9; Technical risk: Low

Use of coloured bycatch reduction devices: Colour perception capability varies significantly across taxa and species. These differences are now being exploited in the design of bycatch reduction devices for traps and pots. In a study of blue crab fisheries in Virginia it was found that there was a an 83% reduction in terrapin bycatch in pots fitted with a red plastic bycatch reduction device compared to the standard pots (Corso *et al.* 2017).

Technology Readiness Level: 9; Technical risk: Moderate

LED lighting: In a study of the Swedish shrimp potting fishery, Ljungberg and Bouwmeester (2018) found that the use of artificial light as an alternative to herring as an attractant resulted in three fold increase in shrimp catch and that the light frequency had a significant influence on bycatch. Green lights increased gadoid bycatch, whilst UV light produced the best catch/bycatch ratio.

Technology Readiness Level: 6-8; Technical risk: Moderate

20.6 Bycatch from longline fisheries

The significant use of bait, long soak times and extended area of operation of longline fisheries tends to attract a wide range of species and has therefore made bycatch a significant concern for this type of gear. Furthermore, there have tended to be significant proportions of protected species involved in longline bycatch, including sharks, seabirds, turtles and whales.

Innovation with a potential for transformative performance improvement

Hook protection systems: Hookpod is a hook protection system used in pelagic longline fisheries to prevent seabird bycatch. The device is attached to the branchline. After the hook is baited the point and barb is inserted into the Hookpod device, which prevents seabirds from getting caught on the hook whilst the line is being deployed. Once the line sinks to a depth of 20m – which is below the maximum dive depth of most seabirds - the pressure release device releases the hook from the Hookpod device so that it is ready for fishing. 95% reductions in seabird bycatch are claimed and the device is approved by the Western Central Pacific Fisheries Commission (WCPFC) as the worlds' first standalone mitigation measure to reduce seabird bycatch.

Technology Readiness Level: 9; Technical risk: Low

Laser-based visual deterrent: SeaBird Saver[1] is a seabird deterrent developed for use in the longline fisheries, where seabird bycatch is a significant problem due to depredation of the baited hooks as they are deployed. The system uses a laser beam that scatters off the sea surface, creating a visual pattern that is disturbing for seabirds. The system also features an acoustic deterrent to supplement the visual deterrent. The system is commercially available, although no data on the systems efficacy in reduce seabird bycatch is publicly available.

Technology Readiness Level: 9; Technical risk: Moderate

Shark repellent bait: Super Polyshark helps to reduce shark bycatch in longline fisheries by tainting the bait with an odour that sharks find unpleasant. A paper tube holds a polymer containing the shark repellent, which is made from a non-toxic and biodegradable semiochemical. Tests results showed a 71% reduction in shark catch between treated and control baits over a four hour window (WWF 2015).

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[1] SeaBrid Saver: https://www.seabirdsaver.com/

Technology Readiness Level: 9; Technical risk: Low

Smart hooks with vibration detection: Researchers at the University of California have developed a ‘smart hook’ that is designed to release catch when vibrations caused by bycatch species are detected, including killer whales (NOAA 2015). No formal trials of the smart hook have been reported to date.

Technology Readiness Level: 3-5; Technical risk: Moderate

Electric and magnetic field deterrents for sharks: Sharks are highly sensitive to electrical fields as they possess Ampullae of Lorenzi and will exhibit a very active avoidance response to electrical voltage gradients of 10mV/m (Marcotte and Lowe 2008) and can detect voltage gradients as weak as 1nV/m. Whilst teleost fish species also display electrosensitive behaviour, the threshold for response is 20-80mV/m. A number of devices are being developed that make use of the heightened sensitivity of elasmobranchs to weak voltage gradients.

SharkGuard[1], developed by Fishtek Marine, is a compact device that is installed in close proximity to the hook on longlines. The device is used to generate a pulsed electrical field in a 40cm radius around the hook, that is sufficient to deter sharks whilst being undetectable by target species such as tuna and swordfish. Sea trials conducted in 2016 found a 90% reduction in sharks hooked on baits protected by the SharkGuard compared to a baited control line. Further trials conducted in the Mediterranean Sea in summer of 2019 are currently being analysed. A similar, electric field generating deterrent was tested by Howard *et al.* (2018) in a laboratory-based study. They found that, when activated, the device led to a 74% reduction in bait consumption by juvenile sandbar shark and a 50% reduction by spiny dogfish.

The use of magnets as an elasmobranch deterrent has been explored with some success (O’Connell *et al.* 2015). However, the high cost of producing magnets, their limited suitability for extended use in the marine environment, inconsistent performance in reducing bycatch and potential for reducing fishing efficiency mean that they are unlikely to be widely adopted (Howard *et al.* 2018).

Technology Readiness Level: 6-8; Technical risk: Low

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[1] SharkGuard: https://www.fishtekmarine.com/sharkguard/

Improved fishing practices: A number of fishing best practices can, in combination, produce a significant reduction in seabird bycatch in longline fisheries (Gilman 2011). These include:

- Nightsetting to avoid peak periods of seabird foraging.
- Setting from the side of the vessel rather than the stern.
- Use of blue-dyed bait and underwater setting devices to reduce detection of bait.
- Increased weight near hooks to ensure hooks descend rapidly.
- Use of deterrents, such as 'tori lines' and water cannons.

Technology Readiness Level: 9; Technical risk: Low

20.7 Post-catch bycatch mortality reduction

For information concerning the reduction of post-catch mortality of bycatch species, please refer to chapter 14 'Fish welfare in wild-capture marine'.

20.8 Monitoring

Robust and accurate monitoring of bycatch and discards is an essential component of a bycatch reduction strategy (WCL 2018). A range of data sources can be employed to support bycatch and discard monitoring, including: data from fishers, on-board observers, electronic monitoring systems etc. Whilst on-board observer data has been viewed as the gold standard, it is a very resource intensive and expensive method of data collection. In the UK, the level of observer coverage of UK-registered vessels is less than 1% (WCL 2018). There is therefore a significant need to identify cost-effective methods for improving monitoring coverage in UK fisheries.

Innovation with a potential for transformative performance improvement

Bycatch mapping tools: A number of tools have been launched in recent years with the aim of helping fishers to avoid areas that are likely to present significant bycatch. A map tool produced by the Marine Institute Ireland and DISCARDLESS project displays the CPUE and proportion of fish above and below Minimum Conservation Reference Size (MCRS) in the Celtic Sea for 11 species (DiscardLess n.d.). Annual or quarterly data can be represented. The map makes use of survey, observer and official landings.

VeriCatch have developed the FisheriesApp, which is an electronic reporting and fisheries management platform that enables fishers to collect, report, and manage catch and landing data. This can be linked to spatial data through integration with vessel monitoring systems. It claims to offer bycatch hotspot mapping, although no details of how this feature functions was identified.

Technology Readiness Level: 9; Technical risk: Low

E-trading platform for live quota trading: In Sweden, where an individual transferrable quota system has been implemented, fishers are now using an e-trading platform known as ‘FishRight’ to enable live quota trading. The platform provides a simple, fast and transparent means to trade quota allocations between fishers and is accessible 24 hours per day through any Internet-enabled computer or mobile device. This means that hauls containing large quantities of non-target species that previously might have been discarded can now be retained as incidental catch and be landed under a quota obtained through the FishRight platform (Kosviner 2018).

An added benefit of the FishRight system is that the trading data available through the platform can be used as another data source for bycatch monitoring that can be used by the Swedish authorities for fisheries management (Hook and Net Magazine 2018).

Technology Readiness Level: 9; Technical risk: Moderate

Innovation with a potential for incremental performance improvement

Remote electronic monitoring: Remote electronic monitoring involves the capture and live data transmission to land-based observers of video streams, position, gear usage and catch data from fishing vessels. The objective is to provide a sufficient range and quality of data sources such that a land-based observer can perform a similar role to an on-board observer, but with a significant reduction in cost. A recent report on the potential of remote electronic monitoring for the UK estimated that to provide 10% video review monitoring across the over-10-metre fleet across the UK would cost in the region of £5 million. This equates to roughly a quarter of the money spent on more traditional systems which deliver less than 1% at-sea coverage (WWF-UK 2017). Whilst remote electronic monitoring technology has been trialled in the UK since 2009, the participation of UK vessels has declined in recent years from 48 in 2014 to 20 in 2017 (WWF-UK 2017).

The cost of remote electronic monitoring systems has been reducing due to advancement in hardware costs, although subsidies for hardware purchase European Maritime and Fisheries Fund may be last as part of the UK's departure from the European Union.

Commercial remote electronic monitoring solutions are available from a number of providers including SeaTube system from Satlink[1], and Electronic Eye from Marine Instruments[2].

Whilst the technical risk is considered low due to the maturity of this technology and its existing, limited adoption in the UK, a key challenge for large-scale roll out of the technology will be in gaining acceptance from fishers and fleet owners. Early engagement and discussion with these stakeholders is recommended to address any questions and concerns.

Technology Readiness Level: 9; Technical risk: Low

Artificial intelligence-based vision systems to monitor discards: Improvements in remote electronic monitoring have made it possible to identify occurrences of bycatch and discards on vessels. These data can be very valuable for research and fisheries management purposes but currently require manual analysis that is time-consuming and requires well-trained observers. French *et al.* (2019) report on their attempt to automate the analysis of discards through the use of onboard CCTV camera footage and 'deep neural network' image analysis. Using training data obtained from either a research vessel or commercial vessels, reasonable levels of agreement were obtained in species identification between the automated analysis and the expert observers. Technical challenges identified for the further development of the system include length estimation, tracking specimens between frames and temporary occlusions.

Whilst still in the early stages of development, this type of technology has the potential to provide a fast, cost-effective and scalable solution to obtaining accurate discard data.

Technology Readiness Level: 3-5; Technical risk: Moderate

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[1] SeaTube: https://satlink.es/en/

[2] Electronic Eye: https://www.marineinstruments.es/

20.9 Policy measures targeting bycatch reduction

Policy measures aimed at reducing unwanted catches were not reviewed in detail as the development of potential policy measures is not an explicit objective of the Seafood Innovation Fund. However, policy measures are highly relevant for bycatch reduction as they can create incentives for fishers to adopt new practices or technologies to reduce bycatch and discards. For instance, EU's Landing Obligation policy represents a fundamental shift in EU fisheries policy from regulation of landings to regulation of catches (Catchpole *et al.* 2018). Whilst the policy came into full effect in January 2019, it is still too early to understand the full implications for fishers and the impact on bycatch and discards. However, it is likely to stimulate development of more selective fishing gears and improved fishing practices.

In this section we focus on policy measures with the potential to have a direct impact on bycatch reduction.

Innovations with a potential for transformative performance improvement

Spatial management of fisheries to reduce bycatch: Spatial management of fisheries, including 'no-take areas' and areas with gear restrictions, are a widely implemented and generally successful approach to reduction of bycatch, particularly for marine mammals and protected species (FAO 2018). For example, a study of New Zealand dolphin populations found that the implementation of marine sanctuaries has led to the recovery of several populations but that problems persist as the sanctuaries were generally too small compared to the habitat of the dolphins (Slooten 2013). Restrictions on gillnets down to the 100m contour throughout the dolphin habitats was proposed as the preferred solution from a bycatch reduction perspective.

Note that whilst the establishment of spatial management systems presents little technical risk, such measures require extensive stakeholder consultation to balance the economic impacts for the seafood industry with the requirements for marine fauna and ecosystem sustainability.

Technology Readiness Level: 9; Technical risk: Low

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Theme 3: Onshore supply chains and added value production

21 Packaging technologies

Contents

From the SIF Executive Board

The method applied in this review has generated numerous examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently happening. It is recognised that there are existing innovations and research areas that are not included here, and new areas where future innovations may occur. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

21.1 Overview: packaging technologies

What is the challenge in the UK?

Packaging plays a vital role in ensuring that seafood products arrive at the consumer in optimum condition. Despite significant efforts by manufacturers and retailers, around 23,000 tonnes of fish and shellfish purchased by UK consumers ends up as waste (WRAP 2018). There is therefore a need for novel packaging systems that can help to reduce food waste.

At the same time, there is significant pressure on retailers and manufacturers to reduce their use of plastic packaging and eliminate non-recyclable packaging. This is driving development of more sustainable packaging materials that are biobased or made from recycled content and are easy to recycle.

There are also significant changes happening in the types of products that consumers are purchasing and how they buy them. Seafood packaging systems will need to adapt to these changes quickly if seafood is to compete with other sources of protein.

What are the most promising innovation categories?

- Chitosan-based antimicrobial packaging film
- Gelatine-based freshness indicator
- Nanocomposite and nano encapsulation of antimicrobial agents

Where are their important knowledge gaps?

- Development of packaging systems suitable for e-commerce
- Functional packaging systems that are easy to recycle

According to a recent survey, seafood shoppers placed more priority in their purchase decisions on ‘packaging’ than origin, smell, brand, or ethical production methods (Seafish 2019). Packaging will also have a direct influence on other key factors mentioned in the survey, including ‘ease of use’, ‘quality’, ‘healthy option’ and ‘familiarity with the product’.

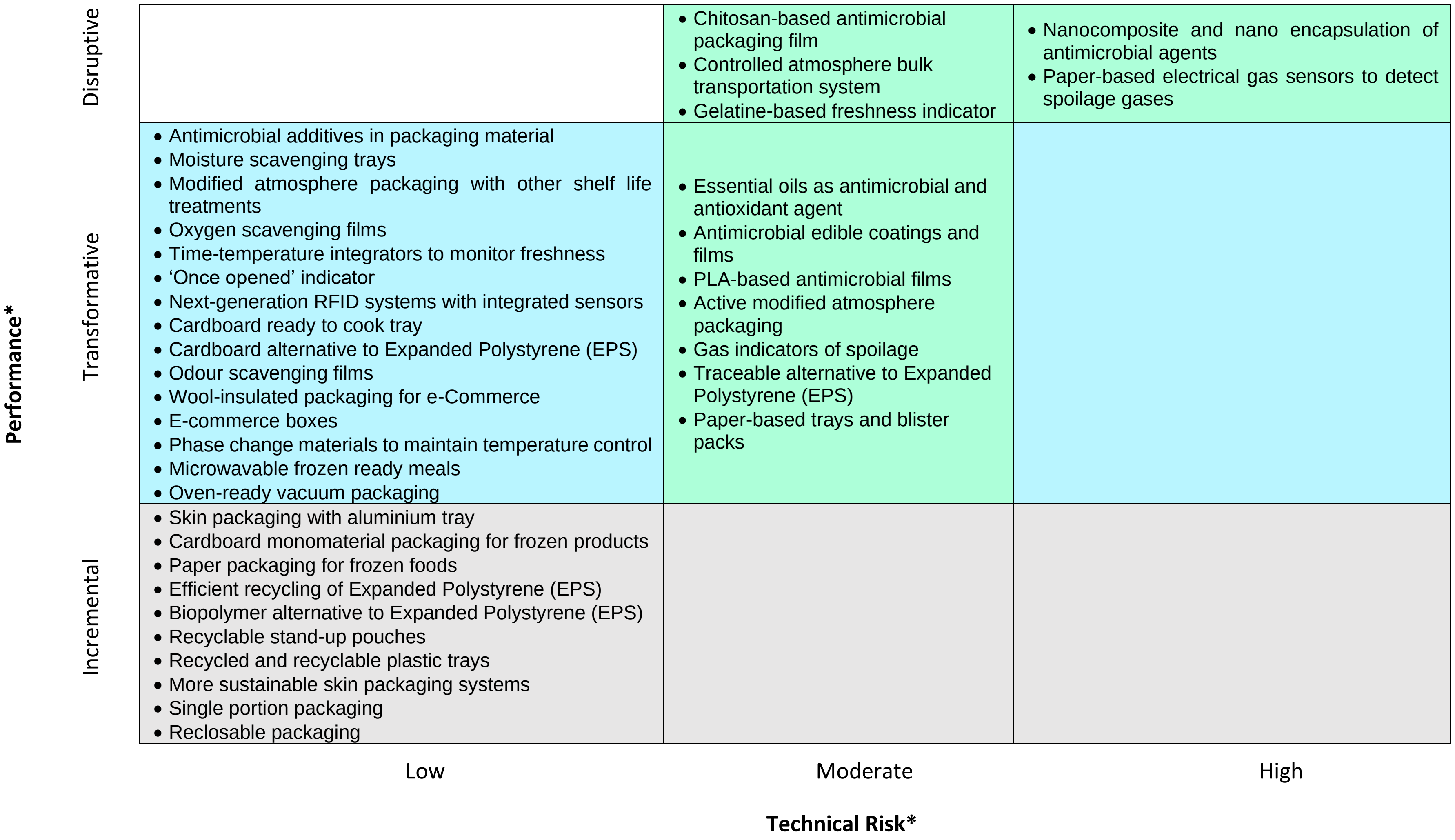
Of course, the primary purpose of packaging is to protect the product and ensure that it arrives at the consumer in optimum condition, but it is clear from the survey mentioned above that packaging must fulfil a wide range of functions. In addition, food packaging is subject to a range of complex regulatory and technical requirements concerning issues such as hazardous substance content, moisture and gas barrier performance, thermal performance, optical performance, colour, seal quality, suitability for use in high-speed packing lines etc. All these functions and requirements must be fulfilled whilst costing no more than a few pence or tens of pence per packet. These complex challenges mean that innovations in packaging require significant development activity and testing, often requiring several years. Nonetheless, a wide range of innovations relevant to seafood products have been identified, covering issues including maintaining freshness and shelf life, monitoring product condition, reducing environmental impacts and responding to changing consumer and sales channel requirements.

The focus in this chapter is primarily on retail packaging rather than the packaging used elsewhere in the supply chain as around 70% of post primary production food loss and waste occurs in the household or in retail, versus 18% in manufacturing (WRAP 2019). This included 23,000 tonnes of fish and shellfish with a value of £260 million (WRAP 2018). Whilst the packaging design process, aesthetic design of packaging and consumer communication are important considerations within packaging innovation, the scope of this chapter was limited to novel packaging technologies in keeping with the technology focus of the SIF.

Two significant areas where identified by packaging experts as knowledge gaps. The first was packaging for e-commerce. Whilst there are a number of packaging systems developed for e-commerce, the increasing importance of this sales channel for the food industry is likely to generate demand for a wider range of solutions that are adapted to the requirements for the diverse range of seafood products available and the variations in ambient temperature that occur over the course of a year.

The second knowledge gap identified was ‘functional’ packaging - meaning packaging that offers some additional function beyond basic protection of the product - that is easy to recycle. For example, there is a trend towards packaging systems that are ‘oven-ready’ so that the product can be cooked in the packaging for convenience and less mess. However, the plastics that are currently widely recycled, such as PET and HDPE, tend to have relatively low melting point and may not be suitable for in-package cooking. There is therefore a risk that trends towards functional packaging will lead to increased use of plastics for which recycling technology and infrastructure is not yet available in the UK.

An overview of the potential performance improvement rating of recent (2015-2019) innovations for packaging technologies are outlined in Figure 15-1.



Performance*	Low	Moderate	High
Disruptive		• Chitosan-based antimicrobial packaging film • Controlled atmosphere bulk transportation system • Gelatine-based freshness indicator	• Nanocomposite and nano encapsulation of antimicrobial agents • Paper-based electrical gas sensors to detect spoilage gases
Transformative	• Antimicrobial additives in packaging material • Moisture scavenging trays • Modified atmosphere packaging with other shelf life treatments • Oxygen scavenging films • Time-temperature integrators to monitor freshness • ‘Once opened’ indicator • Next-generation RFID systems with integrated sensors • Cardboard ready to cook tray • Cardboard alternative to Expanded Polystyrene (EPS) • Odour scavenging films • Wool-insulated packaging for e-Commerce • E-commerce boxes • Phase change materials to maintain temperature control • Microwavable frozen ready meals • Oven-ready vacuum packaging	• Essential oils as antimicrobial and antioxidant agent • Antimicrobial edible coatings and films • PLA-based antimicrobial films • Active modified atmosphere packaging • Gas indicators of spoilage • Traceable alternative to Expanded Polystyrene (EPS) • Paper-based trays and blister packs	
Incremental	• Skin packaging with aluminium tray • Cardboard monomaterial packaging for frozen products • Paper packaging for frozen foods • Efficient recycling of Expanded Polystyrene (EPS) • Biopolymer alternative to Expanded Polystyrene (EPS) • Recyclable stand-up pouches • Recycled and recyclable plastic trays • More sustainable skin packaging systems • Single portion packaging • Reclosable packaging		

Technical Risk*

Figure 21-1: Performance and technical risk rating of innovations in packaging technologies.

**See section 4.4 for definitions of the performance and technical risk rating scales.*

21.2 Maintaining freshness and shelf life through active packaging

Maintaining freshness and ensuring maximum shelf life are significant challenges for all types of food but is particularly relevant for seafood due to its highly perishable nature. There is therefore significant interest in the concept of 'active packaging' systems in which the package, packaging environment and the product interact positively in order to improve product safety and to accomplish some other desired characteristics (Ahmed *et al.* 2017). Below we present a range of active packaging innovations being developed for the food industry.

Innovation with a potential for disruptive performance improvement

Nanocomposite and nano encapsulation of antimicrobial agents: One of the key challenges for active packaging systems is to ensure sustained release of the active ingredients. Direct mixing of antimicrobial agents, such as essential oils, into the packaging material is a simple way to achieve this but can negatively impact the mechanical properties of the packaging material and so care must be taken.

There is now significant research interest in the use of nanocomposite materials and nanoencapsulation techniques to enable sustained release of active ingredients (Gan and Chow 2018; Kowsalya *et al.* 2019; Prakash *et al.* 2018). As an example, the EU-funded NanoPack project[1] has developed sustained release mechanism based on halloysite nanotubes, which are naturally occurring hollow aluminosilicate clay mineral fibres with a typical diameter of less than 100 nm. The technology has proven successful in extending the shelf life of bread, cheese and cherries and future development activities will focus on solutions for fish (Packaging Insights 2019).

It should be noted that the food safety consequences of nanomaterials in food contact applications is a relatively new and evolving field (Hardy *et al.* 2018). This implies a high technical risk for organisations involved in the development of food applications of nanomaterials.

Technology Readiness Level: 3-5; Technical risk: High

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[1] Nanopack project: https://www.nanopack.eu/

Chitosan-based antimicrobial packaging film. Scottish company CuanTec have developed an antimicrobial packaging film produced from chitosan. Chitosan has natural antimicrobial properties (Kong *et al.* 2010). The company is using novel bio-fermentation technology to extract chitin from langoustine processing waste, which results in higher yields and quality compared to the standard chemical process. Their deacetylation process to process chitin into chitosan involves five times less sodium hydroxide than the conventional chemical process.

The final packaging film is biodegradable and is due to be trialled by Waitrose in some of their fish products (Waitrose & Partners 2019).

Technology Readiness Level: 6-8; Technical risk: Moderate

Controlled atmosphere bulk transportation system: BluWrap[1] is a system designed to maintain the freshness of chilled seafood during long-distance transportation. The aim is to enable products such as fresh salmon produced in Europe to be transported to Asia by rail or sea freight rather than air freight, without compromising quality. The fresh product is packed into special containers that allow gas flow across all the containers on a pallet. Each pallet has a BluWrap unit on top, which uses a fuel cell system and sensors to reduce and monitor oxygen levels in the containers. The pallets are placed in refrigerated containers to keep the produce chilled. The developers claim that the system can extend the shelf life "well beyond 40 days." The company is currently developing plans to support shipping of salmon from Norway to China using the Trans-Siberian Railway (Evans 2020).

Technology Readiness Level: 6-8; Technical risk: Moderate

Innovation with a potential for transformative performance improvement

Essential oils as antimicrobial and antioxidant agent. The use of essential oils as natural antimicrobial and antioxidant agents for food packaging and coatings has been widely explored (Ju *et al.* 2019). One example in a seafood context comes from Djenane (2015), who conducted lab tests to assess the efficacy of lemon, orange and bergamot essential oils in inhibiting microbial growth and lipid oxidation in sardines. Sardine samples were inoculated with *Staphylococcus aureus* and then sprayed with essential oils before being stored at 8 degrees Celsius for seven days. It was found that spraying the sardines with bergamot

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[1] BluWrap: https://www.bluwrap.me/

essential oil (3200 parts per million) completely reduced the growth of *S. aureus* from day two until the end of storage. The same treatment reduced lipid oxidation by 56%.

Technology Readiness Level: 6-8; Technical risk: Moderate

Antimicrobial additives in packaging material: Antimicrobial additives can be introduced to packaging materials during compounding to provide an antimicrobial effect. In the UK, Addmaster produce Biomaster[1], a silver ion-based additive that offers a 99.9% reduction in E.coli and Staphylococcus aureus and is also effective against Campylobacter, Salmonella and Listeria as well as moulds and yeast. The technology has been applied in meat and poultry packaging. The performance and safety of silver-based antibacterial additives in food contact applications are currently under review as part of the EU's biocidal products regulation (European Commission 2012).

Technology Readiness Level: 9; Technical risk: Low

Edible coatings and films: A wide variety of edible coatings and films have been tested that offer antimicrobial properties and enable shelf life extension. Many use some combination of fish gelatin and chitosan – a polysaccharide derived from the chitin present in crustacean shells. Feng et al (2016) found that a chitosan plus 7.2% gelatin coating applied to golden pomfret fillet resulted in significant reduction in microbial load when stored at 4 degrees Celsius for 17 days. Further benefits in terms of reduced water loss and colour change were reported.

Alternative types of antimicrobial films have been tested. Kormaz at al (2019) found that a quinoa starch-based biofilm was effective in reducing microbial load in rainbow trout fillets stored at 4 degrees Celsius for 12 days.

Edible coatings made from leftover plant skins and stems have been commercially introduced in the USA by Apeel. The coating forms an oxygen and moisture resistant barrier that has proven successful in extending the shelf life of fruit and vegetables, such as avocado. The Apeel technology has not yet been tested in seafood applications.

It should be noted that edible coatings and films are a potential source of allergens that consumers may not be aware of.

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[1] Biomaster: https://www.addmaster.co.uk/biomaster/industries/packaging

Technology Readiness Level: 6-8; Technical risk: Moderate

PLA-based antimicrobial films: Yang et al (2019) have developed an antimicrobial packaging film based on polylactic acid (PLA) blended with poly (butylene succinate adipate) (PBSA) that incorporated the active ingredients carvacrol and thymol (from herb essential oils). Bags produced using the PLA-PBSA film were found to have better mechanical properties compared to similar PLA-based films. The active ingredients offered good antibacterial and antioxidant properties when tested with salmon slices, resulting in a shelf life extension of three to four days.

Technology Readiness Level: 6-8; Technical risk: Moderate

Moisture scavenging trays: Aptar Food and Beverage have developed a range of moisture scavenging trays that they claim helps to increase the shelf life of chilled and frozen seafood products by up to 50%. The Seawell Protective Packaging System[1] utilises recyclable polypropylene trays that include wells filled with a superabsorbent polymer. The key challenge in this application is to ensure that the absorbent retains free liquid but does not dry out the product.

Technology Readiness Level: 9; Technical risk: Low

Active modified atmosphere packaging: Modified atmosphere packaging is a well-established technology for shelf life extension for seafood products (DeWitt and Oliveira 2016). Optimal use of the technology requires an understanding of the dominate spoilage mechanisms for the species to be processed and adjustment of the processing conditions and gas mix accordingly. For instance, fat-rich fish such as salmon are highly susceptible to lipid oxidation. MAP can be used to create low oxygen environment within the packaging head space can help to slow this process.

Whilst the technology is gained significant adoption in seafood sector, there are disadvantages, such as higher production costs and reduced volumetric efficiency in transportation.

The next generation of MAP technologies are aiming to further increase shelf life whilst maintaining quality through further optimisation of the package gas mix during its usage. This principle has been applied by Hansen et al (2016) who have developed a moisture absorbent

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[1] Seawell Packaging: https://www.maxwellchase.com/product/protective-packaging-systems/

pad that also acts as a CO_2 emitter. In tests with cod stored at 2 degrees Celsius, they found that conventional MAP gave a shelf life of around 9 days whilst the combination of MAP with the CO_2 emitter pad resulted in a shelf life of around 13 days.

Technology Readiness Level: 6-8; Technical risk: Moderate

Modified atmosphere packaging with other shelf life treatments: Studies have shown that the shelf life benefits of MAP work synergistically with other shelf life treatments for seafood, such as essential oil treatment, high pressure processing, sodium chloride, potassium sorbate and acetic acid (Gokoglu 2019).

Technology Readiness Level: 9; Technical risk: Low

Oxygen scavenging films: Seafood products with high-fat content are prone to degradation through oxidation. Modified atmosphere packaging or vacuum systems can significantly reduce oxygen in the packet, but these technologies are not suitable for emulsions and so alternative methods, such as the use of oxygen scavenging films are required.

A wide variety of oxygen scavenging compounds have been developed and tested for use in food packaging (Dey and Neogi 2019). Johnson et al (2018) have tested the commercially available oxygen scavenging film Ageless Omac™ with fish oil-in-water emulsions. The film reduced dissolved oxygen content by more than 95% and helped to reduce mineral degradation. The Ageless Omac film is suitable for retort pouches and can be boiled.

Technology Readiness Level: 9; Technical risk: Low

Innovation with a potential for incremental performance improvement

Skin packaging with aluminium tray: Advanta Packaging has launched an aluminium tray that is compatible with vacuum skin packaging technology (Food Processing Technology 2018). The company claims that the technology enables a shelf life increase of up to 300%. The foil tray is shaped to neatly fit a whole chicken and adds convenience for the consumer as they can simply removal the film layer and place the product in the oven in the tray.

Technology Readiness Level: 9; Technical risk: Low

21.3 Monitoring product condition through intelligent packaging

In modern supply chains a wide variety of information about the product, such as its condition and location, can be obtained thanks to ‘intelligent packaging’ systems. The function of intelligent packaging systems lies in their detection of changes to the properties of the packaged product or its environment and their communication to the outside world (Kerry, O’Grady, and Hogan 2006). The traceability functions associated with intelligent packaging systems are addressed in chapter 22 ‘Quality and food safety management systems and accreditations’. Below we present a range of innovations primarily focused on food spoilage indicators.

Innovation with a potential for disruptive performance improvement

Gelatine-based freshness indicator: Studies in the UK have suggested that food loss and waste could be reduced by 50% or more if food date labelling practices where modified to eliminate the ‘buffer’ time that is often included by producers (WRAP 2015). One reason for the inclusion of these buffer periods is to allow for real-world deviations from the specified storage conditions, such as thermal mistreatment of the product.

Mimica Touch[1] is a temperature sensitive indicator of product freshness that helps to provide a real-world indicator of product freshness. It consists of a label or cap that is placed on the outside of the product at the point of production. Inside the label there is a layer of gelatine that covers a ridged plastic layer. When first applied, the label feels smooth but as the gelatine layer decays and breaks down the plastic ridges underneath can be felt. An advantage of this system is that it is suitable for visually impaired consumers, unlike standard labels.

The gelatine layer can be tailored to match the spoilage rate of the product. The first commercial application of the Mimica Touch will be for fresh juice products, with further applications for milk and meet expected.

Technology Readiness Level: 6-8; Technical risk: Moderate

Paper-based electrical gas sensors to detect spoilage gases: Researchers at Imperial College London have developed a sensor that can detect spoilage gases ammonia and

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[1] Mimica Touch: https://www.mimicalab.com/product

trimethylamine in meat and fish products (Barandun *et al.* 2019). The sensors are made of carbon electrodes printed onto cellulose paper. The signal from the sensor is transmitted via an NFC tag to the user's smartphone where an associated app tells the user if the product is still safe to eat. The main advantages of the system compared to other spoilage gas sensors being developed are the low cost (less than two pence per sensor), reduced sensitivity to non-spoilage gases, and the ability to operate at nearly 100% humidity environments (compared to 90% for most sensors).

Technology Readiness Level: 3-5; Technical risk: High

Innovation with a potential for transformative performance improvement

Time-temperature integrators to monitor freshness: Time-temperature integrators (TTIs) are low cost labels that provide a visual indicator of the time-temperature history of a package, which can help in estimating the remaining shelf life of a product. The labels typically consist of a reactive layer, which changes colour when exposed to temperatures that exceed the specified storage temperature range or after a certain period of time. Various reaction mechanisms have been utilised, including polymerisation, thermochromic/photochromic reactions, diffusion or enzyme reactions. Whatever the reaction mechanism, the key challenge is to ensure that the TTI label accurately reflect the condition of the product.

TTI labels have been shown to be a reliable indicator of product shelf life for frozen seafood (blueshark slices and arrow squid) (Tsironi *et al.* 2016) and other chilled, highly perishable product such as fresh chicken (Brizio and Prentice 2014). Commercial providers of TTI labels include Smart Dot[1] from Evigence Sensors and Bizerba USA, whose labels have been implemented for own label products by the Fresh & Easy retail chain in North America (Lingle 2015). In the UK, TTI labels producers include Insignia Technologies[2] and Timestrip, who produce the Timestrip Seafood[3], which is FDA approved for the prevention of Clostridium botulinum management.

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[1] Smart Dot TTI labels: https://evigence.com/unit-level-cold-chain-management/

[2] Insignia Technologies: https://www.insigniatechnologies.com/products_foodretailsolutions.php

[3] Timestrip Seafood: https://timestrip.com/products/seafood-3-degree/

Technology Readiness Level: 9; Technical risk: Low

'Once opened' indicator: A 'once opened' indicator has been developed by Insignia Technologies in the UK which can be applied to a variety of packaging types. A version of the indicator label can be used with MAP packaging[1]. A central dot on the label starts off brown when 'just opened' then begins to turn red ('use soon'), before finally turning purple ('past best'). The speed of the process can be calibrated to match consumer guidance for various products.

Technology Readiness Level: 9; Technical risk: Low

Gas indicators of spoilage: Amine production is linked with the microbial growth and can therefore be used as an indicator of product spoilage. A wide variety of indicators and sensors have been developed to detect the presence and level of amines in the headspace of meat and seafood packaging. These sensors are often coupled with some form of simple electronic transmitter such that readings from a sensor located within the packaging can be interrogated by a reader outside (Bhadra *et al.* 2015). The problem with such systems is that they contain non-food contact approved materials.

Dudynk et al (2018) have overcome this challenge with a sensor film that is produced entirely from edible materials. The sensor film is made with apectin matrix containing a red cabbage extract as a colorimetric indicator. Tests with whiting and shrimp found that the sensor colour changes where closely correlated with the increase in amines, measured as total volatile basic nitrogen (TVB-N) with tests at both chilled (4 degrees Celsius) and ambient (21 degrees Celsius).

Despite significant and promising academic research in this field, there do not appear to be any low cost, commercially available solutions available for amine detection suitable for seafood packaging. It appears some companies have attempted commercialisation of gas spoilage indicators, such as the SensorQ from Food Quality Sensor International (Food Ingredients First 2007) and Toxinguard by Toxin Alert Inc (Ghaani *et al.* 2016). The subsequent lack of information concerning these products suggests they have since suffered commercial failures. The reasons for these failures are not clear.

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[1] Insignia After Opening Freshness Timer: https://www.insigniatechnologies.com/products_foodretailsolutions.php

Of the currently active commercial developments in this field, one of the most advanced solutions is the Freshcode indicator[1], which has been developed for chicken products and has received a favourable initial review from the European Food Safety Authority. However, it is not yet commercially available. Also see the paper-based electrical gas sensors mentioned earlier in this section, which has the potential to be a low-cost solution but is still at the academic research stage.

Technology Readiness Level: 6-8; Technical risk: Moderate

Next-generation RFID systems with integrated sensors: These innovations are discussed within the traceability section of chapter 22 ‘Quality and food safety management systems and accreditations’.

Technology Readiness Level: 9; Technical risk: Low

21.4 Reducing environmental impacts through sustainable packaging

In response to concerns about plastics waste and issues such as marine plastic litter, the European Commission has established a requirement for all packaging to be 100% recyclable by 2030 (European Commission 2018). In response many major retailers, manufacturers and packaging producers have established targets to eliminate non-recyclable plastic packaging from their product ranges, with many choosing 2025 as the target deadline, including Nestle, Unilever, DS Smith, and Amcor. Some companies such as Iceland, are going further, with a commitment to eliminate all plastic packaging from their own brand ranges by 2023 (Iceland Foods 2018).

In the rush to reduce plastic usage in packaging, it is important to ensure that the alternative being adopted are truly more sustainable. As the packaging development team from Young’s Seafood have noted, the primary factor in their choice of packaging solutions is that it must not increase food waste (IntraFish 2019c).

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[1] Freshcode indicator: http://freshcodelabel.com/

To avoid the situation in which improvements are made in reducing sustainability impacts in some parts of the value chain, only for these to be offset by larger impacts being generated elsewhere, it is important to adopt a life cycle perspective. Approaches such as lifecycle thinking and life cycle assessment can help to quantify sustainability impacts across the product lifecycle, provide a rigorous and scientific method for evaluating and comparing new packaging systems and identify possible solutions to minimise the overall sustainability impacts (O'Hare *et al.* 2017).

Below we present a range of innovations that can help to improve the sustainability performance of packaging systems.

Innovation with a potential for transformative performance improvement

Cardboard ready to cook tray: Ready to cook products are often packaged with aluminium foil trays. Frosta, who have adopted a life cycle approach to assessing the sustainability impacts of their products, concluded that the large amount of energy required to produce virgin aluminium foil meant that a coated cardboard tray would be better for the environment for their 'Schlemmerfilet' range (Frosta AG 2016). An added benefit is that the product can now be cooked in the microwave in 10 minutes from frozen, saving time for the consumer.

Technology Readiness Level: 9; Technical risk: Low

Cardboard alternative to Expanded Polystyrene (EPS): The EcoFishBox[1] produced by Stora Enso is intended as a replacement for EPS fish boxes. It is a flatpack design that is assembled on-site using an automated machine meaning that 85% less storage space is required. Further financial and environmental gains occur across the lifecycle of the product thanks to the much greater density of boxes that can be transported in the flatpack form and a 20% increase in the number of boxes that can be transported when filled due to thinner walls compared to EPS. The double walled boxes still offer good thermal insulation and are waterproof but can be recycled.

The environmental benefits of the EcoFishBox compared to conventional EPS boxes has been examined in detail through a Life Cycle Assessment (Salminen, Kemppi, and Niskanen 2018). The boxes have been adopted by some Finnish fish processors (Undercurrent News 2019).

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[1] EcoFishBox: https://www.storaenso.com/en/products/packaging-solutions/ecofishbox

Technology Readiness Level: 9; Technical risk: Low

Traceable alternative to Expanded Polystyrene (EPS): Another solution offering an alternative to EPS fish boxes is the TomKat KoolPak[1]. The KoolPak comprises three elements: base, thermal liner and lid. Each component features an embedded near-filed communication (NFC) tag, which can be used with a traceability system to track the products progress through the supply chain. The company has partnered with blockchain traceability system provider, Quant, to test the use of the system, including tracking of rotational reuse and recycling (Quant 2019). Cold chain performance data can be captured by the blockchain system as the NFC tag in the KoolPak thermal liner features a battery-less temperature sensor.

The thermal performance of the system has been found to be 20% better than EPS fish boxes in initial tests by Queensland University. Like the EcoFishBox, the TomKat KoolPak is delivered flat-packed to the processor and is 100% recyclable.

Technology Readiness Level: 6-8; Technical risk: Moderate

Odour scavenging films: Malodours can be present with seafood products, even when they are still safe to eat. This means that consumers will sometimes dispose of products unnecessarily. AqFresh[2] by Aqdot makes use of cucurbiturils – barrel-shaped molecules that powerfully attract and capture odours to eliminate them. AqFresh can be added into packaging films by incorporation into the plastic masterbatch.

Technology Readiness Level: 9; Technical risk: Low

Paper-based trays and blister packs: Swedish company BillerudKorsnäs have developed, FibreForm, a 3D-formable paper material that can be used as a heat-sealed tray or blister pack. The system uses 90% less plastic compared to conventional, all plastic systems and an independent life cycle assessment found that the carbon footprint of the FibreForm paper tray was up to 71% lower than standard EPS or APET trays (BillerudKorsnäs 2019). The system is currently being used for packaging of sliced, cooked meat products but may be relevant to seafood products such as smoked salmon.

Technology Readiness Level: 9; Technical risk: Moderate

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[1] TomKat KoolPak: https://www.tomkatlinefish.com/tomkat-koolpak

[2] AqFresh: https://aqdot.com/products/advanced-odour-elimination/

Bioplastic films: A wide variety of bioplastic films have been developed from feedstocks such as starch, sugar and cellulose. Bioplastics can offer significant reductions in terms of life cycle energy and CO_2 emissions. Achieving the same levels of mechanical, optical and vapour barrier performance as petroleum-based plastics has been a major development challenge, but there are now a range of commercially available bioplastic films available from companies such as Bio-Fed[1], A. Warne [2] and Smith and McLaurin[3].

Innovation in the area of bioplastic films is now concerned with developing 'active' packaging systems that help to prolong shelf life. The previously mentioned example of the polylactic acid (PLA) blended with polybutylene succinate adipate (PBSA) film containing essential oils developed by Yang et al (2019) is representative of these developments.

As Schumann and Schmidt (2018) have noted, bioplastics feedstock should ideally come from food processing waste rather than primary sources as this will create land use competition with food production systems. For the seafood sector, the use of chitosan-based bioplastic films is therefore particularly appropriate as this will support a 'circular economy' approach (de la Caba *et al.* 2019) and also offers natural antimicrobial benefits. The previously mentioned chitosan-based bioplastic being developed by CuanTec is a promising example of this. Elsewhere, fish gelatin and myofibrillar proteins from processing waste are being tested as the basis for bioplastic films (Xavier Neves *et al.* 2019).

For innovations in bioplastic films please refer to section 20.4.

Innovation with a potential for incremental performance improvement

Cardboard monomaterial packaging for frozen products: Cardboard is often used in the packaging of frozen seafood products, such as battered fish. To avoid grease spots, which can reduce the strength of the cardboard and look unappealing to consumers, the conventional solution has been to apply a polyethylene coating to the inside layer of the

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[1] Bio-Fed: https://bio-fed.com/our-biomaterials/

[2] A. Warne: https://www.awarne.com/pla-film-supplier-converter//

[3] Smith and McLaurin: https://www.smcl.co.uk/products/environmental/eco-films/

cardboard. As this material is bonded to the cardboard and cannot be separated, it means that the final material cannot be recycled.

MM Karton have produced Accurate Freeze-Grease, a cardboard monomaterial that is recyclable whilst still retaining the grease resistance required for frozen seafood products. The Accurate range is being used in the UK by Young's Seafoods (MM Karton 2018).

Technology Readiness Level: 9; Technical risk: Low

Paper packaging for frozen foods: A patent pending, paper-based packaging system to replace the use of plastic has been implemented by Frosta within their frozen foods and ready meals range (IntraFish 2019a). The system uses a speciality high density paper on the inside to enable resistance to water and grease, whilst the outside layer is designed to be tear resistant, to ensure ease of use on high-speed packing machines. Starch-based glue is used to seal the packets, ensuring high recyclability of the package is possible.

The company is planning to pass on some of the additional cost incurred for the new packaging materials to the consumer through a 20 Euro-cents increase in product retail prices.

Technology Readiness Level: 9; Technical risk: Low

Efficient recycling of Expanded Polystyrene (EPS): 22 million EPS fish boxes are used in UK every year (British Plastics Federation 2013), primarily in the supply chain and for deliveries to the food service sector. Its popularity is due to the material's excellent thermal insulation properties, low mass and low cost. However, EPS has proven inefficient to recycle as it is 98% air making transportation for recycling extremely inefficient. This is made clear by DS Smith, who collected 93,500 cubic litres of EPS every week from Tesco's Irish estate, which only equated to 10 tonnes of material in a year (DS Smith 2018). The solution now implemented by DS Smith is to have a mobile EPS compaction unit installed in an articulated lorry. This allows the EPS material to be compacted at each store before proceeding to the next pick up. The compacted material is then sold to companies for reprocessing into products such as insulation board, garden furniture, and coat hangers.

Technology Readiness Level: 9; Technical risk: Low

Biopolymer alternative to Expanded Polystyrene (EPS): Synbra Technology have developed 'BioFoam' as an alternative to EPS. It is made from polylactic acid (PLA), using sugar cane as a feedstock rather than fossil fuels. The company claims that this offers a 60-70% reduction in carbon footprint for the production of the BioFoam compared to EPS. The thermal and mechanical properties of BioFoam are very similar to that of EPS, which should enable it to be used as a drop-in replacement, requiring no changes for seafood processors.

Technology Readiness Level: 9; Technical risk: Low

Recyclable stand-up pouches: Pouches have become a popular packaging format for a variety of food products in recent years, offering good shelf presentation and being easy to open. Retortable and microwave safe versions of stand-up pouches have enabled reductions in material usage, as well as energy and CO_2 emissions from production and transportation whilst providing consumers with the convenience of ready to heat products. However, the multi-material laminates that have typically been used for these applications were either not recyclable or required separate recycling from mixed waste streams.

Recyclable monomaterial versions of both standard stand-up pouches and retortable pouches are now available. These include X-EnviroPouch[1], made using a polyethene film, and the AmLite HeatfFlex[2], made with a polyolefin film with a silicon oxide coating and is both retort safe and microwaveable.

Technology Readiness Level: 9; Technical risk: Low

Recycled and recyclable plastic trays: Plastic packaging trays are often black in colour as this help to mask imperfections in the product. However, the carbon black pigments used to colour the trays cannot be detected by the near infrared technology used in recycling facilities, meaning that, even though they were often made with recyclable materials, they were not recycled in practice.

Faerch UK & Ireland has developed a tray range that are 100% recyclable and include up to 100% recycled content. For chilled, fresh meat and fish, the MAPET®II and APET products are made from 100% recycled PET. The tray colour will vary as the product uses a mix of recycled content sources and no colour is added during the recycling process, meaning that "The colour of each tray reflects the specific blend of recycled content that it is made from" (Faerch 2019). For ready meals, the Evolve products are made from Crystalline Polyethylene Terephthalate (CPET) with 85% post-consumer recycled content and are 100% recyclable and can still be used in the standard temperature range of -40°C to +220°C.

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[1] X-EnviroPouch: https://www.rpc-bpi.com/rpc-bpi-protect-100-recyclable-stand-non-laminate-bag/

[2] AmLite HeatFlex: https://www.amcor.com/product-listing/amlite-heatfflex

Faerch are making further efforts towards a circular economy by offering retailers the opportunity to join a recycling scheme in which an identical quantity of the volume of Faerch trays a retailer sells through their stores will be sourced as post-consumer waste locally in the UK and recycled into new food grade trays at one of Faerch's production sites (Corbin 2019).

Technology Readiness Level: 9; Technical risk: Low

More sustainable skin packaging systems: Skin packaging systems have typically been produced using a polymer tray (PVC, PP or PET) and a laminate top film that is vacuum sealed over the product. Skin packaging systems have been credited with boosting seafood sales as they enable better shelf presentation (items can be placed vertically on shelves unlike MAP where contents would slide to the bottom) whilst also offer benefits in terms of extended shelf life, inherent tamper evident and easy opening. However, the significant use of plastic and the fact that the laminate top film is typically not recyclable have caused some concern from a sustainability perspective.

A number of innovations are now attempting to address these issues with skin packaging. Young's Seafood have developed skin pack system that is 75% recyclable, although the top film is not yet recyclable (IntraFish 2019b). In terms of trays, SealedAir now offer the Cryovac Brand[1] tray that uses a combination of recycled PET and Plantic plant-based resin. Meanwhile, Sealpac have developed a cardboard replacement for the conventional plastic tray called FlatSkin[2]. The board layer, which can be made with unbleached fibre, can be printed on both sides as the board is coated with a polymeric protective layer that can easily be removed once the pack is opened. The cardboard component and the plastic film layers can then be recycled separately. The company claims this system offers a 70% reduction in plastic usage compared to standard skin packaging systems.

Technology Readiness Level: 9; Technical risk: Low

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[1] Cryovac Brand tray: https://sealedair.com/food-care/food-care-products/cryovac-brand-darfresh-10k-otr-made-plant-based-resin

[2] FlatSkin: https://www.sealpacinternational.com/brochures/FlatSkin-uk.pdf

21.5 Responding to changing consumer and sales channel requirements

In order to compete with other sources of protein, seafood processors are having to develop packaging systems that more effectively respond to the requirements of consumers. According to one expert, consumers are now looking for '…packaging that is easy to use (easy open/close, re-sealable, portionable/individually-wrapped), effective (leak-proof, easy to handle), informative (nutrition facts, cooking instructions), and sustainable (recyclable, reusable, extends shelf life/reduces waste).'(Seafood Source 2018).

At the same time the sales channels through which seafood products are changing, with a small but steadily growing percentage now being sold through e-commerce routes. Online sales of food and beverage products are expected to reach 15-20% by 2025. Major seafood producers, such as Trident, Pacific Andes and American Seafoods have signed agreements with online retailers in China.

To help producers to adjust to the new demands that e-commerce will place on their product and packaging Nofima in Norway is currently running a project to explore the implications of this new sales channel (Nofima 2019). In the UK, we are already seeing specialist seafood retailers, such as Fishbox[1], offering seafood as a subscription service with weekly boxes delivered direct to the home.

The move to e-commerce will require changes to packaging systems in order to ensure that the product arrives in optimal condition and can be delivered in a cost-effective manner (Henkes *et al.* 2019). Inspiration for such changes can be sought in adjacent industries, such as the flat wine bottle developed specifically for e-commerce by Garcon Wines [2]. The flat bottle, which is made from 100% recycled PET, is delivered in a cardboard container that can fit through a standard letter box to avoid the consumer frustration of a missed delivery attempt. From a logistics perspective, it is also 87% lighter and 40% smaller than a standard glass wine bottle. Below we present some of the innovations that might help seafood packaging to adapt to the changing requirements of consumers and e-commerce sales channels.

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[1] Fishbox: https://www.fishbox.co.uk/

[2] Garcon Wines: https://www.garconwines.com/

Innovation with a potential for transformative performance improvement

Wool-insulated packaging for e-commerce: UK-based company Woolcool[1] have developed a range of packaging solutions that are suitable for e-Commerce and make use of wool insulation. The range includes boxes with wool liners as well as insulated pouches and envelopes that are made with food grade, recyclable LDPE. The excellent thermal insultation properties of wool mean that produce packed at 1°C will remain chilled below 5°C for at least 24 hours. Longer chilled periods can be achieved with ice packs. The wool material can be re-used around the home, composted or sent to landfill - where it will decompose rapidly.

Technology Readiness Level: 9; Technical risk: Low

E-commerce boxes: A very small but increasing quantity of fresh, chilled produce is being delivered direct to households using couriers. The use of refrigerated vehicles for 'last mile' deliveries is typically expensive and relatively inefficient and so produce will need to remain chilled whilst in ambient temperature transportation systems. The IsoPro Box[2] from Cool Direct has been specifically designed for e-Commerce applications. It consists of a standard carboard box with a separate thermal liner. When used with coolants, the system was able to keep produce at between -2°C and +4°C for 48 hours in ambient temperatures of up to 30°C. The range include boxes with capacities from 6 litres to 41 litres and is delivered flat-packed to the producer for more efficient transportation and storage.

Technology Readiness Level: 9; Technical risk: Low

Phase change materials to maintain temperature control: Phase change materials offer the potential to provide more efficient cooling for produce in transport. CrodaTherm[3] is an organic phase change material derived from plant-based feedstocks and has the form of a crystalline wax or oily liquid (depending on temperature). The product uses the latent heat associated with phase changes to store 'cold energy'. When the ambient temperature rises above the target temperature the phase change material will begin to release the 'cold energy', helping to keep the produce at the desired temperature.

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[1] Woolcool: https://www.woolcool.com/

[2] IsoPro Box: https://www.cool-direct.com/e-commerce-box.html

[3] CrodaTherm: https://www.crodatherm.com/en-gb/products-and-applications/crodatherm-wax/food-and-refrigeration/food-delivery-and-supply-chains

Technology Readiness Level: 9; Technical risk: Low

Microwavable frozen ready meals: In response to the consumer demand for quick and simple ready to heat products, Young's Seafood have developed a 'Just Steam' range of frozen ready meals that can be cooked in a microwave in 8 minutes. The packaging consists of 'Perfect Steam Tray' made from cardboard, with a film top layer that is vacuum sealed, plus a partial cardboard sleeve. The clear film enables the consumer to see the product and the presentation in the tray is maintained by the vacuum sealing, allowing the user to handle the product. Two variants have been launched within Tesco stores: a salmon fillet and sweet chili, and a haddock fillet and parsley version (Undercurrent News 2018).

Technology Readiness Level: 9; Technical risk: Low

Oven-ready vacuum packaging: SealedAir have developed oven-ready packaging systems that are also compatible with vacuum packing. Products such as fish fillets are placed in the Oven Ease[1] packaging and vacuum packed as normal. The consumer can then place the whole packet in the oven at temperatures of up to 204 degrees Celsius for 4 hours. This helps to reduce mess in preparation and oven clean-up after cooking and can help to retain moisture in the cooked product.

Technology Readiness Level: 9; Technical risk: Low

Innovation with a potential for incremental performance improvement

Single portion packaging: The USDA reports that the typical American family throws away up to 40 percent of the fresh fish, meat, and poultry they purchase (Lilienfield 2015). UK households waste around 6,000 tonnes of seafood each year because they cooked, prepared or served too much (WRAP 2018). The use of single portion packaging may help to reduce this waste.

Whilst not a new innovation, the use of single portion packaging is becoming increasingly popular due to the rising number of one or two person households (Processing 2013). Examples include single portion packaged frozen salmon fillets and individual ready meals. Whilst this trend invariably leads to an increased use of packaging materials, this may be

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[1] Oven Ease: https://sealedair.com/food-care/food-care-products/cryovac-oven-ease

justified if it can be shown that such a move would lead to reduced food waste and reduced sustainability impacts over the life cycle of the product (Lilienfield 2015).

Technology Readiness Level: 9; Technical risk: Low

Reclosable packaging: The ability to open and then reclose packages, without the need for additional plastic wrap or transferring the contents to another container, is another aspect of consumer convenience that has been noted (Seafood Source 2018). To address this demand, Schur Flexibles has developed FlexiClosere[1], which is a polyofelin-based film lid for MAP systems that can be reclosed. The high-barrier film can be reclosed at least 10 times and is fully recyclable in mixed recycling streams.

Technology Readiness Level: 9; Technical risk: Low

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[1] FlexiClosere: https://www.schurflexibles.com/sites/default/files/2018-10/schur-flexiclose-re_flyer_EN_SCREEN_0.PDF

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22 Primary processing technologies

Contents

From the SIF Executive Board

The method applied in this review has generated numerous examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently happening. It is recognised that there are existing innovations and research areas that are not included here, and new areas where future innovations may occur. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

22.1 Overview: processing technologies

What is the challenge in the UK?

To date the adoption of R&D activity surrounding novel processing technologies in the UK have been limited, with exception to salmon and trout farming. Due to high costs, state-of-the-art processing remains the domain of larger, vertically integrated companies, such as those in Iceland and Russia. Still, UK enterprises facing labour shortages may opt for incremental, modular upgrading with “quick win” equipment.

What are the most promising innovation categories?

- **Big data integration –** Real-time communication between various stakeholders of data from harvest to market, for best utilisation and profit
- **Cutting –** Computer vision systems and water jet cutting enable processing of a variety of species and sizes
- **Chilling –** Automated and sustainable solutions lead to significant improvement in product quality from point of harvest

Where are important knowledge gaps?

- Optimisation of processing systems for diverse range of wild-catch sizes
- Limited innovation activity in shellfish processing

Fish processing entails the processes involved between the time the fish (and other seafood) are caught or harvested and delivered to consumers. Primary processing, the focus of this chapter, encompasses the earliest stages of these processes in which fish are slaughtered and cut for sale in either frozen or fresh formats. Throughout the past decades, innovations in automation, quality control and animal welfare have revolutionised the industry, often taking inspiration from other food processing sectors.

Today, following in the footsteps of the automotive, telecommunications and livestock and poultry industries, Industry 4.0 has come to fish processing (IntraFish 2018b). Industry 4.0

refers to the “fourth industrial revolution” in manufacturing, which builds on the computers and automation of its 3.0 predecessor, with smart and autonomous systems fuelled by data and machine learning. A combination of cyber-physical systems, the Internet of Things and the Internet of Systems make the smart factory a reality, ultimately leading to greater efficiency and productivity, as well as less waste (Forbes 2018). The FAO recently noted that despite limited adoption at present, “if well-managed, disruptive technologies offer immense opportunities to enhance the technical and financial efficiency of the sector, to create new work opportunities, and to improve food security and livelihoods” (FAO 2018).

From harvest to market, tools from Industry 4.0 are helping to break new ground in various areas in onshore primary processing of products from fisheries and aquaculture. Data-driven solutions will allow for horizontal connection throughout the value chain, improving quality, transparency and compliance, as well as resulting in smart solutions to simultaneously increase yield and sustainability. Together, these can lead to greater flexibility and choice for consumers.

In addition to improved performance, motivations for this shift are commercial – equipment leaders such as Marel have branched into software as a new USP to maintain relevance in an increasingly competitive global market, and is spending over £50 million annually (6% of its revenue) on innovations (IntraFish 2017).

Big strides have been made towards automation in seafood processing with notable examples such as Norway’s Lerøy moving towards full automation in its salmon facilities. Indeed, the Norwegian seafood industry has achieved tremendous efficiency gains through automation. Salmonid aquaculture processing volume has increased almost 130% between 2007 and 2016 in approved onshore facilities to 23,000 MT (Optimar 2018). According to Icelandic fish company Visir, technological advances are also helping to make wild fish processing more competitive, even with the aquaculture industry and thus, the wild-capture sector “needs to embrace the rapidly advancing processing industry and be more aware of the many opportunities technology offers for companies to maximise value from their catch.” Taking advantage of these may also reduce reliance on outsourcing processing overseas (IntraFish 2018a).

However, with claims of waste through inefficiencies in seafood processing reaching as high as 35% and less than 5% of data gathered in manufacturing plants analysed for insights, “reactive rather than proactive" processors still have yet to harness the full potential of emerging technologies (IntraFish 2017; 2018b). With its low margins and high volume, the seafood processing sector still needs to improve in terms of profitability with respect to processing and distribution (IntraFish 2017).

Despite their potential, the greatest barrier to widespread adoption of these technologies remains their cost, which is prohibitively beyond reach for most small and medium-sized enterprises. With even basic water-jet cutting and portion grading equipment costing as much as £425,000, a healthy return-on-investment was said to only be possible from harvesters and processors achieving volumes of 15 to 20 tonnes per day (personal communication). Coupled with high satisfaction with the status quo, upgrading remains a tough sell for a historically conservative industry (personal communication).

Indeed, numerous interviewees commented that due to high costs, state-of-the-art processing is primarily the domain of larger, vertically-integrated companies overseeing everything from harvest to processing and trade, such as the case in Iceland and Russia. These players, backed by capital investment to experiment and upgrade, can derive the most benefit from reduced labour through automation, as well as big data to maximise efficiency and profit throughout the value chain (personal communication).

In the UK, adoption of novel fish processing technologies as a whole has been “conservative and incremental”, even amongst large farmed salmon and trout operations. Low adoption was also confirmed in the USA, where small and medium-sized operations dominate (personal communication).

In 2018, there were 96 confirmed primary processing sites in the UK, of which 56% employed the smallest size band of one to ten full-time equivalent jobs (FTE) (Seafish 2019). Low availability of suitable candidates is a key barrier to recruitment in the seafood processing sector and nearly half of respondents to a recent survey said they would invest in machinery or automation in response to difficulties in recruiting sufficient numbers of staff. Seafish did confirm however, “that for some sectors or specific jobs the shift to automation may be prohibitively expensive or not possible given the variable nature of the work” (Seafish 2018).

According to a processing equipment manufacturer, the trend in the UK is for an incremental, modular upgrading of “quick win” equipment such as those for filleting, due to a general wariness towards their high capital investment (personal communication). In the short-term, the company will continue to focus on the aquaculture sector, namely salmon and trout. However, they felt that data-driven solutions can still benefit smaller enterprises, especially with respect to traceability, as a means to command higher prices for products backed by a “story” (personal communication) . Regardless of the size of the operation, modernisation will require step-wise cost-benefit analyses weighing equipment expenditures against reduced labour costs (personal communication).

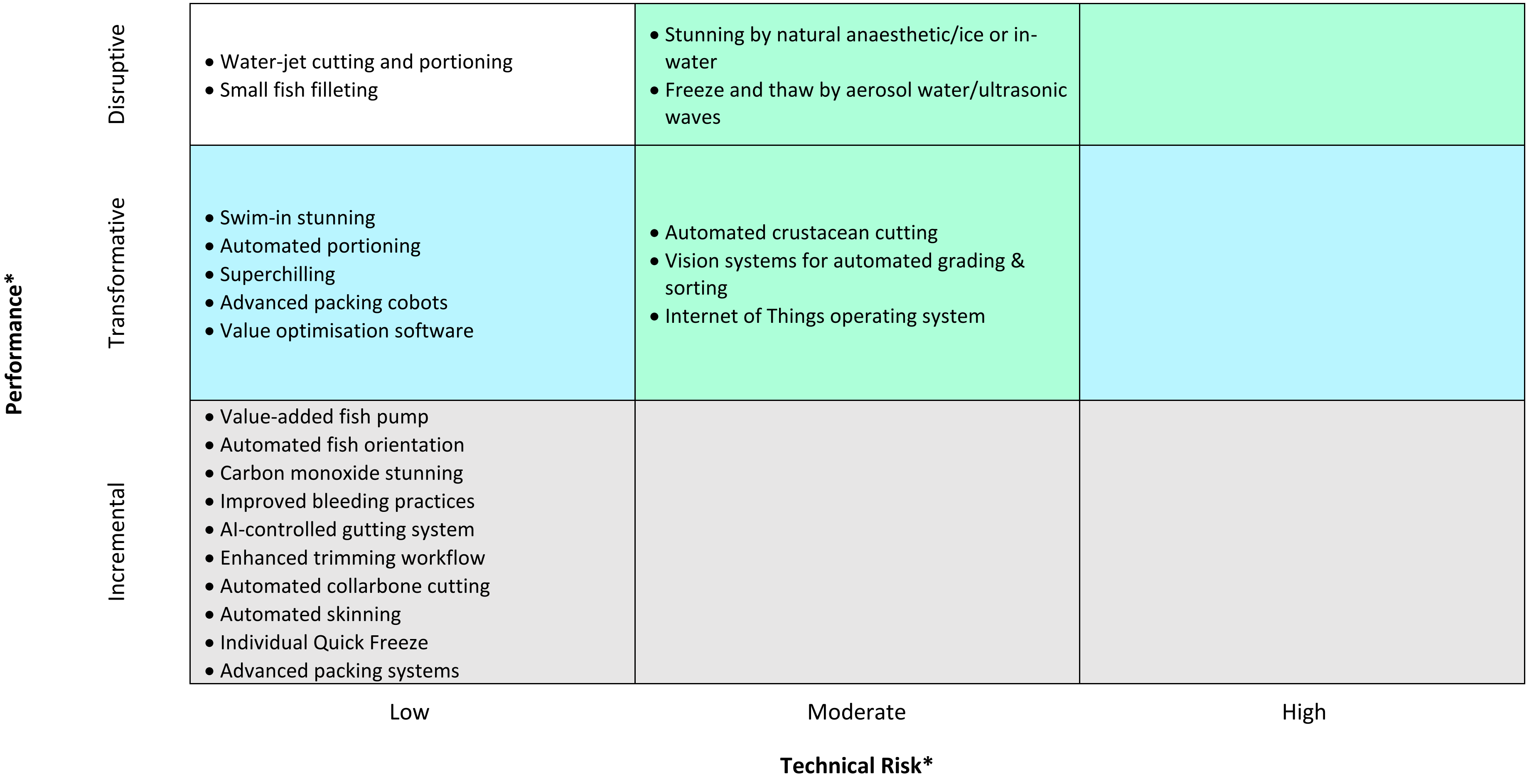
Since 2015, innovations in the area of onshore primary processing technologies have mainly been driven by industry, particularly in Western Europe and Scandinavia. Due to the proprietary nature of R&D efforts, much information is only available after commercialisation. Patent activity is strongest in China, although for species and value-added products with little relevance to the UK.

N.B. This chapter will explore innovation in primary processing onshore. Onboard processing innovations are covered in chapter 18 ‘Onboard processing’.

Innovations pertaining to the improvement of the quality, and mitigation of deterioration will be covered in the chapter 22 ‘Quality and food safety management systems and accreditations’, among others.

For by-product processing, please refer to chapter 24 ‘Waste reduction and valorisation’.

An overview of the potential performance improvement rating of recent (2015-2019) innovations in onshore primary processing technologies are outlined in Figure 22-1.



Performance*	Technical Risk*		
	Low	Moderate	High
Disruptive	• Water-jet cutting and portioning • Small fish filleting	• Stunning by natural anaesthetic/ice or in-water • Freeze and thaw by aerosol water/ultrasonic waves	
Transformative	• Swim-in stunning • Automated portioning • Superchilling • Advanced packing cobots • Value optimisation software	• Automated crustacean cutting • Vision systems for automated grading & sorting • Internet of Things operating system	
Incremental	• Value-added fish pump • Automated fish orientation • Carbon monoxide stunning • Improved bleeding practices • AI-controlled gutting system • Enhanced trimming workflow • Automated collarbone cutting • Automated skinning • Individual Quick Freeze • Advanced packing systems		

Figure 22-1: Performance and technical risk rating of innovations in onshore primary processing.

**See section 4.4 for definitions of the performance and technical risk rating scales.*

22.2 Fish handling

From the point of landing, effective and efficient handling is required to convey fish between various processing steps. Advancements in pumping and conveyor belt technologies have largely automated these activities.

Innovations with a potential for incremental performance improvement

Fish pumps: A redesigned version of Skaginn's ValuePump can move 60 metric tons of pelagic fish across a 200-metre distance every hour, via a 16-inch diameter pipe. The new pipe is based on the Archimedes screw, moving fish steadily via a liquid medium - water, fluid ice or additive solution - in a closed, low-pressure system via slow pipe rotations. The new pumping system enables value-added processes that chill and sanitise the product while also eliminating the need for transport vehicles (Undercurrent News 2019a).

Technology Readiness Level: 9; Technical risk: Low

For further examples of innovative fish pump designs, please refer to chapter 6 'Farmed animal health and welfare'.

Automated fish orientation: In 2015, a patent filed by German equipment manufacturer Baader was granted for a fish transporting device that automatically feeds fish to a processing machine that aligns fish in a head/tail orientation (Dann and Holtz 2015).

Technology Readiness Level: 3-5; Technical risk: Low

22.3 Grading and sorting

For one large seafood processor considering automation, integration of disruptive technologies for grading and sorting was considered a priority to overcome bottlenecks of working with variable species and sizes inherent to whitefish capture fisheries (personal communication).

Innovations with a potential for transformative performance improvement

Vision systems for automated grading and sorting: The Icelandic processing manufacturer Skaginn 3X have various automatic sorting solutions for pelagic fish, based on advanced and highly efficient technology for pelagic processing plants. The main benefits of the system are the fast and precise sorting ability, sorting up to 12 different size categories and inspecting each fish in terms of size, weight species and condition through automatic Vision-based quality control. The newest feature of the system is the addition of Vision units that control product flow from the grading machine and distribute the product traffic among different QC-Vision Batcher stations. This rapid and highly accurate automated process means that grading is rarely if ever a limiting factor in processing. The system is ideal for both onshore and onboard pelagic processing facilities. The onboard solution is described in chapter 18.

Technology Readiness Level: 6-8; Technical risk: Moderate

22.4 Slaughter

Once fish are landed, slaughter encompasses the steps from stunning/bleeding to gutting, cleaning and heading fish. Weighing, grading and sorting may occur during this process.

22.4.1 Stunning

While vast improvements can be made to animal welfare and product quality (that can then be sold onto consumers at a premium), most capture fisheries continue to place little importance on this area. Early adopters of stunning equipment will likely come from the aquaculture industry first (personal communication).

Innovations with a potential for disruptive performance improvement

Anaesthesia/ice: ICE2LAST is an EC Horizon 2020-funded project by Spanish ice manufacturer CUBI-PLAYA S.L., in response to widespread lack of stunning practices in fish farms. Fish stunning is caused by an anaesthetizing natural substance. When included into crushed ice, it causes the complete stunning of the fish in less than one minute. By shortening the stunning process, fish flesh quality improves, and spoilage can be delayed more than 50%, compared to traditional slaughtering methods. ICE2LAST is claimed to be a cost-effective and easy to handle solution, which leads to enhanced quality, reduced losses and improved animal welfare (European Commission 2016). R&D efforts ongoing.

Technology Readiness Level: 3-5; Technical risk: Moderate

In-water electric stunning: Ace Aquatec (UK) worked together with Scottish Sea Farms to develop a bespoke, in-water electric stunner to integrate with their existing hand-fed automatic bleeding system. Their HSU electric stunner rendered all fish unconscious before leaving the water, meaning the highest possible welfare standards were being met while reducing inherent risks to staff handling large, stressed fish. As a result, harvest rate was doubled (Ace Aquatec 2018).

Technology Readiness Level: 9; Technical risk: Low

Innovations with a potential for transformative performance improvement

Swim-in slaughter: German food processing equipment manufacturer Baader offers a humane and efficient method for percussive stunning and bleeding salmon/trout and other fish species, utilising percussive stunning and bleeding technology. Their Baader SI automated harvest system takes advantage of the fish's natural behaviour where they swim into the stun/bleed machines, keeping stress to a minimum as well as improving flesh quality, up to 20 – 30% improved shelf life and processing efficiency and reduced wastage during further processing (gutting, heading skinning and filleting) (Baader 2015). Optimar has also introduced similar swim-in technologies (Fishermen's News 2019).

Technology Readiness Level: 9; Technical risk: Low

Innovations with a potential for incremental performance improvement

Carbon monoxide: Though uncommon, and controversial in some markets (mainly when using CO for colour preservation of e.g. tuna), combining carbon monoxide (CO) treatment with other slaughter methods (e.g. electrical stunning), shows promise for future and humane fish slaughter. CO enhances flesh colour by preventing discolouration caused by myoglobin and haemoglobin oxidation and may improve quality in salmon and white fish (Concollato *et al.* 2015). In another study, the quality of Atlantic salmon fillets just after slaughtering with CO and after 14 days of refrigerated storage at 2.5 °C did not change (Secci *et al.* 2016).

Technology Readiness Level: 3-5; Technical risk: Low

Please also refer to chapter: Fish Welfare in Wild-Capture Marine Fisheries

22.4.2 Bleeding

Innovations with a potential for incremental performance improvement

Improved bleeding practices: Good exsanguination of fish allows for improvement of quality and the value of the catch. Recent work on wild cod by Nofima showed that fish stunned by percussion or electricity had a flat or gradual increase in the amount of residual blood in the muscle during short-term storage due to recovery of some fish. Short-term storage of fish after electric or percussive stunning pending bleeding was therefore not recommended for fish welfare. Conversely, controlled slaughtering (stunning, bleeding and gutting) of fish immediately when they come onboard, or live storing of the catch onboard prior to slaughter, works well in terms of residual blood. Stunning fish prior to bleeding/gutting is also safer for the crew. It was found that bleeding and exsanguination in seawater was mostly completed within the first three minutes following cutting. Cooling the seawater during exsanguination can be beneficial to prevent blood coagulation, remove blood residuals and prolong the shelf life of the fish (Nofima 2018).

Technology Readiness Level: 6-8; Technical risk: Low

22.4.3 Heading and gutting

Innovations with a potential for incremental performance improvement

Salmon deheader: In 2018, Marel launched the automatic Salmon Deheader MS 2720[1], which measures each fish before each of the different cuts (neck, shoulder, and tail) to achieve the best cutting result, while also maximising yield. Up to 20 fish per minute can be processed.

Technology Readiness Level: 9; Technical risk: Low

AI-controlled gutting system: Baader is already using artificial intelligence (AI) in some of its salmon processing solutions, such as its new generation machine for salmon gutting (Baader 144), which includes a machine learning algorithm to optimise performance via image recognition (IntraFish 2018).

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[1] Marel Salmon Deheader: https://marel.com/products-solutions/salmon-deheader-ms-2720/#tab_overview

Technology Readiness Level: 9; Technical risk: Low

22.5 Cutting

Loosely speaking, cutting involves all the physical and mechanical steps taken to prepare fish prior to landing and may include: filleting, trimming, pin bone removal, skinning and portioning. One of the challenges that processors face is that customers are continually requesting narrower product specifications, requiring flexible and precise technologies. Today, fish cutting, including portioning can be completely automated with little to no manual handling. Automatic water-jet cutters that remove pin-bones from fillets, cut portions and feed into fully automatic graders and packaging equipment are a big development coming out of Iceland (Fishermen's News 2019).

One area where there remain significant challenges is in the automated cutting of wild-caught whitefish species due to their more varied bone structure and size range (Undercurrent News 2019b). Indeed, two interviewees highlighted the challenge of optimising whitefish systems (personal communication). Effective automated filleting and de-heading machines are anticipated in the future.

Innovations with a potential for disruptive performance improvement

Automated water-jet cutting and portioning: Water-jet cutting was highlighted as a major innovation in fish processing by two interviewees. Two Icelandic companies, Marel and Valka, have been at the forefront of developing automated water-jet cutting and portioning equipment. Scans of each fillet using for instance, X-ray and 3D scanners allow software to deliver the best cutting pattern to remove pin-bones and portion the fillet for greater yield and less waste.

Marel launched the FleXicut automatic pinbone removal and portioning system in 2015. This can be combined with FleXisort handling system, which automatically allocates each of the various outputs to different product streams, thereby saving time and increasing efficiency. The system handles up to 50 fillets a minute, leading to a doubling in processing thanks to reduced handling. A system specially developed for salmon is also available (Marel 2015).

The Valka Cutter system[1] provides similar functionality to the Marel technology but in 2019 a new version was released that enables cutting of salmon in the pre-rigor stage. Previously, processors have had to wait for the fish to pass the pre-rigor stage and debone the fillets post-rigor. With this new technology, the pin bone can be removed immediately after filleting, extending product shelf life (Seafood Source 2019).

Technology Readiness Level: 9; Technical risk: Low

Small fish filleting: The Swedish Fish Processing Machine manufacturer SEAC AB is a specialist in small fish such as sprats, Baltic herring and anchovy. Their machines can do up to 400 fish pockets/min and can potentially reduce the number of operators by up to 40 people. In 2019, their FPM-400 fillet machine made a world record for size, filleting and belly-cleaning small sprats of 5-6 gram full weight (MSP Magazine 2019).

Technology Readiness Level: 9; Technical risk: Low

Innovations with a potential for incremental performance improvement

Automated collarbone cutting: Whitefish processors may underutilize up to 8% of fish meat during inefficient cutting of fish collarbones. Backed by EC Horizon 2020 and Norwegian Seafood Research Fund (FHF) funding, Icelandic company Curio is developing 4CWhite, the first computer-controlled fish processing machine designed to cut the collarbone of different de-headed whitefish species. 4CWhite aims to increase the loin yield up to 2% to be profitable in further processing, in comparison with current alternatives. Launch expected in 2020 (European Commission 2018).

Technology Readiness Level: 6-8; Technical risk: Low

Enhanced trimming workflow: Marel’s StreamLine[2] for manual trimming of seabass, seabream and tilapia replaces a manual table, conveyor or tray-based trimming system by weighing batches and transporting them to individual, human operators for trimming. Real-time performance monitoring encourages operators to perform at their best.

Technology Readiness Level: 9; Technical risk: Low

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[1] Valka Cutter: https://valka.is/cutting/

[2] Marel StreamLine: https://marel.com/products-solutions/streamline-for-fish/

Automated skinning: Marel has adapted its salmon skinner for whitefish such as cod, haddock and mahi-mahi, which can handle 25 fillets per lane per minute at maximum capacity (Undercurrent News 2019b). Skinning was also suggested by one interviewee as an area of innovation potential (personal communication).

Technology Readiness Level: 9; Technical risk: Low

22.6 Shellfish processing

One interviewee commented on the dearth of processing innovation with regards to shellfish, with the main focus to date on depuration, half shelling, brine preservation and freezing. They suggested that there is significant scope for value addition in this area (personal communication).

Innovations with a potential for transformative performance improvement

Crustaceans: A recent US patent presents a method and apparatus for cracking crustacean shells, that includes controllers for directing processing of a crustacean body part, and the manufacture of pre-cut seafood items (Fogarty 2019). Another patent granted for the Canadian Centre for Fisheries Innovation concerned an invention that provides a sensor-guided, automated system that is capable of intelligently cutting crustaceans, such as crab and lobster, into a plurality of portions (King and Hearn 2019).

Technology Readiness Level: 3-5; Technical risk: Moderate

High pressure processing: HPP is increasingly used for shellfish as a way to both kill and process, slowly bringing the cost of equipment down. It is being used for crustacean meat removal and for mollusc shucking, with the benefits of an increased yield (nearly 100% meat recovery), increased food safety and extended shelf life. Leading manufacturers in this field include Hiperbaric[1] and Avure[2]. For further information on HPP please refer to chapter 22 ‘Quality and food safety management systems’.

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[1] Hiperbaric: https://www.hiperbaric.com/en/seafood

[2] Avure: https://www.avure-hpp-foods.com/hpp-foods/seafood/

22.7 End of Line

End of line involves finishing steps that may include quality control, chilling/freezing and packaging.

22.7.1 Quality control and traceability

Please refer to chapter 22 ‘Quality and food safety management systems and accreditations’.

22.7.2 Defrosting, refrigeration and freezing

Temperature control remains an area for improvement. While good progress has been made, there are numerous steps in land-based processing, such as packing, in which temperatures are detrimentally high. With the expansion of robotics, manufacturers should strive for high functionality of their equipment at 0°C. Developments in defrosting have allowed for high-quality, “fresh from frozen” offerings that are now commonplace in supermarket fresh fish counters (personal communication) .

Innovations with a potential for disruptive performance improvement

Aerosol/Ultrasonic waves: FRISH is an EC Horizon 2020-funded project headed by German refrigeration company Ungermann that employs aerosol water as air humidification in combination with ultrasonic waves to freeze and/or defrost fish and to reduce energy input, while improving quality and reducing waste. FRISH aims to reduce microbial contamination (up to 35%), and time (up to 80%) and save energy (up to 70%), among other advantages (European Commission 2017).

Technology Readiness Level: 6-8; Technical risk: Moderate

Ultrasound defrosting: The Bremerhaven Institute for Food Technology and Bioprocess Engineering (BILB) has developed a new energy-saving, ultrasound method that can be used to defrost frozen fish in record time, without impairing quality. Fine water vapour is generated by ultrasound, which penetrates frozen fish and increases heat conductivity enormously. Depending on the size and weight of the frozen item, this technique can defrost up to 30% more quickly than using conventional defrosting methods (Bremen Invest 2017).

Technology Readiness Level: 9; Technical risk: Low

Innovations with a potential for transformative performance improvement

Superchilling: A method that makes ice (accounting for up to 20% transport weight) redundant in cooling and storing fish uses new technology to cool fish to -1° to -2°C, on the borderline of being frozen, but cooling it beyond what can be achieved with ice. A Norwegian study on farmed salmon confirmed superchilled salmon holds its water content better throughout the production and storage processes, and has a better culinary yield, e.g. when poached. The qualities and the firmness of the fish remain for longer, maintaining quality more effectively through production. Microbiological analysis has also confirmed that the fish stays fresher for longer than conventionally chilled fish, also confirming that superchilling can extend the shelf life of the finished product by as much as a week (Nordic Innovation 2016). One interviewee stated that superchilling has been popular in the UK salmon industry, especially with exports thanks to the high-quality it affords, and for its sustainability. However, convincing the industry to replace standard ice has been a slow process (personal communication).

Technology Readiness Level: 9; Technical risk: Low

Innovations with a potential for incremental performance improvement

Individual Quick Freeze (IQF): In order to leverage favourable access to increased landings, US scallop processors have invested in the development of new products, such as individually quick frozen (IQF) scallops (Georgianna, Lee, and Walden 2017).

Technology Readiness Level: 9; Technical risk: Low

22.7.3 Packing

The following is a sampling of primary processing-related packing examples. For information on packaging please refer to chapter 20 ‘Packaging technologies’.

Innovations with a potential for transformative performance improvement

Advanced packing: Advanced packing, labelling and palletising systems use data collected throughout processing to pack fish into target-weight, fixed-weight and other types of packs. Marel’s aquaculture packing solution has a capacity of up to 125 fish per minute (Marel 2017).

Technology Readiness Level: 9; Technical risk: Low

Cobots: Columbia/Okura LLC, a US provider of custom engineered robotic palletising systems, entered a strategic alliance with Universal Robots, a maker of collaborative robots (cobots) in the development of miniPAL, a mobile collaborative palletising product with a 10kg payload and 1300mm reach. Able to address a wide range of applications in machine tending, palletising, and packaging, average payback is 8 to 10 months (Packaging World 2019).

Technology Readiness Level: 9; Technical risk: Low

22.7.4 Value chain optimisation

Innovations with a potential for transformative performance improvement

IoT operating system: Baader has teamed with Siemens to create MindSphere, a cloud-based, open Internet of Things (IoT) operating system, which connects products, plants, systems, and machines, while providing advanced analytics (IntraFish 2018b).

Technology Readiness Level: 9; Technical risk: Moderate

Value optimisation software: In an EC Horizon 2020-funded project, Valka is developing a reinforced learning-based consultancy software (FishPro), to optimise the value of the whole load and match the raw material with sales orders. The software provides recommendations for optimal processing of the catch to maximise value. (e.g. market, type of fillets, conditioning), ensuring optimal matching of the products with demand, thereby minimising waste. An estimated 25% improvement in profitability compared to current automatization procedures is anticipated (European Commission 2019).

Technology Readiness Level: 6-8; Technical risk: Low

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23 Quality and food safety management systems and accreditations

Contents

From the SIF Executive Board

The method applied in this review has generated numerous examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently happening. It is recognised that there are existing innovations and research areas that are not included here, and new areas where future innovations may occur. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

23.1 Overview: quality and food safety management systems and accreditations

What is the challenge in the UK?

Seafood processors in the UK generally have mature systems for managing food quality and safety, with widespread implementation of food safety certifications, such as the BRC Global Standard for Food Safety. However, the United Kingdom is now ranked 17th in Global Food Security Index, with seafood-producing competitors such as Norway, Sweden, Finland and the USA scoring significantly higher in terms of food quality and safety.

Imports of semi-processed and processed products, particularly from outside of the EU, represent a risk to UK processors in terms of food fraud and inadvertently supporting illegal, unregulated and unreported fishing activities and the worker welfare abuses linked to such activities.

New technologies for product authenticity verification, combined with blockchain traceability technology offer a potential route to addressing these challenges but there appears to be limited development and trials of such technologies in the UK to date compared to Nordic countries and the USA.

What are the most promising innovation categories?

- Smartphone based sensors for analysis of food safety
- Blockchain-based traceability systems
- Product authenticity: stable isotope and trace element analysis

Where are their important knowledge gaps?

- Limited adoption of novel traceability technologies such as blockchain and next generation RFID tags in the UK.

Product quality and safety are key concerns for seafood processors but there can be many alternative interpretations of what is meant by ‘quality’. Within the International Standards Organisation (ISO) standards, product quality is defined in very broad terms as “the totality of features and characteristics of a product that bear on its ability to satisfy stated or implied needs”. For seafood products, Freitas *et al.* (2020) state that there are four main characteristics that are key to product quality: freshness, safety, traceability and authenticity.

Freshness is concerned with understanding and managing the changes in the sensory properties of seafood products due to autolytic enzymatic, bacteriological, oxidation and hydrolysis processes that occur post-harvest.

Safety is concerned with ensuring that the levels of all food safety hazards, including pathogenic organisms, toxic chemicals and physical hazards, are below predetermined safe limits. In the UK, the Food Standards Agency is making significant changes to the way that food safety regulations are implemented and enforced through the ‘Regulating our Future’[1] programme. This will involve enhanced requirements for the registration of food processing companies, greater leveraging of ICT to demonstrate compliance with food safety regulations, changes to the structure of enforcement bodies, enhanced sharing of information with regulators on food safety issues.

Traceability is concerned with identifying and tracking the raw materials and ingredients of a product as it moves along the supply chain from production and harvest through to finished products. Whilst the principles of traceability are well established and have been implemented in most value chains, the development of technologies such as blockchain are opening new possibilities in terms of the quantity, reliability and transparency of data communicated across the value chain.

Authenticity is concerned with ensuring that consumers have confidence that their food is safe and what it says it is. Authenticity is closely linked with ‘food fraud’, which includes practices such as (Food Standards Agency 2019):

- Adulteration - including a foreign substance which is not on the product’s label to lower costs or fake a higher quality.
- Substitution - replacing a food or ingredient with another substance that is similar but inferior.
- Misrepresentation - marketing or labelling a product to wrongly portray its quality, safety, origin or freshness.

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[1] Regulating our Future programme: https://www.food.gov.uk/about-us/regulating-our-future

- Waste diversion - illegally diverting food, drink or feed meant for disposal, back into the supply chain.

Around 68.3% of professionals working in the food and drink production industry feel that food fraud it is a growing problem for the UK[1].

To address the issues of freshness, safety, traceability and authenticity in a systematic and comprehensive manner, food processing companies have adopted food quality and safety management systems. The developments in the application of food quality and safety management systems are discussed in the following section. The subsequent sections present the challenges related to food safety, freshness traceability and authenticity.

Finally, the scope of this chapter is limited to onshore supply chains, but it should not be forgotten that activities in the production and harvest stages can have a major impact on the final quality of the product. For example, the type of fishing gear used in wild-caught fish can have a significant impact on product quality. Atlantic cod caught using longline gear resulted in better quality fish in terms of colour, texture, and overall sensory quality than fish caught by trawling (Rotabakk *et al.* 2011). Therefore, quality improvement initiatives should consider all phases of the product lifecycle, from point of catch through to point of retail.

An overview of the potential performance improvement rating of recent (2015-2019) innovations in quality and food safety management systems and accreditations are outlined in Figure 22-1.

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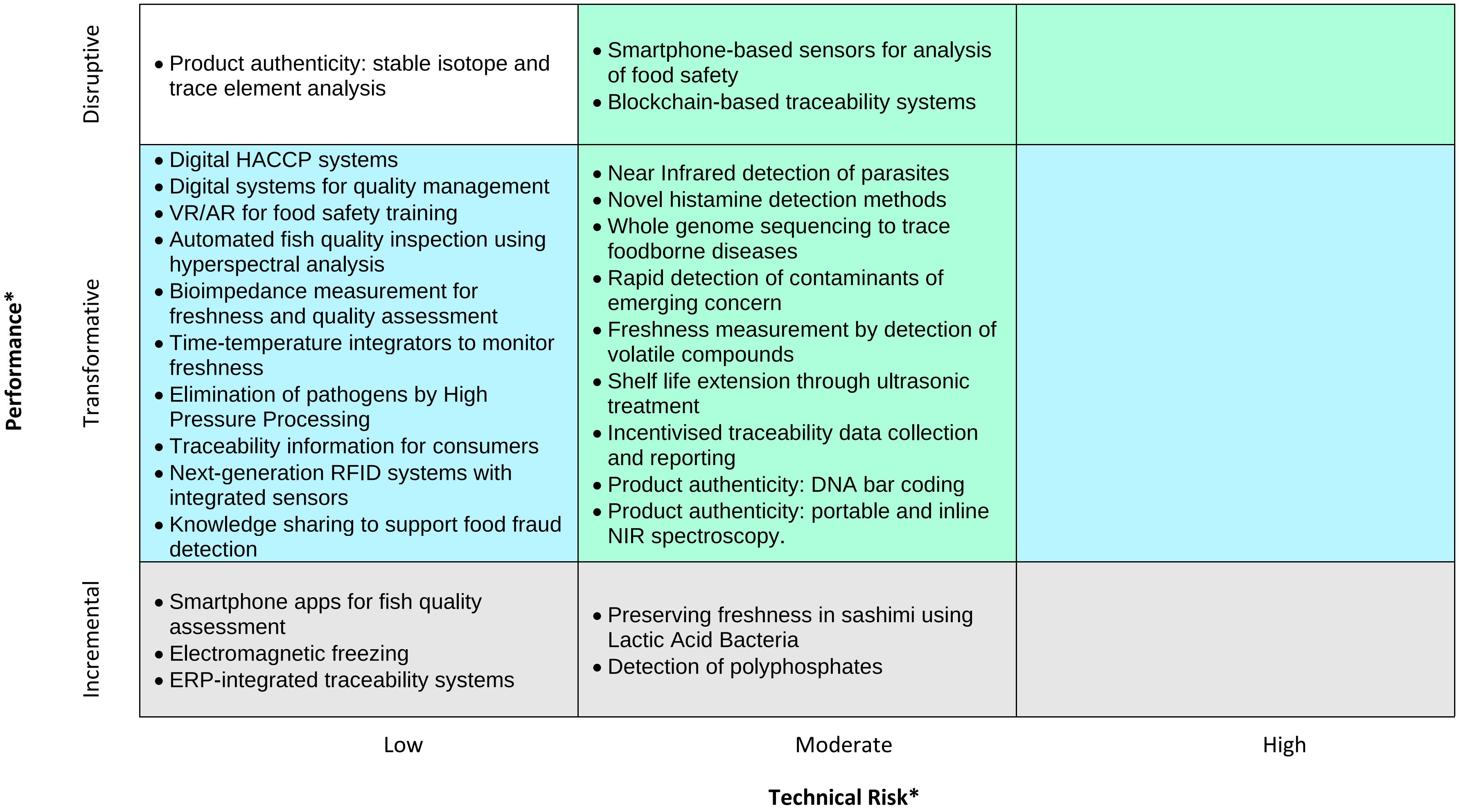
[1] https://www.foodmanufacture.co.uk/Article/2018/07/05/Food-safety-survey-results



	Low	Moderate	High
Disruptive	• Product authenticity: stable isotope and trace element analysis	• Smartphone-based sensors for analysis of food safety • Blockchain-based traceability systems	
Transformative	• Digital HACCP systems • Digital systems for quality management • VR/AR for food safety training • Automated fish quality inspection using hyperspectral analysis • Bioimpedance measurement for freshness and quality assessment • Time-temperature integrators to monitor freshness • Elimination of pathogens by High Pressure Processing • Traceability information for consumers • Next-generation RFID systems with integrated sensors • Knowledge sharing to support food fraud detection	• Near Infrared detection of parasites • Novel histamine detection methods • Whole genome sequencing to trace foodborne diseases • Rapid detection of contaminants of emerging concern • Freshness measurement by detection of volatile compounds • Shelf life extension through ultrasonic treatment • Incentivised traceability data collection and reporting • Product authenticity: DNA bar coding • Product authenticity: portable and inline NIR spectroscopy.	
Incremental	• Smartphone apps for fish quality assessment • Electromagnetic freezing • ERP-integrated traceability systems	• Preserving freshness in sashimi using Lactic Acid Bacteria • Detection of polyphosphates	

Figure 23-1: Performance and technical risk rating of innovations in quality and food safety management systems and accreditations.

**See section 4.4 for definitions of the performance and technical risk rating scales.*

23.2 Food safety and quality management systems

There are a variety of food safety and quality management certifications that seafood processors can use to demonstrate high levels of food safety and quality. The ISO 22000 Food safety management standard developed out of the more general ISO 9001 Quality management standard. In the UK, BRC Global Standard for Food Safety is a popular and well established, with 93% of sites renewing their BRC Food Safety certification awarded the top 'A' grade in 2015 (BRC 2015). BRC Global Standard for Food Safety is approved by the Global Food Safety Initiative (GFSI), which is a global collaboration of public and private sector organisations that has supported harmonisation of private certification programmes in order to enable a global "once certified, recognised everywhere" approach[1].

There are a several other schemes that align with either the ISO or GFSI standards and each has slight differences in emphasis and scope. Common to all food safety schemes is the inclusion of Hazard Analysis and Critical Control Point (HACCP) principles to manage food safety risks.

Whilst the requirements of each of the certification schemes are updated on a regular basis to reflect developments in industry best practices, the overall approach advocated is mature and stable. There is therefore little innovation in the certification schemes themselves, but there are some innovations in how they are being implemented. This section presents some of the innovations that are trying to help companies to implement food safety and quality management systems in a more robust and efficient manner.

Innovation with a potential for transformative performance improvement

Digital HACCP systems: A number of different suppliers are now offering fully digital HACCP systems that make implementing and managing a HACCP system simpler. Typical features include the ability to record deliveries, capture and record food cooking, cooling and storage temperatures, record cleaning and maintenance operations, alerts when process parameters

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[1] Global Food Safety Initiative: https://mygfsi.com/what-we-do/harmonisation/

are out of specification, and provide summary reports. Examples include the iQ00 system from Retail Solutions[1] and 3iVerify from Primority [2].

Technology Readiness Level: 9; Technical risk: Low

Digital systems for quality management: Quality management systems are also becoming fully digital. Emydex provide a digital quality management module[3] as part of an integrated data collection and management system. The software integrates with hardware, such as barcode scanners, temperature sensors, enabling real-time capture and analysis of data. Quality surveys can be designed for each step of the process, reminders generated when surveys need to be completed and the results captured by operators using ruggedised tablet PCs or workstations.

The system has been implemented by a variety of fish and seafood processors in the UK and Republic of Ireland.

Technology Readiness Level: 9; Technical risk: Low

VR/AR for food safety training: Food processing and food service companies are now using Virtual Reality (VR) and Augmented Reality (AR) to train staff on food safety principles and procedures. Using these technologies offers many of the efficiency and scalability offered by elearning with the added benefit of the immersive and realistic experience offered by VR/AR technologies.

In the UK, the fish processor Icelandic Seachill, working with the TEC Partnership and Seafish, have piloted the use of the Microsoft HoloLens AR technology for training of production operatives, as well as technical and quality team staff (Atherton 2017). The system recreated the production line as a ‘mixed reality’ environment including the typical sounds experienced on the production line. Whilst not specifically focused on food safety, this initiative demonstrates the important role that AR and VR technologies are likely to have in training activities in the seafood sector.

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[1] iQ00 system: https://www.retailsolutions.ie/product/rs-iqoo/

[2] 3iVerify system: https://www.primority.com/modules

[3] Emydex quality management software module: https://www.emydex.com/software-modules/quality-compliance-software/

Technology Readiness Level: 9; Technical risk: Low

23.3 Assessment of food safety

Seafood safety involves ensuring that the product reaches the consumer in a state whereby all food safety hazards, including pathogenic organisms, toxic chemicals and physical hazards, are below predetermined safe limits. In this section we present innovations in the methods used to detect various types of food safety hazard.

Innovation with a potential for disruptive performance improvement

Smartphone-based sensors for analysis of food safety: FoodSmartphone[1] is an EU-funded, collaborative research project investigating the potential for smartphone apps and connected sensors to perform preliminary analysis of food samples to improve food safety and reduce food fraud. The concept is based on biorecognition-based smartphone analysers for on-site testing of allergens, antibiotics, biotoxins, food spoilage and marine toxins. The technology is designed for use by non-expert users.

The objective is to enable an increased number of samples to be analysed at various steps along the value chain by using low cost, portable equipment to identify possible food safety or food fraud concerns. Definitive analysis would still need to be completed at approved laboratories but, by using smartphone-based sensors as an initial screening mechanism, less expensive laboratory time would be required for routine samples and the higher sampling rate should lead to improved detection of food safety hazards and food fraud.

Technology Readiness Level: 6-8; Technical risk: Moderate

Innovation with a potential for transformative performance improvement

Near Infrared detection of parasites: The EU-funded Parasite project[2] has developed a near infrared (NIR) scanner for the detection of anisakid nematodes (Kroeger *et al.* 2018). The

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[1] FoodSmartphone project: http://www.foodsmartphone.eu/

[2] Parasite project: http://parasite-project.eu/project

device is used to perform the Viability Test, which is a test of nematode presence and viability for fish products that is normally performed manually by visual inspection. These manual methods can sometimes fail to identify viable nematodes as they rely on identifying movement by the nematodes. The visual inspection can fail to detect slow movements and nematodes can remain in a temporary motionless state for several hours.

The NIR scanner is used to identify nematodes in a sample and determine their viability using geometric analysis of their shape and shape energy by modelling the nematode as a membrane. Tests using anisakid nematodes isolated from wild-caught herring found that the Viability Test Device results correlated closely with the results obtained by expert visual inspections and was able to provide graduated results with defined permissible limits.

Technology Readiness Level: 6-8; Technical risk: Moderate

Novel histamine detection methods: Histamine poisoning, or scombroid, is one of the most common forms of seafood poisoning (Ansdell 2019). Fish from the Scombridae family have naturally high levels of histidine in the flesh. Histidine is converted to histamine by bacterial overgrowth in fish improperly stored after capture. Histamine is resistant to cooking, smoking, canning, or freezing.

A wide variety of histamine detection methods are available but generally require significant sample processing and expensive laboratory equipment to perform and therefore difficult to deploy in the field.

In a review of novel histamine detection methods, Yadav et al (2019) have identified a number of nanomaterial-based technologies that employ either electrochemical sensors or optical sensors. Whilst many of the optical and electrochemical sensors offered greater sensitivity and selectivity of detection than conventional methods, the electrochemical sensors offered the greatest potential, with limits of detection down to picomolar levels and greater potential for field deployability.

It should be noted that improved histamine detection methods are not by themselves sufficient to reduce incidents of histamine poisoning. These technologies must be implemented as part of an effective HACCP system with appropriate, risk-based sampling plans. Guidance for food business operators and policy-makers on controlling histamine risks in the fish value chain have been developed by James et al (2013).

Technology Readiness Level: 3-5; Technical risk: Moderate

Whole genome sequencing to trace foodborne diseases: PulseNet is the US national laboratory network that detects foodborne disease outbreaks. It has started using whole genome sequencing to precisely identify the bacteria involved in cases of foodborne disease. This allows the network to identify links between outbreaks. These data, combined with additional from patients – such as what and where they ate before becoming sick, enable the investigators to identify the source of the outbreak.

PulseNet estimates that the whole genome sequencing has enabled them to solve three times more outbreaks than the previous method and that the PulseNet network saves $500 million in reduced illness and medical costs annually (Centers for Disease Control and Prevention 2019).

Technology Readiness Level: 9; Technical risk: Moderate

Rapid detection of contaminants of emerging concern: ECsafeSEAFOOD project[1] attempted to assess food safety impacts of emerging environmental contaminants, such as toxic algal blooms and marine microplastics. A number of rapid detection methods were developed including a magnetic bead-based direct immunoassay for the detection of azaspiracids (Leonardo *et al.* 2017), a multi-residue method for the determination of antibiotics (Serra-Compte *et al.* 2017), and liquid chromatography-tandem mass spectrometry for the simultaneous determination of bisphenol A (BPA) and tetrabromobisphenol A (TBBPA) (Cunha, Oliveira, and Fernandes 2017).

The project also launched a database[2] to collate scientific studies on contaminants of emerging concern in seafood species.

Technology Readiness Level: 6-8; Technical risk: Moderate

23.4 Assessment of fish freshness and quality

Traditionally, fish quality assessment has been done using well-trained staff to assess the organoleptic properties of the fish or seafood. This type of sensorial assessment can be

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[1] ECsafeSEAFOOD project: http://www.ecsafeseafood.eu/

[2] ECsafeSEAFOOD database: http://www.ecsafeseafooddbase.eu/

subjective, leading to potential inconsistencies in quality assessment results between organisations or individual testers. Today, a wide range of analytical methods exist to determine fish freshness based on detection of chemical indicators of fish spoilage, such as Trimethylamine (TMA), total volatile basic nitrogen (TVB-B), or on physical properties, such as colour (Prabhakar *et al.* 2020).

For fish processors, the quality of fish purchased can have a major impact on the final profit margins. Estimates from Norway suggested that, when purchasing cod loins and blocks for 17 Norwegian Krona (NOK) per kg, fish that proved to be of high-quality generated a profit margin of 16.49 NOK per kg whilst the fish that proved to be of poor quality resulted in a loss of 12 NOK per kg (Sogn-Grundvåg and Henriksen 2014).

Below we present novel technologies that enable more systematic and objective measurement of freshness and quality of seafood products. These include technologies for use in the factory as well as packaging embedded sensors that can be used to monitor the freshness of product after it has left the factory (further details of the latter can be found in chapter 20 ‘Packaging technologies’).

Innovation with a potential for transformative performance improvement

Automated fish quality inspection using hyperspectral analysis: Fish sorting and grading can be a labour-intensive process. Prediktera (2019) have developed a software that uses images from very near infrared (VNIR) hyperspectral cameras to identify the species of fish whilst also performing a basic quality inspection by identifying blood associated with damage.

The system has been applied for species including cod, haddock and saithe by Leroy Seafood in Norway. A similar technology for automated quality inspection is being developed by Valka in Iceland (Nero 2019).

Technology Readiness Level: 9; Technical risk: Low

Bioimpedance measurement for freshness and quality assessment: It has been shown that analysis of the bioimpedance properties of fish can help to detect the body composition (e.g. fat, protein and water) as well as changes at the cellular level during different spoilage stages (Sun *et al.* 2018). This phenomenon has been used to develop fish freshness metres and fat metres. In the UK, Distell offer the ‘Torrymetre’ freshness metre[1]. The product sensors

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[1] Distell freshness meter: https://www.distell.com/fish-freshness-meter/general-description/

are pressed firmly against the skin of the fish. A freshness score from 1 to 18 (where 18 is the freshest) is then displayed on the LCD display. The metre can be set to measure the freshness from up to 16 specimens from a batch. It will then automatically display the average freshness value for the batch. Distell also offer a separate fat meter[1].

In the USA, Seafood Analytics have developed the Certified Quality Reader[2], which offers multiple readings using one product including time since harvest, remaining shelf life, sensory equivalence scores (FDA and Torry), and 'Certified Quality' number – a proprietary freshness assessment rating developed by Seafood Analytics. Suppliers that complete training on the Certified Quality system and utilise the Certified Quality Reader in their operations are eligible to apply the Certified Quality Seal on their products.

Both systems enable digital data capture and upload to quality/food safety management systems to help demonstrate fish quality and freshness at the point of dispatch/reception.

Technology Readiness Level: 9; Technical risk: Low

Time-temperature integrators to monitor freshness: Time-temperature integrators (TTIs) are low cost labels that provide a visual indicator of the time-temperature history of a package, which can help in estimating the remaining shelf life of a product. The label consists of reactive layer, which changes colour when exposed to temperatures that exceed the specified storage temperature range or after a certain period of time. Various reaction mechanisms have been utilised, including polymerisation, thermochromic/photochromic reactions, diffusion or enzyme reactions. Whatever the reaction mechanism, the key challenge is to ensure that the TTI label accurately reflect the condition of the product.

TTI labels have been shown to be a reliable indicator of product shelf life for frozen seafood (blueshark slices and arrow squid) (Tsironi *et al.* 2016) and other chilled, highly perishable product such as fresh chicken (Brizio and Prentice 2014). Commercial providers of TTI labels include Smart Dot[3] from Evigence Sensors and Bizerba USA, whose labels have been implemented for own label products by the Fresh & Easy retail chain in North America (Lingle

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[1] Distell fat meter: https://www.distell.com/fish-fatmeter/general-description/

[2] Certified Quality Reader: http://certifiedqualityseafood.com/what-is-cq/#meet-the-cqr

[3] Smart Dot TTI labels: https://evigence.com/unit-level-cold-chain-management/

2015). In the UK, TTI labels producers include Insignia Technologies[1] and Timestrip, who produce the Timestrip Seafood[2], which is FDA approved for the prevention of Clostridium botulinum management.

Technology Readiness Level: 9; Technical risk: Low

Freshness measurement by detection of volatile compounds: Spoilage organisms produce volatile compounds, including trimethylamine (TMA), dimethylamine or DMA and ammonia, which are known collectively as total volatile basic nitrogen (TVB-N). A wide variety of technologies are being developed for the detection of spoilage-related volatile compounds, including electrochemical sensors, electronic ‘noses’ and ‘tongues’, enzyme-based biosensors, and sensor arrays – which use a combination of methods for improved precision and lower detection limits (Prabhakar *et al.* 2020).

An example of the electrochemical approach is the study by Bhadra et al (2015), who have developed and tested a low cost, wireless sensor for the detection of volatile compounds with a detection limit of 1.5 ppm. The sensor, consisting of a hydrogel-pH-electrode pair, a voltage sensing circuit and a spiral inductor. The sensors resonant frequency varies linearly with the TVB-N concentration. The resonant frequency of the senor can be measured through packaging materials using an interrogator coil.

Tests conducted using Tilapia samples at 4 and 24 degrees Celsius found that the sensor was able to identify when the total viable count of spoilage organisms exceeded a level of 107 colony forming units per gram, indicative of end-of-shelf life.

Subsequent work on this type of food spoilage detection sensors has led to battery-free sensors that can be read up to 50cm from the package (X.-T. Cao and Chung 2019).

Technology Readiness Level: 3-5; Technical risk: Moderate

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[1] Insignia Technologies: https://www.insigniatechnologies.com/products_foodretailsolutions.php

[2] Timestrip Seafood: https://timestrip.com/products/seafood-3-degree/

Innovation with a potential for incremental performance improvement

Smartphone apps for fish quality assessment: The Quality Index Method is a well-established method for the assessment of fish freshness and quality. Various quality attributes, such as skin smell, pupil colour and gill mucus, are assessed and scored on a scale of zero to three. The scores are then summed to give a maximum score of 24. The score obtained can then be used to estimate the remaining days of shelf life using species-specific calibration curves. The Quality Index Method has been implemented as a smartphone app entitled ‘How fresh is your fish?’[1] and is available in 11 different languages. The app guides the user through the Quality Index Method assessment, providing pictures and notes to support consistent scoring.

Technology Readiness Level: 9; Technical risk: Low

23.5 Maintaining freshness and extending shelf life

The perishability of seafood products creates a challenge for supply chains to deliver product in optimal condition to the consumer within a limited time frame. There is therefore considerable interest in technologies that can maintain the sensory properties associated with freshness as long as possible. Below we present some of the recent developments that are intended to maintain freshness and extend shelf life in seafood products.

N.B. Chilled storage are freezing are two of the key methods used to maintain freshness and extend shelf life of seafood products however the challenge of cold chain management was not prioritised for investigation and therefore only alternatives to standard cold chain technology are discussed in this section.

Innovation with a potential for transformative performance improvement

Elimination of pathogens by High Pressure Processing: High Pressure Processing (HPP) is a food processing technology that is primarily used to improve food safety and extend shelf life without use of heat or preservatives. The process, sometimes referred to as ‘cold pasteurisation’, involves placing the produce in a pressure vessel that is filled with

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[1] How fresh is your fish?:https://play.google.com/store/apps/details?id=com.relectus.com.freshfish

water and then subjected to very high pressures (up to 600 MPa), killing any bacteria, viruses or pathogens present.

A variety of studies of the microbial load reduction in fish muscle have shown that HPP can offer significant microbial load reduction (0.5 to 5 log reduction in total viable count), enabling an extension in shelf life of 6-10 days for hake, 2-19 days in salmon, and 0-7 days in sea bass (Truong *et al.* 2015).

However, the use of HPP can have detrimental impacts on other quality parameters in fish such as increase of pH, hardness, whitening, decrease in water holding capacity, as well as initiation of lipids and proteins oxidation (Oliveira *et al.* 2017). Hence, careful optimisation of the processing parameters is required in order to strike a balance between microbial load reduction (for shell life extension) and impact on sensory properties.

HPP can be used with most types of food and beverage product that has a water content of 85%. Due to the very high pressures applied, the product must be able to withstand up to 20% product shrinkage and the packaging must be waterproof and flexible.

Technology Readiness Level: 9; Technical risk: Low

Shelf life extension through ultrasonic treatment: Ultrafish is a Horizon 2020, EU-funded research project that is developing ultrasonic technology for use in fish processing. The technology replaces the conventional washing and thawing with a combination of ultrasonic baths and UV light to reduce microbiological contamination of cod and halibut fillets. The claimed benefits of the technology include:

- 5 days longer shelf life
- 50% reduction in water usage in processing
- 30% reduction in energy usage in thawing
- 50% reduction in thawing time
- Eliminates use of additives

The technology is being implemented by the industrial partner, Scanfisk.

Technology Readiness Level: 6-8; Technical risk: Moderate

Innovation with a potential for incremental performance improvement

Preserving freshness in sashimi using Lactic Acid Bacteria: Cao et al (2015) have reported on using a Lactic Acid Bacteria dip (*Lactobacillus plantarum* 1.19) to maintain freshness in tilapia fillets prepared for sashimi. The period that tilapia fillets could be used as sashimi material extended from 24 hours to 48 hours after the treatment.

Technology Readiness Level: 3-5; Technical risk: Moderate

Electromagnetic freezing: It is claimed by manufacturers of electromagnetic freezing systems that the use of oscillating magnetic fields during quick freezing of seafood helps to enhance water supercooling, inhibit ice crystallization, accelerate heat transfer and that these factor lead to reduced loss of quality that is often associated with the freezing process. Technologies such as the Cell Alive System (CAS) from ABI, Japan, have been adopted in the tuna industry due to the perceived benefit in terms of reduced loss of colour.

Studies in Europe have failed to demonstrate significant benefits of the technology. Otero *et al.* (2017) found no significant differences in drip loss, water-holding capacity, toughness, and whiteness of crab sticks frozen using a commercial electromagnetic freezer and a standard forced-air quick freezer over freezing periods from 24 hours to 12 months. Similarly, in a study of Atlantic cod, Erikson et al (2016) found no significant differences between fillets frozen using the electromagnetic freezer system and those frozen using the standard quick frozen method.

Technology Readiness Level: 9; Technical risk: Low

23.6 Traceability

Traceability in seafood value chains is the foundation to several important challenges. Traceability is required to ensure that products have not been sourced from illegal, unreported and unregulated fishing (IUU) activities and help to address worker welfare abuses in the fishing industry. In January 2018, the USA implemented the Seafood Import Monitoring Program (NOAA 2019), which requires importers to report enhanced traceability data for 13 fish species and fish products that are considered vulnerable to illegal, unreported, and unregulated fishing and/or seafood fraud - including Atlantic cod.

Traceability is a prerequisite for obtaining product sustainability certifications as a chain of custody between the consumer and the certified fishery must be maintained. It is a legal requirement under food safety regulations and a requirement for food safety management certifications as, in the case of a product recall, producers must be able to identify the source of problematic ingredients or processes and to whom affected products were sold. Finally, good internal traceability helps seafood processors with challenges of efficient production, stock management and avoidance of waste.

For stakeholders within seafood value chains, the aim is to have ‘full chain traceability’ - the ability to track forward and trace back at any point along the full supply chain, from the original point of production or harvest through to the point of purchase by the consumer.

The complexity of modern, global value chains and the proliferation of traceability systems means that another important requirement of a traceability systems is interoperability - the ability of one traceability system to work with other traceability systems to seamlessly exchange and interpret key data elements across all critical tracking events in the supply.

Standards for seafood traceability developed and published by organisations such as GS1, the Marine Stewardship Council (MSC) and the International Standards Organisation (ISO) have helped to provide the necessary foundations for full chain traceability and interoperability of traceability systems. Nevertheless, the complexity and diversity of many seafood value chains means that the implementation of traceability systems remains a significant challenge for the industry (Bhatt *et al.* 2016).

Innovation with a potential for disruptive performance improvement

Blockchain-based traceability systems: Blockchain technology has been popularised through the rise of cryptocurrencies such as Bitcoin. Blockchain essentially provides an immutable and transparent ledger of transactions. The advantage of using blockchain technology over conventional bookkeeping methods is the ability to encrypt end-to-end traceability data and allow consumers to access this information easily (Galvez, Mejuto, and Simal-Gandara 2018).

A number of blockchain-based food traceability systems are being developed. These include IBM Food Trust[1] and SAP Logistics Business Network[2] as well as some specific to the seafood

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[1] IBM Food Trust: https://www.ibm.com/blockchain/solutions/food-trust

[2] SAP Logistics Business Network: https://www.sap.com/assetdetail/2019/10/4036ab60-6e7d-0010-87a3-c30de2ffd8ff.html?infl=0ff76940-730f-499f-8ee1-791491517ace

sector, such as Fishcoin[1] and Seafood IQ[2]. These systems make numerous claims about the potential benefits of applying blockchain technology within traceability. They suggest that blockchain will enable improvements in security, transparency, speed of recall and waste reduction. However, evidence of these benefits is limited to date as there are very few real-world examples of blockchain-based full chain traceability in operation, and those that do exist are often pilot studies based wholly in developed economies in short or vertically-integrated supply chains, such as the North American Atlantic scallop fishery (Lobley 2019).

A few large multinational companies, such as Bumble Bee Foods (Ledger Insights 2019a) have begun to introduce blockchain technology into their traceability system for tuna and in June 2019 the National Fisheries Institute (NFI) launched a pilot of a multi-company, multi-species seafood traceability programme making use of the IBM Food Trust platform and funded by the Seafood Industry Research Fund (Chase 2019).

In the UK, the Food Standards Agency (FSA) has collaborated with processors in the beef industry to trial blockchain traceability to investigate how the technology can be used to share ‘permissioned’ data with the FSA for regulation monitoring and enforcement purposes (Food Standards Agency 2018). However, no reports have been identified to date of blockchain-based traceability being applied in the UK seafood industry.

Some of the key challenges for blockchain-based traceability systems include the relatively high cost of establishing and maintaining a blockchain-based traceability system due to the additional ICT infrastructure required for the blockchain system. This has tended to limit interest in blockchain to date to high-value products, although costs are likely to decrease as the technology matures.

A more fundamental challenge is that, whilst data submitted to the blockchain cannot be modified, it does not guarantee that the initial data submitted was accurate (Galvez, Mejuto, and Simal-Gandara 2018). Also, blockchain-based traceability systems generally rely on labels and RFID tags that are attached to the packaging/containers to provide data about the status of the product as it flows through the value chain. This does not guarantee that the product in the container has not been adulterated or substituted in some way since the original label or tag was applied to the container. Mass-balance checks can help identify

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[1] Fishcoin: https://fishcoin.co/

[2] Seafood IQ: http://seafoodiq.com/

discrepancies, but addressing this issues is likely to require authenticity and adulteration checks at the start of the blockchain, to ensure that the source raw material is what is says it is, and further checks at various points along the value chain, to ensure that the product has not been tampered with along the way. Product authenticity testing is discussed further in the following section.

Other challenges include the need for inter-operable systems, to allow organisations using different blockchain platforms to exchange data efficiently, differences in regulatory requirements across jurisdictions and the practical challenges of enabling digital capture of traceability information across complex supply chains, particularly in developing economies with limited ICT infrastructure (Galvez, Mejuto, and Simal-Gandara 2018).

Technology Readiness Level: 9; Technical risk: Moderate

Innovation with a potential for transformative performance improvement

Incentivised traceability data collection and reporting: One of the challenges for any traceability system is how to motivate stakeholders across the value chain to contribute detailed and accurate data that can be used for traceability purposes. Providing any information beyond the statutory minimum can be time-consuming and so, if such information is not requested by a stakeholder’s immediate customer, there is little or no incentive to complete this additional work. Fishcoin is an attempt to address this problem. Within the Fishcoin system, stakeholders across the value chain are requested to use the mFish app[1] to record traceability data and transactions. In return for providing the requested traceability data, the stakeholders receive Fishcoin tokens that can be used to purchase mobile data top-ups for their mobile phone. This provides the incentive for stakeholders to provide more data than the statutory minimum. Being implemented by Thai Union in Thailand as part of their Sea Change program.

The World-Wide Fund for Nature (WWF) and UnionBank are collaborating with blockchain technology firms to develop the Tracey mobile app, which will incentivise supply chain stakeholders to submit data to a blockchain traceability system (Ledger Insights 2019b).Stakeholders will receive token payments through the app and records of their income

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[1] mFish app: https://play.google.com/store/apps/details?id=com.eachmile.fishcoin&hl=en_US

will be shared with the bank so that they can begin to build a credit rating so that they can gain access to microfinance.

Technology Readiness Level: 6-8; Technical risk: Moderate

Traceability information for consumers: One of the recent trends in seafood traceability is to provide the consumer with the means to discover more detail about the fish they are purchasing. A typical example of these systems is This Fish[1], in which every product sold had a tag with a reference code. The consumer can then input the code on the This Fish website to access details, such as when and where the fish was caught, the name of the fisher and further details about the species. This type of information is appealing for consumers that want to be confident that they are supporting sustainable fishing practices and fishing communities.

Technology providers are also exploiting blockchain technology to support enhanced traceability information for consumers. The IBM Food Trust system is built on blockchain technology and allows consumers to scan a QR code printed on the product label to access a ‘CV’ for the fish. The CV contains comprehensive information about the fish; its origin, when it was hatched, which fresh water facility it came from, how big it was when it was transferred to seawater, at which sea water facility it has been farmed, as well as health and welfare information such as which vaccinations it has received, what it has been fed, and when it was harvested. The system has been implemented by Cermaq - a Norwegian salmon and trout aquaculture company (Fish Focus 2019).

A similar, blockchain based system has been implemented by Bumble Bee Foods for their tuna products, making use of the SAP blockchain platform (Ledger Insights 2019a).

UK-based company, Provenance have completed a 6-month trial of a blockchain-based traceability system for the south-east Asian pole and line-caught tuna fishing industry (Provenance 2016). Near Field Communication (NFC) tags were applied to retail packaging and on restaurant menus that allowed the consumer to access full chain traceability information. Provenance are also investigating the potential for open product traceability standards, open blockchain platforms for traceability and low-cost alternatives to NFC tags.

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[1] This Fish: http://this.fish/trace/

The additional cost of collecting and publishing traceability remains a barrier to the widespread adoption of this technology, particularly for smaller producers, but commercial implementations of such systems exist today with costs likely to reduce over time.

Technology Readiness Level: 9; Technical risk: Low

Next-generation RFID systems with integrated sensors: In recent years a number of companies, such as Craemer[1], have launched fish boxes that have integrated radio-frequency identification (RFID) technology. The advantages of using RFID boxes is that the time spent scanning in boxes is reduced significantly. Also, labels can sometimes fall off or become difficult to read when covered in frost, which is not a problem when using RFID.

PST Sensors and Zebra Technologies have developed a flexible, thin film RFID with integrated temperature sensor that has been approved for use in the food sector. It includes a printable battery and memory with up to 24 months battery life. Using special RFID readers, a pallet full of individually labelled fish boxes can be scanned automatically simply by driving the pallet through the sensor gate. The system is being implemented as part of the Seafood Trace[2] traceability platform from Seafood IQ

Technology Readiness Level: 9; Technical risk: Low

Innovation with a potential for incremental performance improvement

ERP-integrated traceability systems: Diomac[3] have developed an Enterprise Resource Planning (ERP) system that integrates a traceability system. The ERP system offers standard production management features such as purchasing, scheduling, inventory management, and accounting as well as data analytics. The traceability system is built on GS1 standards that are compliant with EU regulations and are recognised around the world. The system offers instant traceability to facilitate product recalls and compliance with food safety requirements and the system can be used to generate product labels, compliant with EU requirements. The

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[1] Craemer RFID fish boxes: https://www.craemer.com/uk/storage-and-transport-containers/fish-boxes/

[2] Seafood Trace: http://seafoodiq.com/solutions/

[3] Diomac ERP: http://diomac.com/index.html

system has been implemented by a number of fish and seafood processors in Ireland and France.

Technology Readiness Level: 9; Technical risk: Low

23.7 Authenticity and food fraud

Food fraud which is defined as ‘food which is deliberately placed on the market for financial gain, with the intention of deceiving the consumer’ (Fox *et al.* 2018). Globally, the costs of food fraud to the food industry are estimated at $30-40 billion per annum (PricewaterhouseCoopers n.d.).

The EU has established the Administrative Assistance and Co-operation (AAC) system, which allows Member States to request co-operation in tackling instances of food fraud. ‘Fish and fish products’ was the most commonly cited category, with 45 requests in 2018 (European Commission 2018). Mislabelling, replacement/removal and unapproved treatment/process where the top three adulteration types associated with the fish and fish products category. A global meta-analysis of mislabelling in the seafood industry estimated that around 30% of all seafood is mislabelled to some extent, with higher rates of mislabelling in restaurants and takeaways (Pardo, Jiménez, and Pérez-Villarreal 2016).

Imported products present a higher risk of food fraud as they are often imported after primary processing has been conducted in developing economies, meaning that morphological features that can help identification are no longer present. This has led to the development of PAS 1550 (BSI 2017), which provides seafood processors with a framework for performing due diligence in the sourcing of imported seafood products to ensure that they are not supporting IUU fishing or abuses of workers rights in the supply chain.

Whilst traceability system improvements offer the potential to provide better insight into the true nature and source of seafood practices, traceability systems alone cannot guarantee product authenticity or prevent food fraud. This can only be achieved by a combination of product authenticity testing and robust, full chain traceability systems. Whilst there are a variety of laboratory-based methods for testing product authenticity, they are generally very expensive and time-consuming to perform and require highly skilled workers. Below we present a summary of the key developments in product authenticity testing with a focus on technologies that have the potential to be deployed by industry across the value chain.

Innovation with a potential for disruptive performance improvement

Product authenticity: stable isotope and trace element analysis: Lower trophic species have a distinct isotopic signature depending on where in the world their habitat is. Higher trophic species that consume assimilate the isotopic signature of the lower species they consume through a process known as fractionation (Gopi *et al.* 2019). Oritain have commercialised a system for provenance determination based on analysis of the stable isotope and trace elements present in the product. These data form the ‘fingerprint’ of the product. In cases of suspected food fraud, the fingerprint from suspicious products can be compared to the fingerprint of the authentic product. Oritain claim that the origin of the product can be determined down to the farm-level for aquaculture products. The system has been adopted by the Loch Duart salmon farm in Scotland to help identify fish wholesalers involved in this type of food fraud (Black 2019).

Similar technology for tracing the origins of wild-caught seafood is currently being developed in the UK by Sea Stable Isotopes, a spinout from National Oceanography Centre Southampton. Less precision is possible than for aquacultured products, but a study using this study found that the origin of 75% of scallops sampled could be traced to an area roughly 30% of the North Sea (Trueman, MacKenzie, and St John Glew 2017).

Technology Readiness Level: 9; Technical risk: Low

Innovation with a potential for transformative performance improvement

Product authenticity with DNA bar coding: DNA barcoding works by using a short genetic sequence of mitochondrial DNA to identify the fish as belonging to a particular species. DNA testing is considered the definitive method for species detection and has been formally adopted by the Brazillian government as part of its food authenticity testing programme (Carvalho *et al.* 2017).

The significant infrastructure cost, expertise and time required to perform DNA analysis has meant that such where generally only completed by government laboratories, and only on a very small proportion of the traded goods. There is therefore interest in rapid, simple to use, low-cost systems for DNA analysis of fish and seafood products that could be implemented at scale within industry.

Two EU-funded projects - LABELFISH[1] and SEATRACES[2] - have investigated the mislabelling of seafood products in the Atlantic coast region of the EU and the potential for DNA testing methods suited to the cost, time and infrastructure requirements of industry. The projects have led to the development of hardware and protocols for completion of rapid DNA microarray assays. The technology can deliver assay results in four to five hours and tests with 10 commercially important species, including Alaska pollock, Atlantic cod, Atlantic salmon, Atlantic herring, found that the technology reliable identified the correct species (Kappel *et al.* 2020).

Future developments in this field are targeting further improvements in terms of the speed and cost effectiveness of the technology to enable adoption at scale and investigation of the potential to identify the region of origin as well as species (Mariani 2018).

Technology Readiness Level: 6-8; Technical risk: Moderate

Product authenticity: portable NIR spectroscopy: Grassi et al (2018) have compared the accuracy of a handheld near infrared (NIR) device and a benchtop Fourier Transform-NIR device in assessing the authenticity of fish fillets and patties. In a test that involved distinguishing Atlantic cod from haddock samples, there were no significant differences in the results achieved by the handheld and benchtop spectrometers.

The Visum Palm[3] is a similar, handheld NIR spectroscopy device that has been commercialised by Visum for the composition analysis of various food and beverage products, although no applications in the seafood industry are reported. Visum also produce the Visum Inline[4] for high-speed analysis of products on the production line.

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[1] LABELFISH project: http://labelfish.eu/

[2] SEATRACES project: https://www.seatraces.eu/

[3] Visum Palm: http://www.seeingnewdata.com/visum/files/2018/10/VisumPALM-Datasheet-VISUM-ENG.pdf

[4] Visum Inline: http://www.seeingnewdata.com/visum/files/2018/10/VisumNIR-Datasheet-VISUM-4pgENG.pdf

Finally, Tellspec have developed the Tellspec Enterprise Scanner[1], which is a very compact NIR spectroscopy device. The unit relies on a Bluetooth connection to transmit the spectral data to the cloud-based database and artificial intelligence to identify the ingredients present in food products. The results are then relayed back to the users smartphone where they are displayed in the associated app. The company are currently developing specific apps for seafood quality control and fraud detection apps.

Technology Readiness Level: 9; Technical risk: Moderate

Knowledge sharing to support food fraud detection: For large scale food processors, the challenge of verifying the authenticity of the ingredients they buy can be enormous if dealing with hundreds of suppliers and potentially thousands of ingredients. For any single processor, performing extensive authenticity tests for every batch of every ingredient would be prohibitively expensive. Due to the many overlaps in the supply base amongst food processors, it would be logical for processors to share data on authenticity testing in order to reduce the overall cost of testing for the industry and avoid duplication of effort. This was one of the recommendations on the Elliott review into the integrity and assurance of food supply networks (Elliott 2014). However, sharing of data amongst competitors is difficult in practice as the data could be used by competitors to gain insight into the purchasing practices of their rivals.

The Food Industry Intelligence Network[2] is an industry-led initiative in the UK that enables sharing of anonymised data concerning food traceability and authenticity testing. On a quarterly basis, members submit data relating to raw material or ingredient testing, including both analytical and/or supply chain traceability, into the Food Industry Intelligence Network via an independent law firm. This data is then anonymised and consolidated, and a report is produced using the combined data.

Sharing of the data in this way enables members to identify areas of their supply chain that have received little or no authenticity testing allowing them to focus future test resources on these potentially high-risk areas.

Technology Readiness Level: 9; Technical risk: Low

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[1] Tellspec Enterprise Scanner: http://tellspec.com/eng/

[2] Food Industry Intelligence Network: https://www.fiin.co.uk/

Innovation with a potential for incremental performance improvement

Detection of polyphosphates: Inorganic polyphosphates (tripolyphosphate, pyrophosphate and higher polyphosphates) are legally permitted food additives that are used to improve water holding capacity in fish fillets and shrimp. However, excessive use of these additives can be considered as economic fraud as, for example, weight gains of up to 50 percent have been reported when sodium tripolyphosphate (E541) was used in processing Vietnamese pangasius (Reilly 2018).

Wang et al (2015) have developed a process for the detection of polyphosphates in fish and shrimp muscles by capillary electrophoresis with indirect UV detection. Whilst the method was found to be reliable in detection of polyphosphates, the sample preparation process included the use of high-pressure processing for phosphatase inhibition, the cost of which is likely to be prohibitively expensive for widespread commercial use.

Kim et al (2019) have used microwave processing for the pre-treatment of samples. This, combined with ion chromatography, proved to be an effective and quick method for the detection of polyphosphates in fish and shrimp samples. Interestingly, several of the commercially available processed shrimp and dried shredded squid sampled exceeded the maximum allowable levels specified in the CODEX standard.

Technology Readiness Level: 6-8; Technical risk: Moderate

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24 Sustainability accreditations and labels

Contents

<u>From the SIF Executive Board</u>

The method applied in this review has generated numerous examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently happening. It is recognised that there are existing innovations and research areas that are not included here, and new areas where future innovations may occur. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

24.1 Overview: sustainability accreditations and labels

What is the challenge in the UK?

The main challenge in the area of sustainability accreditation and labels lie in the number of different schemes which can be confusing for the consumer. Improving existing technologies for better monitoring are expected to lead to incremental performance enhancement.

What are the most promising innovation categories?

There are a many accreditation schemes available which should ensure consumers seafood they buy is either from a sustainable fishery, from a well managed aquaculture facility or has been produced looking at welfare of the fish and/or other species. Innovation is expected to happen in the use of better monitoring technologies. These can include the use of blockchain technology, as well as improved vessel tracking methods, using satellite-based earth observation technologies. Whether these technologies will be used for existing certification schemes or allow the emergence of new schemes is yet to be seen

Where are important knowledge gaps?

No major knowledge gaps in this area have been identified

The first ’green stamps’ for the seafood industry were launched in the early nineties in the USA. They focused on a specific bycatch issue, such as the dolphin bycatch by tuna seiners (dolphin safe), or the turtle by catch of shrimpers (turtle safe). In 1997, a public awareness-raising campaign in the USA ’give swordfish a break’ turned out to be the first wide-scale campaign asking consumers to help to have an impact on fishing practices. In 1997, the Marine Stewardship Council (MSC), today the world -leading ecolabel, was created (Josupeit 2016).

Sustainability accreditation and labels cover the following issues:

- Sustainable fishing practices, ensuring sustainability of fish stocks (e.g. friends of the sea).

- Environmental and social impacts of aquaculture (e.g. Aquaculture Stewardship Council, Global G.A.P.).
- Fish welfare (e.g. RSPCA).
- Labels promoting practices for the wellbeing of specific species (e.g. “Dolphin safe” labels).

Related to sustainability accreditations are:

- Labels concerned with food safety.
- Tracking labels, which assure that the species on the label and the actual species of the fish are the same (a study in 2013 identified 59 % of fish labelled as tuna in grocery markets around the world as mislabelled) (ConsenSys 2019).

Some of the standards recommend practices that diverge, and occasionally are even contradictory. For example the use of acoustic deterrent devices to scare away predators in aquaculture are forbidden by the ASC (Aquaculture Stewardship Council) label, the SSPO (Scottish Salmon Producers’ Organisation) states that they ““should be used where and as permitted,” and the RSPCA standard requests them at sites that are “recognised as having a high risk of attack” or have “suffered an attack in the past.” (Amundsen, Gauteplass, and Bailey 2019). The strategic policy advisor from Which?, Sue Davies, also commented that “labels can be confusing and food company policies can vary”. (Harvey 2019).

The Global Sustainable Seafood Initiative (GSSI)[1], formed in 2013, created a Global Benchmark Tool for seafood certification schemes, based on the FAO Code of Conduct for Responsible Fisheries and the FAO Guidelines on Ecolabelling. This tool comprises seven steps:

- The submission of application and supporting documentation by the certification scheme.
- Preliminary review by Independent Experts.
- An Office Audit and Desktop Review by Independent Experts.
- Review by multi-stakeholder Benchmark Committee.
- Stakeholder consultation.
- Recognition decision by Steering Board.

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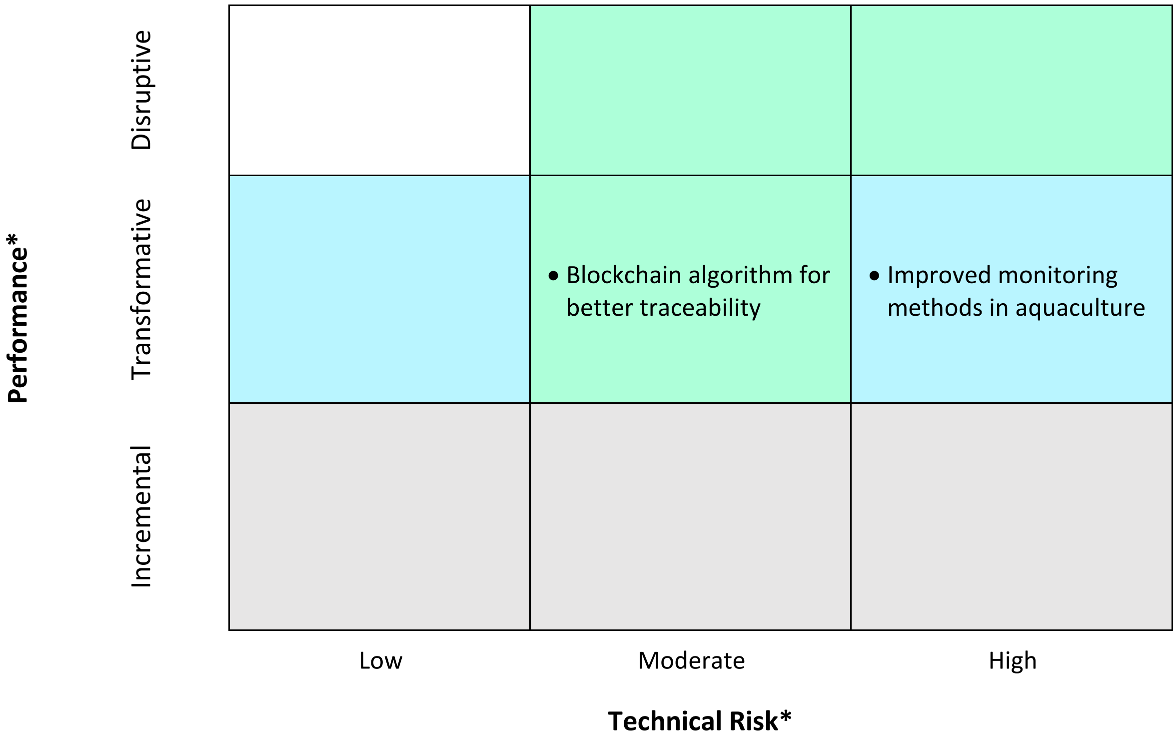
[1] GSSI: https://www.ourgssi.org/about-the-tool/

- Monitoring of compliance of recognised schemes on a regular basis.

Standards and accreditation schemes may bar developing countries from certain markets: It was shown that in Asia uptake by consumers and retailers has not been as prolific as in European and North American markets and recommendations are given to developing countries in order for them not to be unnecessarily barred from certain markets because they lack the capacity to comply with or prove compliance with third-party standards (Tsanitris, Katherine, Zheng, Lingfeng, and Chomo, Victoria 2018).

An overview of the potential performance improvement rating of recent (2015-2019) innovations in sustainability labels are outlined in Figure 23-1.



	Low	Moderate	High
Disruptive			
Transformative		• Blockchain algorithm for better traceability	• Improved monitoring methods in aquaculture
Incremental			

Figure 24-1: Performance and technical risk rating of innovations in sustainability labels.

**See section 4.4 for definitions of the performance and technical risk rating scales.*

24.2 Improved tracking methodology for fisheries

Improved tracking methodology will allow more transparency in the tracking of fish through the supply chain. This is of particular interest to fish sourced from outside the UK where there is less trust in the supply chains.

Innovations with a potential for transformative performance improvement

Blockchain algorithm in fisheries: The blockchain algorithm became prominent when used in cryptocurrencies such as bitcoin. The algorithm has also applications in supply chain monitoring, as entries cannot be falsified and are therefore traceable.

One example is OpenSC, a global digital platform developed in Australia, which allows users to scan QR codes with a smartphone camera to see where the seafood product came from, when and how it was produced and follow its journey along the supply chain. The platform was launched by the WWF and investment firm GCG Digital Ventures and uses blockchain technology (Reuters 2019). The WWF also published a document on how the blockchain algorithm can transform the seafood supply chain (Cook, 2018)

Another example is Pacifical[1], a global tuna market development company jointly set up by the 8 PNA Western Pacific island countries in 2011. They recently partnered with a Swiss food company to make their MSC certified canned and pouched tuna brand traceable, using Ethereum blockchain. Consumers are able to scan a QR code on the can label which – via a website – leads them to all relevant traceability information.

Technology Readiness Level: 9; Technical risk: moderate

24.3 On board electronic monitoring

Onboard electronic monitoring systems allows fishing activities on board to be monitored remotely, without there being observers onboard of a vessel.

Data can be used to create trust between various members within a supply chain.

For a further discussion on recent advances see chapter 17 ‘IUU fishing and vessel monitoring’.

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[1] Pacifical: https://www.pacifical.com/gustav-gerig-launches-blockchain-for-pacifical-msc-tuna-products/

24.4 Improved monitoring methods in aquaculture

Currently, aquaculture accreditation labels are awarded after physical visits by inspectors who inspect facilities and may take water samples. Automated ways of checking the water quality with data being sent back at regular time intervals to a localised inspection facility could enhance inspection procedures and also improve the monitoring of fish farms. Water quality can give information on standards being obtained (e.g. whether antibiotics are detected in the water) and also on whether certain fish welfare standards are maintained.

Innovations with a potential for transformative performance improvement

Improved monitoring methods in aquaculture: A patent application filed by inventors in Italy suggests a device and method for certifying the life cycle of an organic product. The sensing system is fully automated and allows for detecting water quality. The sampling system and data storage is packed in such a way that no tampering is possible and data can be used for certification processes of agro-alimentary products (especially fish). (Talamo and Casagrande 2018)

Technology Readiness Level: 3-5; Technical risk: high

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25 Waste reduction and valorisation

Contents

<u>From the SIF Executive Board</u>

The method applied in this review has generated numerous examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently happening. It is recognised that there are existing innovations and research areas that are not included here, and new areas where future innovations may occur. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

25.1 Overview: waste reduction and valorisation

What is the challenge in the UK?

Overall, waste collection systems for fish processing waste works relatively well in the UK. However, while much waste goes into lower value products, there is little evidence of their higher value counterparts. There is particularly very little evidence of shellfish waste being used for higher value products in the UK.

What are the most promising innovation categories?

The most promising innovation categories include:

- Technologies to remove the bitter taste from fish protein hydrolysates, for potential use in the production of higher value products
- Biorefineries for processing fish waste – currently at concept stage only
- Alternative process for chitin extraction from crustacean waste using fermentation, rather than purely chemical processes
- Use of crustacean waste-derived chitin as plastic alternatives

Where are important knowledge gaps?

- No significant technical knowledge gaps were identified in the extraction of raw materials from fish processing wastes
- Gaps are mainly in the identification of market opportunities, where these raw materials can be converted into competitive, higher value products

It has been estimated that more than 50% of fish tissues including fins, heads, skin and viscera are discarded as "waste" (Caruso 2016).

In a fish processing plant, waste can be reduced by either carefully operating the plant and ensure that manufacturing guidelines are used to reduce waste (WRAP 2015), or by utilising the waste materials and turning them into products, the latter of which will be the primary focus of this chapter. It is understood that very efficient processing machinery and operations have been in place in the industry for a considerable time, and improvements to waste reduction are very incremental and dependent on the business in question. Therefore, this chapter focuses on the use of materials which are currently regarded as waste.

Figure 25-1 below illustrates the market pyramid for different value-added products from fish waste. The lowest value per volume are for products which require the least processing of waste. Products with high value require more processing, and not all waste materials can be used.

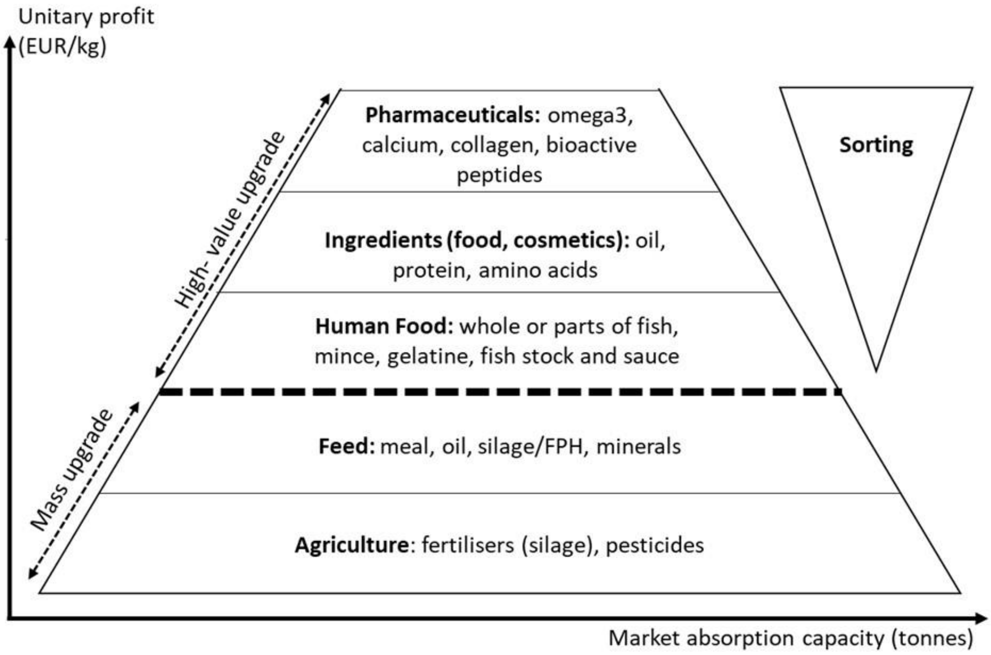

Figure 25-1: Market pyramid for different value-adding applications, adapted from (Jouvenot 2015), and (Anais, Raul, and Jean-Pascal 2013).

In most markets, shifting the practice from waste disposal to deriving value on a large scale will focus initially on high volumes and low-value end products at the bottom of the pyramid. Then gradually there can be a shift up the pyramid towards higher-value applications where waste raw material must be kept at a higher quality. An important consideration is that high value options will require high-quality waste. Sorting and careful handling/storage will be crucial for achieving products at the top of the pyramid.

The principles of the diagram were confirmed in an interview with a major fish processor, which aims in the next five years to move away from its current production of animal feed, fish protein hydrolysate and biogas to higher value products for human consumption such as those for pharmaceutical and cosmetic applications (personal communication).

It should be noted that there are mortalities before slaughter in the aquaculture sector. For regulatory reasons, these remains cannot be put back into the human or animal feed chains (category 2 waste), in contrast to waste from fish processing facilities (category 3 waste). This chapter is mainly concerned with category 3 waste from fish processing facilities, unless otherwise specified, e.g. particularly after specific treatments, but the end-applications may differ (e.g. feed for fur animals vs. pig feed).

In the UK, fish processing waste is generally collected for further processing in centralised fishmeal production plants (personal communication).

An overview of the potential performance improvement rating of recent (2015-2019) innovations in waste reduction and valorisation technologies are outlined in Figure 24-2.

Performance*	Low	Moderate	High
Disruptive			• Crustacean shell biorefinery
Transformative	• Silage process for fish protein hydrolysate with low bitter taste (for human food products) • Food supplement from fish protein hydrolysate • Protein and oil food supplements • On-board fish silage systems • Process of extracting chitin by biological fermentation • Removal of fishy odours from biological materials • Snack products from fish processing waste • More energy-efficient processes for fish oil/ fish protein production		• New processes to extract chitin: ○ using carbonic acid ○ using deep eutectic solvents ○ to obtain high-purity chitin • Process to extract astaxanthin from pink shrimp waste • Chitooligosaccharides by enzymes
Incremental	• Odour removal of fish hydrolysates for fertiliser applications • Advanced fish protein hydrolysate process • Advanced fish ensiling process • Food grade fish oil from new species • Biogas by anaerobic digestion from fish waste • Textile additive from chitin, to avoid odours • Feed supplements from fish bones – enhancing uptake of astaxanthin in feed • Improved collection system for fish blood • Washable fish leather	• Fish skin as substitute for human skin in wound healing • Plastic-like material from fish wastes • Optimisation of processing conditions for bioactive peptides	• Collagen films from fish bone as wound dressing material • Medical products and cosmetic products including bioactive substrates derived from fish

Technical Risk*

Figure 25-2: Performance and technical risk rating of innovations in waste reduction and valorisation.

**See section 4.4 for definitions of the performance and technical risk rating scales.*

25.2 General fish processing waste: fish protein hydrolysate and fish silage

Fish processing waste can be ensiled to create a shelf-stable product with applications as either animal feed or fertiliser/ soil conditioner. The process is similar to that of making fish sauce for human consumption, and results in a liquid product.

The terms “fish protein hydrolysate” and “fish silage” are frequently interchanged. In both processes, proteins are split into peptides of different sizes with antioxidant, antimicrobial, antihypertensive, anti-inflammatory, or antihyperglycemic properties, among others. Various methods of protein hydrolysis have been described and widely used. These were recently reviewed by Juan Zamora-Sillero et. al (2018).

For the purpose of this report, fish protein hydrolysate (FPH) shall refer to a product created using added enzymes, while fish silage shall refer to a product where no enzymes are added and instead relies on enzymes naturally present in the fish viscera. In some cases, the word FPH is used only for the protein fraction, while in other cases it is used for products containing both oils as well as the protein fraction. The protein fraction devoid of oils is sometimes also referred to as fish protein concentrate. Fish emulsion is another term typically used to refer to a fertiliser emulsion that is produced from the liquid remains of fish industrially processed for fish oil and fish meal.

Fish silage can be created by three different processes (Feedipedia n.d.; Olsen and Toppe 2017):

1. Addition of organic (formic, acetic or propionic) or inorganic (hydrochloric or sulphuric), acids to the fish waste to a point where the product becomes stable.
2. Addition of inorganic or organic acids to lower the pH to a point at which intrinsic enzymes will liquefy (which are normally most active around pH 4 and at temperatures between 35 to 40 °C)
3. Addition of carbohydrates and fermentation in order for lactic acid bacteria to create a stable environment (this process takes generally longer (~10 days) than hydrolysis by added acids)

FPH is made by a similar process (i.e. addition of acids), but enzymes (proteases) are also added in order to speed up the hydrolysation process. Enzymes for FPHs are readily commercially available by e.g. Novozymes[1], Enzyme Supplies[2] or Enzyme Innovation[3]. A recent review on the production of fish protein hydrolysates is available (Petrova, Tolstorebrov, and Eikevik 2018).

In 2014, 258,150 tonnes of by-products from processing of farmed and wild fish were preserved by silage in Norway. Silage production there typically uses formic acid with added antioxidants and is carried out at many local, coastal fish processing plants. The silage is then collected by truck or boat and transported to a few centralised plants. There, the silage is separated into an oil product and hydrolysed proteins. The oil and protein hydrolysate are used in feed for pigs, poultry and fish other than salmon (Olsen and Toppe 2017).

In the UK, the installation of fish ensiling units in the aquaculture industry is currently on the increase (FishFocus 2018). However, while ensiling of fish waste is common practice in Norway, in the UK fish processing waste continues to mainly be transformed into fishmeal.

Fish silage can be used in fish feed and may fully or partially replace fishmeal (Barreto-Curiel *et al.* 2016). It also has applications as soil conditioner / fertiliser, with added benefits. For example, using fertiliser from fish silage was shown to increase salt resistance in wheat (Ovissipour, Bledsoe, and Rasco 2015).

Equipment used in ensilage are mainly tanks, stirring equipment and pumps. One equipment manufacturer is the Danish company Landia, who offers a range of solutions for handling by-products and dead fish, including the silaging system BioChop. In 2019, Landia supplied a silage plant as part of an onshore pilot at Atlantic Sapphire for by-products from slaughterhouses as well as fish that die prior to slaughter (Landia 2019; Anaerobic-Digestion 2018).

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[1] Novozymes: http://www.novozymes.com/en/advance-your-business/food-and-beverage/protein

[2] Enzyme Supplies: http://www.enzymesupplies.com/

[3] Enzyme Innovation: https://www.enzymeinnovation.com/

Innovation with a potential for transformative performance improvement

Low bitterness FPH: A silage process resulting in a fish protein hydrolysate (FPH) with low bitter taste was developed at the University of Bergen, Norway. This is particularly important for the use of FPH in human food products (Aspevik 2016; Nofima 2016).

Technology Readiness Level: 6-8; Technical risk: Low

Innovation with a potential for incremental performance improvement

Human food supplement: UK company CellsUnited developed a human protein food supplement from Atlantic salmon processing waste. The product contains all 20 essential and non-essential amino acids together with key micronutrients. The product is marketed as a sports nutrition supplement for post workout recovery due to the very fast absorption of the nutrients and excellent bioavailability (PR Newswire 2017).

Technology Readiness Level: 9; Technical risk: Low

Onboard silage system: Norwegian company PG Flow Solutions has developed a silage system that claims to produce high-quality fish protein concentrate (FPC) that can generate a market value of NOK 12-15 per kilogram, compared to the standard NOK 2 per kilogram. The solution, called PG Silage, is suitable for long-distance fishing vessels, typically 70-100 metres long, with quotas allowing for long trips. The PG Silage method manages to reduce 1,700 m^3 of fish waste (equivalent to the waste generated from 1,000 m^3 of fish fillets) to approximately 310 m^3 of fish oil and 530 m^3 concentrated FPC. The concentrated product can be stored up to two months (Johansen 2017). Danish company Landia has also developed an on-board silage systems for trawlers (Williams 2018).

Technology Readiness Level: 9; Technical risk: Low

Innovation with a potential for incremental performance improvement

Odour removal of fish hydrolysates for fertiliser applications: An organic fertiliser containing fish hydrolysate has been formulated by US company True Organic Products Inc[1]. The company states that 'fish soluble by-product' (fish hydrolysate or fish protein stabilised by acid) has been historically unpopular with the fertiliser industry due to its smell and thickness. In a patent application, True Organic Products claim that they have discovered a process for making fertilisers from 'Fish soluble by-product', which does not have a strong odour (Evans 2017).

Technology Readiness Level: 9; Technical risk: Low

Advanced FPH process: BioMarinus[2] is part of New Zealand company United Fisheries, located in Christchurch. The company owns a 5,000 m^2 fish processing facility and process approximately 7-8 m^3 of waste per day in their silage containers. The silage, which results from their proprietary enzymatic process is marketed under the brand name 'BioMarinus'. New Zealand farmers buy the product at 1 USD per litre for use as feed or fertiliser (wholesale price, large quantities). Recently the company has expressed interest in investing in independent research, as they believe that by adding hydrolysed liquid fish and urea to feed soil, dairy farmers can reduce their use of synthetic nitrogen by 80% (Fulton 2019).

Technology Readiness Level: 9; Technical risk: Low

Advanced silage process: Australian company SAMPI[3] has a factory transforming tuna factory waste from tuna aquaculture into hydrolysate. Their product is used as fertiliser, feed (poultry and aquaculture), feed supplement (e.g. can be added to water for poultry and shrimp feed) and bait (Howieson 2017). Recently it was shown that replacing fishmeal partly with SAMPI FPH (5 and 10%) for juvenile barramundi resulted in higher final body weight and specific growth rate than a control group (Siddik *et al.* 2018).

Technology Readiness Level: 9; Technical risk: Low

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[1] True Organic Products: https://true.ag/

[2] BioMarinus: https://biomarinus.co.nz

[3] SAMPI: http://www.sampi.com.au/

25.3 General fish processing waste: fishmeal and fish oil

Fishmeal and fish oil can be marketed in different industries: for animal consumption as aquaculture or land-animal feed, and for human consumption (e.g. as fish oil capsules or in pharmaceuticals). The primary market is currently aquaculture, accounting for 73% of fishmeal consumption and 71 % of fish oil consumption in 2010 (IFFO 2013).

Fishmeal and fish oil are produced mainly from whole fish species for which there is little or no demand for human consumption. It is estimated that only 25- 35 % of all fish oil and fishmeal are made from fish by-products and processing waste, although this figure is expected to grow (Seafish 2018).

The traditional manufacture of fishmeal and fish oil is a process by which the fractions of water, oil and solids of fish are separated, and the water then removed by evaporation and drying. The process is very energy-intensive due to the high temperatures required in the evaporation step.

There are three different types of fishmeal:

- High-quality - usually for small-scale aquaculture units (trout farms) or marine species.
- Low temperature (LT) meal - highly digestible and used in salmon and piglet production.
- Prime fair average quality (FAQ) - lower protein content feed ingredient for pigs and poultry.

Fish oil can be categorised in two types:

- Body oil - contained in the muscles.
- Liver oil - obtained from liver and viscera.

Each oil type has different properties and value. Fish freshness is a particular factor for oil production as spoilage breaks down valuable components.

Innovations with a potential for transformative performance improvement

Fish protein and fish oil as ingredients for human food: Advance International[1] is a US company marketing fish protein powder and fish oil from "100 % wild, certified sustainable ocean fish". They applied for patent protection for a specifically developed process to extract protein and omega-3 oil from animal tissue (Ghorbani and Coltun 2016).

Technology Readiness Level: 6-8; Technical risk: Low

More energy-efficient process for fish oil and fish proteins: SINTEF has developed improved methods of extracting high-quality oils and proteins from fish. Traditional processes are typically optimised for either oil production or protein production. In this new profitable process, the oil is initially separated at low temperatures, followed by enzymatic hydrolysis to extract the proteins (SINTEF 2015; Slizyte *et al.* 2018).

Technology Readiness Level: 6-8; Technical risk: Low

More energy-efficient process for fishmeal production: Scientists from Sweden recommended an alternative to fishmeal production, whereby proteins from high bone/low meat sources such as fisheries by-products can be extracted through a "pH shift process" using acid or alkaline water (Fish Farming Expert 2019b).

Technology Readiness Level: 3-5; Technical risk: Low

Innovations with a potential for incremental performance improvement

Food grade fish oil from new species: A novel process has been developed by Icelandic start-up company Margilidi[2]. Winterization is a type of dry fractionation process for removing undesirable high melting point components of oil, frequently referred to as stearin, such as waxes and certain triglycerides. Margildi specialises in North Atlantic species such as capelin, herring and mackerel, which have a high stearin content. These species were not processed for oil for human consumption with conventional winterization techniques until Margildi developed its patented process (Hreggvidsson 2018).

Technology Readiness Level: 9; Technical risk: Low

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[1] Advance International: https://advanceprotein.com/

[2] Margiligi: http://margildi.is/

25.4 General fish processing waste: biogas by anaerobic digestion

Anaerobic digestion is a complicated, but naturally occurring biochemical process in which anaerobic bacteria break down organic matter in the absence of oxygen, leaving biogas and digested substrate. Production and use of biogas instead of petroleum gas are one way to reduce fossil fuel use and carbon dioxide emissions. For years, this process has been applied to municipal and agricultural waste streams to reduce environmental impact. The anaerobic digestion process depends on a specific microorganism consortium to break down biomass. The biogasification process is highly dependent on environmental and/or ambient conditions such as temperature, pH, C/N ratio, C/P ratio, particle size, inhibitors, and type of substrate. Waste from fish processing poses distinct technological problems because it releases high levels of ammonia when digested. This can reduce or inhibit the digestion of substrates (Ivanovs, Spalvins, and Blumberga 2018).

Innovations with a potential for incremental performance improvement

Biogas from salmon processing waste: Salmon processing waste is ensiled, pasteurised and integrated with other household and garden waste in an anaerobic digester at the local authority Comhairle nan Eilean Siar's (CnES) household waste and recycling centre near Stornoway, Scotland. The facility produces biogas which can then be used to fuel a local combined heat and power plant (Fish Farming Expert 2019a).

Technology Readiness Level: 9; Technical risk: Low

Computer modelling of anaerobic digestion processes: Modelling of fish waste was advanced by researchers in Riga, Latvia. The team took into account the specificity of the substrate composition but suggested that further experiments for data acquisition are needed (Ivanovs, Spalvins, and Blumberga 2018).

Technology Readiness Level: 1-2; Technical risk: Low

25.5 Crustacean waste: chitin and chitin derivatives

Every year, some 6 to 8 million tonnes of crab, shrimp and lobster shell waste are produced globally — of which about 1.5 million tonnes come from Southeast Asia alone. Whereas 75% of the weight of a tuna fish can be extracted as fillets, meat accounts for only approximately 40% of a crab's mass. In developing countries, waste shells are often discarded in landfill or the sea. Burning of shell waste is environmentally costly due to the low burning capacity of shells (Sanuja, Kalutharage, and Cumaranatunga 2017; Yan and Chen 2015).

In the EU, processing of crustaceans is estimated to result in more than 750,000 tonnes of shell waste per year. For one shellfish processor generating between 420 and 480 tonnes of crab shell waste per year the cost of waste disposal was estimated at over €20,000 per year to have the waste rendered into fish meal by another company (Mitchell 2014).

Crustacean shells are composed of 20–40% protein, 20–50% calcium carbonate and 15–40% chitin (Yan and Chen 2015). A common route of utilisation for crustacean shell waste is to extract chitin, $(C_8H_{13}O_5N)_n$, the most abundant aminopolysaccharide polymer occurring in nature. However, the chemical process to extract chitin from crustacean shells uses a concentrated sodium hydroxide solution, creates environmentally harmful effluents and uses upwards of 1,000L of process water per kilogram of shrimp waste (Gómez, Peña, and Cota 2016; Yan and Chen 2015). The advantage of chitin compared to other forms of biomass waste, such as cellulose, is that chitin contains nitrogen. Therefore, nitrogen-containing chemicals, which are currently synthesized starting from petrochemical products under high cost of energy may be produced more energy efficiently using chitin as a starting point. This has so far been achieved on small laboratory scales (Yan and Chen 2015).

While shrimp and crab shells are sources of α-chitin, pens from squid are a source of β-chitin (Wang *et al.* 2019).

Chitin can be converted to its most well-known derivative, chitosan, by treatment with alkali solution. As with chitin, chitosan is water insoluble. However, chitosan is soluble in aqueous organic acid solutions. The water insolubilities of chitin and chitosan limit their applications in many industries.

The physical, chemical or enzymatic depolymerization of chitin and chitosan result in chitooligosaccharides (COS). These are water-soluble and low molecular weight derivatives, and superior to their parent polymers in multiple aspects. COS exhibit an enormously wide range of biological activities and potential to be applied in various industries (Liaqat and Eltem

2018). Research in the area of COS is not only focused on applications, but also on finding new COS by applying novel chitinase enzymes.

Applications for chitin include:

- Precursor for chitosan and chitooligosaccharides production – see below.
- Production of glucosamines (GLcN), which is the number one dietary supplement in the USA used for pain relief of osteoarthritis (Liaqat and Eltem 2018).

Applications for chitosan include:

- Chitosan in agriculture - Chitosan not only provides an antimicrobial film that prevents mould growth, but also causes a reaction that improves the immune system of plants (Tidal Vision n.d.).
- Chitosan for water treatment - Chitosan from crustacean shells has applications in water treatment and also as a fining agent for the beverage industry. US company Tidal Vision claims that using chitosan reduces the amount of inorganic metal coagulants by 70 – 100 % (Tidal Vision n.d.).
- Chitosan for food products - The cationic chemical structure of chitosan provides an ability to bind directly to the outer cell membrane of microorganisms, providing antimicrobial activity without the use of antibiotic chemicals. Chitosan is widely used for the preservation of foods by providing a barrier to microbes which exist in the environment. Edible food coatings which contain chitosan have been widely researched and are said to be used industrially (Tidal Vision n.d.; Kumar *et al.* 2019).

In terms of the applications for chitooligosaccharides (COS), the properties of COS include antimicrobial, antioxidant (shown to be stronger than chitosan), anti-inflammatory and immunostimulatory (medical and food) activity, as well as drug carriers and food additives (preservative, prebiotic). The molecular mechanisms of these properties, particularly the antimicarobial property, are not yet fully understood (Liaqat and Eltem 2018).

COS can find uses as fungicide and other agricultural applications. Furthermore, they are used in various medical applications, including the improvement of blood cholesterol, anti-obesity properties and improvement of the immune system as well as biotechnological applications. For example, Irish company Megazymes offers chitooligosaccharides for use in research, biochemical enzyme assays and analytical applications.

It has been suggested that the biological effects of COS could prove as beneficial inputs for the biotechnological industries as leads in various formulations (Thomas *et al.* 2015).

Innovations with a potential for disruptive performance improvement

Shell biorefinery: The concept of a crustacean shell biorefinery has been suggested by researchers in Singapore (Yan and Chen 2015; Hülsey 2018). The refinery would be able to convert crustacean waste, particularly chitin, into valuable chemicals including e.g. proximicin A and antibiotics as well as amines and alcohols. It can be envisioned that a large range of oxygen- and especially nitrogen-containing compounds can be synthesized from chitin.

Technology Readiness Level: 1-2; Technical risk: High

Innovations with a potential for transformative performance improvement

Process of extracting chitin by biological fermentation: CuanTec[1] is a Scottish company which developed a process of extracting chitin by biological fermentation rather than using traditional chemical means. The chitin can then be transformed into chitosan and made into products such as e.g. cling film. The company is currently working on the development of a totally biological method to produce chitosan, replacing sodium hydroxide from the process. The first product developed with their chitosan is an antimicrobial, compostable food contact material (FCM) packaging which reduces spoilage and prolongs shelf life of fresh food.

Technology Readiness Level: 9; Technical risk: Low

Process extracting chitin using hot water and carbonic acid: A process developed by researchers at the National University of Singapore describes the extraction of chitin from shell waste using hot water for deproteinisation and carbonic acid for demineralisation (called the HOW-CA process). The method to extract high-purity chitin features high deproteinisation and demineralisation efficiencies (>90%), and the whole process is accomplished within hours (Yang *et al.* 2019).

Technology Readiness Level: 3-5; Technical risk: High

Process of extracting chitin using deep eutectic solvents (NADES): Researchers in Slovenia also looked at the recovery of biomaterials from shrimp shell biomass using deep

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[1] CuanTec: https://www.cuantec.com/

eutectic solvents (NADES). The highest chitin extraction yield obtained was 90% using Choline Chloride-Urea, which can be recycled several times without loss in the shrimp shell fractionation capability (Bradić, Novak, and Likozar 2020).

Technology Readiness Level: 3-5; Technical risk: High

Novel process for the production of high-purity chitin: Mexican company Industrias Vepinsa S.A. patented a chemical and biotechnological process for the production of high-purity chitin from marine waste. The process comprises the following steps: grinding marine waste from for example, shrimp or crab, together with water for the production of a crustacean paste; sterilising the paste of crustacean shells; deproteinising the crustacean paste using proteases; filtering the deproteinised paste in order to produce deproteinised solids; demineralising the deproteinised solids using an acid; filtering and neutralising the demineralised paste using a base; depigmenting the solids using alcohol; filtering the depigmented paste; and drying the depigmented, deproteinised and demineralised solids for the production of chitin in flakes. The process also produces other value-added products, such as proteins, calcium, sodium or potassium salts as well as astaxanthin pigments. The process can also be used for the production of glucosamine, N-Acetylglucosamines and chitosan (Gómez, Peña, and Cota 2016).

Technology Readiness Level: 3-5; Technical risk: High

Process of extracting astaxanthin from pink shrimp waste: Astaxanthin is responsible for the pink to red pigmentation in many crustaceans, as well as in fish (such as trout and salmon). It is frequently added to feed and can be derived from petrochemical sources. It is also a valuable product for human nutritional supplements and is reported to have 10 times the antioxidant activity of other carotenoids. Brazilian researchers describe a process where shrimp waste is dried in a spouted bed with inert particles (Silva *et al.* 2018).

Technology Readiness Level: 3-5; Technical risk: High

Chitinase Chit24: Chitinase Chit42 from *Trichoderma harzianum* hydrolyses chitin oligomers with a minimum of three N-acetyl-d-glucosamine (GlcNAc) units. It was found that the enzyme produced small partially acetylated chitooligosaccharides, which have enormous biotechnological potential in medicine and food. Researches from The Autonomous University in Madrid, Spain, conclude recent work with the statement that production and understanding of how the enzymes generating bioactive chito-oligomers work is essential for their biotechnological application, and paves the way for future work to take advantage of chitinolytic activities (Kidibule *et al.* 2018).

Technology Readiness Level: 3-5; Technical risk: High

Innovations with a potential for incremental performance improvement

Tidal-Tex^{TM}: A textile additive made from crab shells by Tidal Vision, a US company specialising in making products from discarded by-products from sustainable fisheries. The product prevents odours as it is bacteriostatic and antimicrobial and prevents the growth of bacterial and fungal microorganisms. Tidal-Tex can be applied to fibre, yarn, or directly onto a finished woven or knitted textile. The product can be sprayed, dipped, or composited with other materials to provide antimicrobial activity to textiles for a wide variety of applications (Tidal Vision n.d.).

Technology Readiness Level: 9; Technical risk: Low

25.6 Finfish fish processing waste: human food and human food ingredients from waste

Food ingredients from fish and shellfish waste can be similar to feed ingredients (e.g. protein powder). In this case they will be covered in other sections of this chapter. This section is solely describing innovations which are important for the use of fish waste and by-product for human food products.

Where there are opportunities, waste products are already turned into food products for human consumption: dried cod heads and backbones from Scandinavia and the UK are exported to Nigeria, and equipment is available from companies such as Coctio[1] to industrially manufacture bone broths, including fish bone broths. Fish skins can also be used as human food. Skins of some fish species can also be prepared like “chicharron”, the crispy fried pork skin that is found in Mexican cuisine. Another example of the use of fish skin are John Dory skins flavoured with salted egg yolk. Singaporean fast food company Irvin’s Salted Egg was launched in 2015 and currently employs 300 people in 21 outlets in six countries (Guest 2019).

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[1] Cocito: https://www.coctio.com

Innovations with a potential for transformative performance improvement

Removal of fishy odours: Norwegian company Biomega patented a method to modulate trimethylamine (TMA) levels in biological materials. TMA is responsible for the fishy odour or taste in many fish-derived products (Sandnes and West 2019).

Technology Readiness Level: 6-8; Technical risk: Low

Responsible Foods: A company founded by Holly Kristinsson from MATÍS in Iceland, Responsible Foods is setting out to “disrupt the global snack market” by producing highly novel, sustainable and delicious snacks from fish processing waste (EIT Food 2019).

Technology Readiness Level: 9; Technical risk: Low

25.7 General fish processing waste: use of specific separated by-products from fish processing

This section describes specific fish parts which can be made into products not discussed in the other sections.

Blood - In salmon and trout, blood makes up approximately 3.5 to 4.0% of live-weight of the fish. While blood from fish may be a valuable by-product in the future, similar to blood from warm-blooded animals, no evidence of any value-added products has been found (personal communication). Fish blood is different to blood from warm-blooded animals and to date separation of blood plasma and haemoglobin in fish blood has failed. Hence, plasma and haemoglobin products of salmon have yet to be tested by the feed/food industry (Ottesen *et al.* 2016).

Eyes - In Russia there is also an interest in utilising very specific bioactives related to fish eye lenses. Fish eye compounds can be used to arrest early cell division in fish and mussel eggs (Ottesen *et al.* 2016). Traditionally, Norwegian fisherman treated wounds with the eye of *Sebastes marinus* that was squeezed and smeared onto wounds (Ottesen *et al.* 2016).

Squid ink - Squid ink is a mixture of various compounds, of which melanin is the main component, imparting its dark colour. It has been suggested that melanin has antioxidative and anti-inflammatory properties, as well as other positive medical properties (Wang *et al.* 2019).

Bones - Fish bones are low in collagen but are rich in calcium and can also be hydrolysed into fish bone meal, which can then be used as feed supplement. Fish bone contains calcium and phosphorous in the favourable ratio of approximately 2:1 to form hydroxyapatite, which is considered the most bioavailable form of calcium. Products for human consumption and feed supplements are widely available.

Astaxanthin - Astaxanthin is the oxygenated derivatives of carotenoids occurring widely and naturally in marine organisms including crustaceans (lobster, shrimp, crab, and krill) and fish (salmon, sea bream) and are known to give a red colour to marine species. Nearly all commercially available astaxanthin for aquaculture is produced synthetically, however, processes to recycle astaxanthin from crustacean shells are known (Nguyen *et al.* 2017).

Swim bladders - Swim bladders are known to be processed into isinglass, which is used as a fining agent in the beverage industry. They can also be eaten and are highly valued in Asian cuisines.

Offal, roe, eggs - Some fish parts have a value as food products in certain markets. Otherwise offal is disposed of as general fish waste. Provided proper treatment of the “waste” is employed, it can be made into high-value products. A report on the Scottish fish industry highlighted that while for instance, cod livers can be used to extract oils to be used in the food supplement industry, there is a “struggle to get livers in good enough condition” (Zero Waste Scotland 2015).

Other - Other parts of specific fish (e.g. pens from squid) can either be processed into by-products discussed in other sections but have little or no evidence on its uses.

Innovations with a potential for incremental performance improvement

Feed supplement from fish bones: Fish bone processing (e.g. hydrolysis) and methods to produce feed ingredients from fish bone are generally known, and it was recently found that these ingredients may have an effect on flesh pigmentation in fish whose diet includes astaxanthin. A patent by Bergken Teknologioverforing describes that hydrolysed fish bones are capable of enhancing flesh pigmentation arising from dietary astaxanthin (Albrektsen 2018).

Technology Readiness Level: 6-8; Technical risk: Low

25.8 Finfish waste: fish gelatine and fish collagen

Gelatine is a protein produced by partial hydrolysis of collagen. Gelatine from marine sources (warm or cold-water fish skins, bones and fins) is a possible alternative to gelatine from other livestock animals (cattle, pigs) and is typically extracted from fish skin and scales (fish bones contain very little collagen). One major advantage of marine gelatine sources is that they are not associated with the risk of Bovine Spongiform Encephalopathy (BSE) and are acceptable in most religions.

Fish living in warm-water have a different collagen composition to their cold-water counterparts. Gelatine from warm-water fish resembles that of bovine and porcine animals, while gelatine from cold-water fish, by contrast, does not gel for any practical purposes, and thus industrial application has been limited.

While an important part of the warm-water fish gelatine goes to the capsule industry and into food additives, the traditional application for cold-water fish gelatine is micro-encapsulation of heat sensitive vitamins and other nutrients. Norland[1] pioneered this application and was the sole supplier to Roche for many years (Kobbelgaard 2015).

There are many applications and potential applications for fish collagen. A review on this subject was recently written by M. Raman and K. Gopakumar (Raman and Gopakumar 2018).

Innovations with a potential for incremental performance improvement

Collagen films from fish bone as a wound dressing material: *In vitro* studies of collagen films prepared from fish bones of Bluefin Trevally were promising and acceleration of wound healing in CF-treated rats was evident in *in vivo* studies (Rethinam *et al.* 2016).

Technology Readiness Level: 3-5; Technical risk: High

Fish skin as substitute for human skin in wound healing: Kerecis, a US company which develops patented fish-skin products to heal human wounds and tissue damage, recently presented new research on their fish-skin-grafts wound treatments. As there is no disease-transfer risk between cold-water fish and humans, the Kerecis fish skin only needs to be gently processed and makes an ideal substitute for human skin (Kerecis 2019). Furthermore, there is evidence that Brazilian physicians use tilapia skins to treat severe burns. The burn is

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[1] Norland: https://www.norlandprod.com/Fishdefault.html

covered completely with the tilapia skin, which contains a particularly large quantity of collagen type 1 that accelerates the healing process and reduces scar formation (CGTN America 2018).

Technology Readiness Level: 6-8; Technical risk: Moderate

Plastic-like material from fish scales and other fish processing waste: A student from the University of Sussex recently developed 'MarinaTex'[1], a transparent plastic-like material. Very little is known about its composition apart from its use of fish scales and red algae. One cod could give enough material to make 1,400 plastic-like bags, which would biodegrade after use. Development is still in the very early stages and the company is looking for investment to commercialise the product (Bealing 2019).

Technology Readiness Level: 3-5; Technical risk: Moderate

25.9 Leather from fish skin

Fish leather is considered an environmentally friendly eco-material as less of the fish is wasted and may serve to replace bovine leather usage.

There are already various companies dealing in fish leather, including The Fish Leather Company[2] in the UK and Italian company Minardi (2017).

Innovations with a potential for incremental performance improvement

Atlantic Leather: An Icelandic company has found a way to make fish leather that can be washed in a washing machine. The washable fish leather maintains its colour and softness in a washing machine at 30°C washes (Atlantic Leather n.d.).

Technology Readiness Level: 9; Technical risk: Low

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[1] MarinaTex: https://www.marinatex.co.uk

[2] The Fish Leather Company: https://www.facebook.com/TheFishLeatherCompany/

25.10 Peptides and enzymes from fish

Fish-derived bioactive peptides (BAP): BAP are peptides which contain bioactive amino acid sequences. They have been suggested to beneficially influence pathways involved in body composition, hypertension, lipid profile and regulation of glucose metabolism. While research is conducted in this area, it has been suggested that results from published studies on the health benefits of bioactive peptides derived from fish are conflicting (Dale, Madsen, and Lied 2019).

Enzymes: Enzymes play a decisive role as biocatalysts in numerous biotechnological processes, including fish and seafood processing. Fish enzymes from cold-water species have displayed high activity at low temperatures. This enables gentle processing without thermal influences. Proteases are, for example, used for decalcifying or curing seafood products, serve as agents for tenderising fish fillets, or help remove the skin without damaging the meat (Eurofish n.d.).

Note: While there is ongoing research into the benefits of peptides and enzymes derived from fish, details of this was deemed out of scope for this report.

Innovations with a potential for incremental performance improvement

Medical products and cosmetic products including bioactive substrates derived from fish: Zymetech[1] is an Icelandic biotechnology company specialising in research, purification and utilisation of cold-adopted enzymes from deep-sea cod fish. The company's current offering of products is 'PreCold', a mouth spray which forms a protective layer and protects against the common cold and 'Penzim', a skin health product. The company's intellectual property include a patent on novel cod trypsin isoforms, which are useful as pharmaceuticals, in medical device, and cosmetics (Gudmundsdottir, Asgeirsson, and Stefansson 2017) and the use of serine proteases for removal, prevention and inhibition of formation and growth of biofilms (Gudmundsdottir *et al.* 2015).

Technology Readiness Level: 6-8; Technical risk: High (referring to their products in development)

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[1] Zymetech: https://zymetech.com/about-us/

Optimising processing conditions: Antihypertensive and antioxidant BAPs derived from fish could represent a promising alternative to synthetic drugs. BAPs isolated from fish exhibit good stability when applied under moderate physical conditions and after in simulated *in vitro* digestion. Processing can increase the susceptibility of peptides to digestion in the digestive tract as well as improving absorption and immune system responses. Therefore, it is important to determine the optimal conditions under which proteins (and peptides) can be processed in order to maintain their bioactivity. According to a recent review article on this topic, future research efforts on BAPs should be directed towards an elucidation of their activity after technological processes (Korczek, Tkaczewska, and Migdał 2018).

Technology Readiness Level: 1-2; Technical risk: Moderate

25.11 Mollusc shells

Shells are already traded for various applications, including ingredients in poultry and bird feed, biofilter medium, soil liming and as aggregate building materials and to a very limited extent as materials for arts and jewellery. However, shells from the aquaculture industry are widely regarded as a nuisance waste product. As the production and processing of bivalves have increased, efficient use of their shells has become essential, not only to maximise financial return, but also to address waste disposal challenges because of their slow, natural degradation rate (Morris, Backeljau, and Gauthier Chapelle 2019; Jović *et al.* 2019).

In parts of the UK, the proper disposal of shells at a landfill site could cost over £80 per tonne (HM Revenue and Customs standard rate landfill tax as of 1st April 2016) (Morris, Backeljau, and Gauthier Chapelle 2019).

Seashell waste consists mainly of calcium carbonate ($CaCO_3$), and therefore it has been suggested as an alternative for mined, “ground calcium carbonate” for applications such as cement production. Other applications such as filling and whitening agents in paper manufacture require further processing into “precipitated calcium carbonate”.

The scale of $CaCO_3$ production by the aquaculture industry is in orders of magnitude smaller than that of the mining industry. However, aside from a few shell enterprises and numerous small-scale localised initiatives, the majority of shells from aquaculture processing remain a waste product. In Asia (particularly China), the majority of shellfish products are processed, and shells are removed at the point of harvest and regularly discarded back into the water, or along the coastline (Morris, Backeljau, and Gauthier Chapelle 2019).

A key consideration in shell valorisation is the proximity of shell waste production to suitable processing facilities, as well as proximity to regions in which potential shell applications have a market. A recently conducted life cycle assessment (LCA) on oyster shell waste in Brazil found that a distance larger than 323 km between shell source and processing yielded no environmental benefit of shell valorisation over landfill disposal (Morris, Backeljau, and Gauthier Chapelle 2019).

Innovations with a potential for incremental performance improvement

Processing of shellfish waste: A project, undertaken with UK company AeroThermal, found that autoclaving was a suitable treatment of shellfish wastes, which can separate and sterilise flesh from shellfish and the shells. This means that the flesh can be used for e.g. anaerobic digestion, while the shells can be used for further processing. The study concluded that "autoclaving, in conjunction with anaerobic digestion, represents a significant investment and is therefore more suited for large scale, centralised waste treatment facilities, rather than individual processors" (Seafish 2008). While the process is technically ready, there has been no recent evidence of this being taken further (personal communication).

Technology Readiness Level: 6-8; Technical risk: Low

Shellfish waste to make "microshells" for filtration media: A project at the University of Swansea together with the food company Quay Fresh and Frozen Foods (producing 800 tons of crushed whelk shells every year), investigated the possibility of producing an environmentally friendly alternative to microbeads from shellfish waste. These could be used as e.g. water filtration medium, soil conditioners or alternatives to plastic microbeads (BBC News 2017; Tang 2017).

Technology Readiness Level: 3-5; Technical risk: Low

25.12 Waste collection systems

In order to obtain high-quality products from fish processing waste, two technical challenges need to be overcome:

- Sufficient quantity of waste product to enable efficient valorisation.
- High grade of waste product (freshness).

An example of an efficient waste collection and valorisation system is provided by the Japanese company Sanki Shiryou Kougyou Co (Sanki Shiriyou n.d.) - an urban fish meal plant serving Tokyo and surrounding areas. The company produces fish meal and oil for use in livestock feed, fertiliser, pet food, margarine, soap, etc. For their process, fish waste generated by supermarkets and fish processing companies is collected for a fee (significantly cheaper than waste incineration) during evenings/nights and processed immediately to ensure quality and freshness. Final products are shipped within the day.

It was commented that the waste collection system in the UK works well (personal communication). Small improvements can always be undertaken, but during the research for this project, no significant activity with regards to R&D could be found.

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Theme 4: Climate change

26 Climate change adaptation

Contents

From the SIF Executive Board

The method applied in this review has generated numerous examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently happening. It is recognised that there are existing innovations and research areas that are not included here, and new areas where future innovations may occur. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

26.1 Overview: climate change adaptation

What is the challenge in the UK?

Climate change directly affects the distribution, abundance and health of wild fish stocks, and the viability of aquaculture processes and stocks. There is clear evidence that climate change is already affecting UK waters, with productivity in some areas negatively impacted. To date, a wide range of climate change adaptation measures has been applied in the UK, and have tended to focus on capacity building within the sector, policy measures, building resilience through a reduction in other stressors, developing alternative markets or livelihoods and protecting critical infrastructure.

What are the most promising innovation categories?

- **Pen/Cage design –** Allow for farming further offshore and mobile solutions have the potential to seek optimal environments
- **RAS, IMTA and other culture systems –** When economically feasible, may protect against most climate change impacts
- **Species-specific resilience** – Selective breeding, species diversification, aquafeed development
- **Modelling and prediction –** Forecasting for extreme events, safety and vulnerabilities

Where are important knowledge gaps?

- **Fundamental research** - From species thermal biology to vulnerability assessments, critical to guiding development of effective strategies
- Applicability of innovations to the UK scenario

Climate change directly affects the distribution, abundance and health of wild fish stocks, and the viability of aquaculture processes and stocks. It also indirectly affects the survival and growth of fish by impacting on their prey and compounds other pressures arising from human activities, such as over-fishing, with implications on the industry's environmental and economic sustainability (Wentworth and Stewart 2019). There is clear evidence that warming seas, reduced oxygen, ocean acidification and sea-level rise are already affecting UK coasts and seas. Fisheries productivity in some UK waters, particularly the North Sea and Celtic–Biscay Shelf has been negatively impacted by ocean warming and historical over-exploitation (MCCIP 2020). Climate change is challenging the effectiveness of contemporary management strategies and gives rise to significant additional uncertainties and risks to fishers and fish farmers' livelihoods and to the fishing and aquaculture industry (FAO 2018).

The extent to which increasing demand for seafood products can be met will depend on the management of the entire industry, its environmental impact, and its ability to adapt to climate change. Actions are taken to either avoid (or minimise) or take advantage of climate change impacts, either by decreasing vulnerability or increasing resilience.

According to the United Nations Framework Convention on Climate Change (UNFCCC), adaptation refers to "adjustments in ecological, social, or economic systems in response to actual or expected climatic stimuli and their effects or impacts. It refers to changes in processes, practices, and structures to moderate potential damages or to benefit from opportunities associated with climate change" (UNFCCC n.d.).

Parties to the Convention and its Paris Agreement recognise that adaptation is a global challenge faced by all with local, subnational, national, regional and international dimensions and is a key component of the long-term global response to climate change to protect people, livelihoods and ecosystems. The parties also acknowledge that "adaptation action should follow a country-driven, gender-responsive, participatory and fully transparent approach, considering vulnerable groups, communities and ecosystems, and should be based on and guided by the best available science and, as appropriate, traditional knowledge, knowledge of indigenous peoples and local knowledge systems, with a view to integrating adaptation into relevant socio-economic and environmental policies and actions".

To date, a wide range of climate change adaptation measures has been tested, applied and advocated in the North Atlantic region, which also encompasses the UK. These have tended to focus on capacity building within the sector, policy measures, building resilience through a reduction in other stressors, developing alternative markets or livelihoods and protecting critical infrastructure used by the fishing industry (Peck and Pinnegar 2018).

In an Economics of Climate Resilience (ECR) report regarding "sea fisheries", the capacity of the UK fishing industry to adapt to the opportunities and threats associated with future climate change was judged to be relatively high thanks to strong commercial incentives and fishing vessel operators accustomed to constantly changing weather and fish stock sizes. However, small vessel operators were identified amongst those less equipped to adapt, and barriers pertaining to market failures, policy, consumer behavioural constraints, governance and communication have been identified (Defra 2013). Underlying many of these is the low salience of climate change in an industry focused on short-term issues (Marshall 2019).

Furthermore, despite the growing body of knowledge, there remain numerous uncertainties surrounding who, what and where will be impacted by climate change, and to what extent. Indeed, two interviewees have highlighted the need for everything ranging from fundamental research (e.g. vulnerability assessments and biological modelling) to the tools and processes that support it, from which adaptive measures can be determined.

The ultimate goal of adaptation strategies is to protect people and ecosystems from the changes that are brought by a changing climate. Traditional fisheries management tools, such as restrictions on allowable catch, landing size, seasonal closures, gear restrictions, marine protected areas, essential fish habitat protection, and protection of spawning aggregations, are and will remain necessary but may not be sufficient on their own to sustain fisheries in the face of the combined onslaught of climatic and non-climatic stressors in the future (Peck and Pinnegar 2018).

According to the World Aquaculture Society, the control required to respond to climate change relative to providing the projected demand for seafood protein principally resides in aquaculture rather than capture fisheries, an opinion shared by all three interviewees for this chapter (D'Abramo and Slater 2019). Current production systems will have to evolve, leading to new approaches to practices that are based on possible changes in behavioural and other physiological responses as abiotic and biotic conditions become subject to change and resources decline. Implementation of short-term technological solutions for production systems must still constructively fulfil the ever-present, underlying goal of minimising levels of risk.

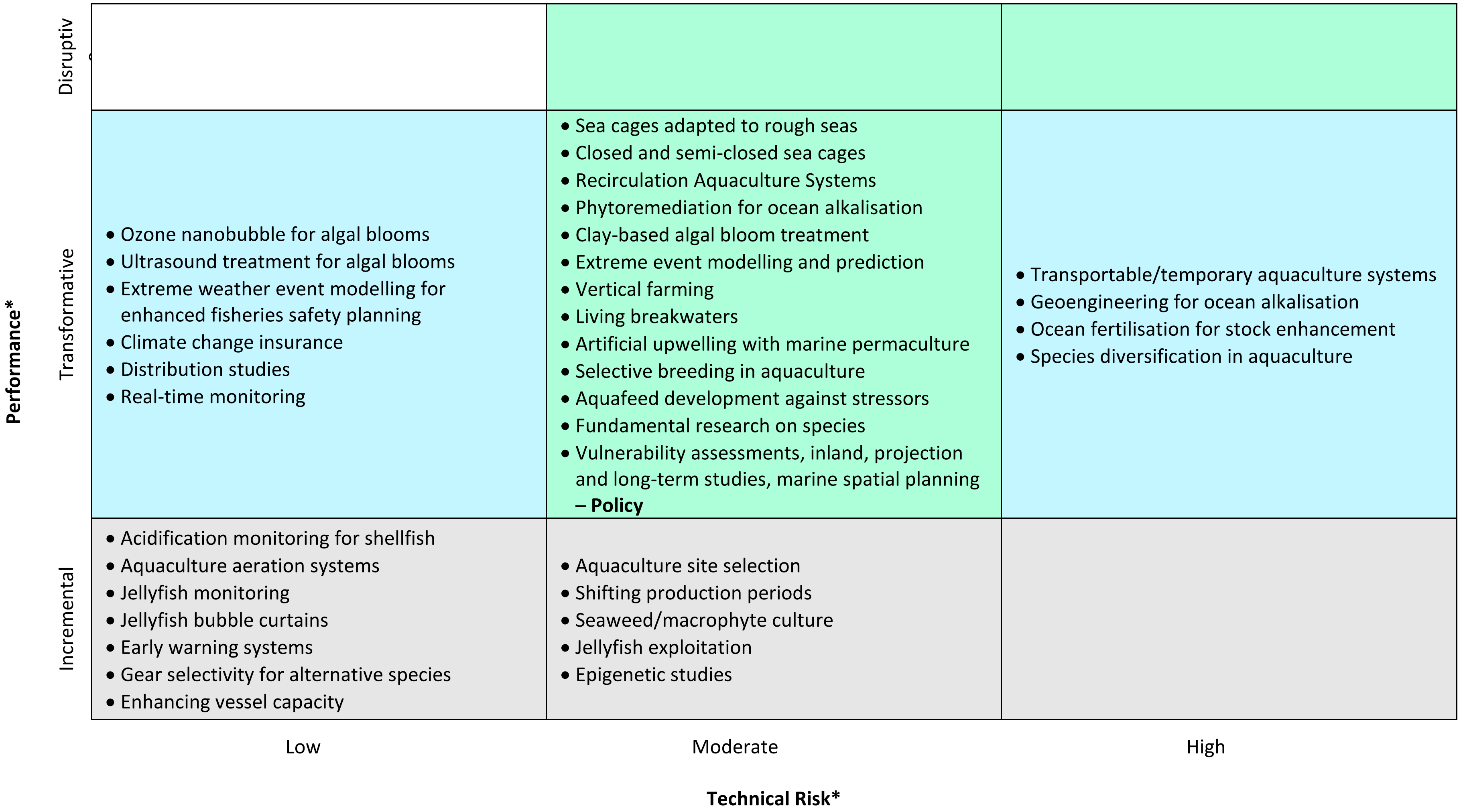
Definitions - For the sake of this chapter, the difference between resilience and adaptation will be addressed. According to the Inter-governmental Panel on Climate Change (IPCC), in natural systems, adaptation is “the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects”. On the other hand, resilience is “the capacity…to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure while also maintaining the capacity for adaptation, learning and transformation” (IPCC 2018).

Given the scope of the Seafood Innovation Fund for "disruptive innovations [that] should bring techniques, skills and processes that can improve on current practices and bring significant benefit to the sector," the following will be excluded from this chapter for either being out of scope and/or lacking novelty within the 2015-2020 timeframe:

- Non-climate stressors e.g. over-fishing, illegal, unreported and unregulated fishing (IUU), pollution, etc.
- Policy: adaptation plans, creating new or enhancing existing policies, and developing adaptive management strategies.
- Conservation and restoration.
- Ecosystem infrastructure and development.
- Stock management: Licenses and permits, management plans, quotas, fishery closures, etc.
- Livelihood security, including diversification.
- Outreach.
- Routes to market.

Additionally, entries covered in other chapters will be referred to the relevant chapter.

An overview of the potential performance improvement rating of recent (2015-2020) innovations in climate change adaptation in aquaculture and fisheries are outlined in Figure 25-1.



Performance*	Low	Moderate	High
Disruptive			
Transformative	• Ozone nanobubble for algal blooms • Ultrasound treatment for algal blooms • Extreme weather event modelling for enhanced fisheries safety planning • Climate change insurance • Distribution studies • Real-time monitoring	• Sea cages adapted to rough seas • Closed and semi-closed sea cages • Recirculation Aquaculture Systems • Phytoremediation for ocean alkalisation • Clay-based algal bloom treatment • Extreme event modelling and prediction • Vertical farming • Living breakwaters • Artificial upwelling with marine permaculture • Selective breeding in aquaculture • Aquafeed development against stressors • Fundamental research on species • Vulnerability assessments, inland, projection and long-term studies, marine spatial planning – **Policy**	• Transportable/temporary aquaculture systems • Geoengineering for ocean alkalisation • Ocean fertilisation for stock enhancement • Species diversification in aquaculture
Incremental	• Acidification monitoring for shellfish • Aquaculture aeration systems • Jellyfish monitoring • Jellyfish bubble curtains • Early warning systems • Gear selectivity for alternative species • Enhancing vessel capacity	• Aquaculture site selection • Shifting production periods • Seaweed/macrophyte culture • Jellyfish exploitation • Epigenetic studies	

Technical Risk*

Figure 26-1: Performance and technical risk rating of innovations in climate change adaptation.

**See section 4.4 for definitions of the performance and technical risk rating scales.*

26.2 Ocean and inland water warming

In the UK, sea temperatures vary regionally but have risen at an average of 0.8°C since 1870 and are projected to continue to increase (IPCC 2013; Frölicher, Fischer, and Gruber 2018; Government Office for Science 2017b). By 2100, sea surface temperature in the North Sea is projected to rise by 2.3–3.7°C, exceeding the global average of 0.6–2.0°C (IPCC 2013; Tinker *et al.* 2016). Furthermore, marine heat waves have become longer and more intense and are projected to increase, including in the large marine ecosystems (Frölicher, Fischer, and Gruber 2018).

A recent international study showed how subtle changes in the movement of marine species that prefer cold or warm-water in response to rising temperatures had significant implications. Namely, warm-water species increase, and cold-water species become less successful as temperatures rises. However, the study also suggests that some cold-water species will continue to thrive by seeking refuge in cooler, deeper water (Burrows *et al.* 2019).

In marine aquaculture, pens prevent fish from tracking thermally-suitable waters and fish maintained at sub-optimal temperatures experience poor growth and reproduction, resulting in lower yields. Inland freshwater production units will be subject to vagaries in the amount and quality of the freshwater resource (including flooding) as well as temperature extremes (D’Abramo and Slater 2019).

There has been significant innovation in the design of pen design to adapt to climate change-driven changes and the new locations being explored for aquaculture. Offshore and deeper waters in the marine environment are less susceptible to temperature and salinity extremes than in nearshore sites. Nonetheless, success in offshore aquaculture enterprise will require unique engineering applications to address the increased incidence of potentially catastrophic storm events (D’Abramo and Slater 2019).

There is significantly more R&D activity in pen design in Norway compared to the UK, largely due to development and commercial farming licenses awarded to innovations in the former (Financial Times 2017). Both countries also differ in their target sites. While Norway is exploring deeper, offshore environments, Scotland is considering more exposed sites than lochs that are removed from, but generally within a one-kilometre distance from the shore. While lessons can be learned from Norway as illustrated with some examples below, the differences are such that direct technology transfer may be unsuitable and require different fundamental modelling systems through to technological solutions, all of which are still underdeveloped.

Please note: the following solutions are applicable only in aquaculture

Innovations with a potential for transformative performance improvement

Sea cages adapted to rough seas: Several approaches are being explored to adapt sea cages for use in rough seas One solution for marine species would be a mechanism whereby sea cages could be lowered to deeper and cooler water during periods of extreme temperature. Norway Royal Salmon subsidiary Arctic Offshore Farming have constructed offshore pens primarily for the purpose of combatting sea lice but are semi-submersible into deeper waters and can withstand 13-metre waves in rough seas (Forbes 2020). Similarly, Norwegian fish farmer Nordlaks will commence operations in 2020 of the stationary, ship-shaped Havfarm 1 measuring 430m in length and with a capacity to accommodate up to 10,000 tonnes of salmon at a time (Ship Technology 2018).

Technology Readiness Level: 6-8, 9; Technical risk: Moderate

Closed and semi-closed sea cages: Closed, offshore farming solutions are being explored to control sea lice, escapes and improve waste management, especially in Norway where lucrative government development licenses are spurring innovation (Fish Farming Expert 2017). However, Norwegian salmon producer Mowi's revolutionary, closed "marine egg" concept has been hampered by spiralling development costs, and thus its future is currently under consideration. A smaller version is expected to be installed in spring, 2020 (Salmon Business 2019).

Technology Readiness Level: 6-8; Technical risk: Moderate

Please also refer to the section 'Tank and cage design' in chapter 10 'Production and handling technologies' and further pen innovations examples in chapter 5 'Environment and ecosystem monitoring and impacts'.

Recirculation Aquaculture Systems (RAS): These closed, land-based systems theoretically protect against most potential impacts of climate change and are potentially disruptive innovations. However, in this early stage, questions remain on animal welfare, and financial and energy costs to justify their adoption (personal communication).

Please also refer to the section on Recirculation Aquaculture Systems (RAS) in chapter 10 'Production and handling technologies'.

Technology Readiness Level: 9; Technical risk: Moderate

Transportable/temporary systems: D'Abramo and Slater state that the exploration of "emergency cooling sites" for short-term holding of animals during weather extremes is worthy of research. Intricate solutions that achieve water cooling in freshwater ponds or at nearshore sites would require large-scale investments and seem to be impractical and energy inefficient. However, such large-scale technical solutions may prove viable if used to overcome short-term extreme events (D'Abramo and Slater 2019). Norwegian fish farmer Nordlaks has plans for a mobile "Dynamic Ocean Farm" that will rely on dynamic positioning and propulsion systems to move between areas depending on the season, weather and wind, environmental conditions or user interests (Nordlaks 2019).

Technology Readiness Level: 6-8; Technical risk: High

Innovations with a potential for incremental performance improvement

Modelling to inform aquaculture site selection: Marked poleward movement of site selection for salmonid farming, particularly for new development in Chile and Norway, indicates that marine aquaculture producers are already heeding predicted polar shifts for marine species in response to increases in water temperature (Perry *et al.* 2005). This strategy is considered risky as temperature shifts can be less predictable than expected and underscores the need for specialist research dedicated to future optimisation of aquaculture site selection (D'Abramo and Slater 2019).

There is increasing interest by industry and academia to move aquaculture into the offshore environment, but one expert highlighted significant knowledge gaps in climate change impacts on these particular ecosystems, as well as the health and welfare of fish reared there (personal communication). Furthermore, the current regulatory landscape is likely to restrict expansion offshore.

The focus at present of site selection for Atlantic salmon in Scotland is in the lateral movement of pens to more exposed offshore sites, rather than northward. Motivations for this trend are to increase carrying capacity, and as a response to public protest. However, licensing and regulations are a major bottleneck for furthering site selection. In the case of Atlantic salmon in Scotland, hydrodynamic modelling is used to optimise site connectivity, as well as waste and disease management.

Technology Readiness Level: 9; Technical risk: Moderate

Shifting production periods: For aquaculture species with production periods of 12 months or more, the option to shift production periods is not feasible, and if sites are to be maintained, then technological solutions must be developed to maintain production during periods of adverse temperatures. For species with a short production cycle, a seasonal change in the production period may offer opportunity to produce animals before temperature extremes become limiting. This shifting requires complementary research to develop methods to reliably produce or collect larvae, spat, or fingerlings when they are commonly unavailable so that challenges posed by stocking under different grow-out conditions are overcome (D'Abramo and Slater 2019).

Technology Readiness Level: 3-5; Technical risk: Moderate

26.3 Acidification and alkalisation

Ocean acidification occurs as some of the excess carbon dioxide (CO_2) in the atmosphere dissolves in sea water, lowering the pH. This is intensified in colder waters, in which CO_2 is more soluble. Based on a medium emissions scenario, the change in global pH by 2100 is expected to be similar to changes that are thought to have caused widespread extinctions of marine animals 56 million years ago (Government Office for Science 2017a). Locally, acidification has been occurring faster in UK seas than in the wider North Atlantic (MCCIP 2017). Local pH variability is driven by factors such as circulation and freshwater input, and is more pronounced in coastal areas.

Conversely, in inland aquaculture systems, the rising atmospheric CO_2 concentration is increasing the solubility of limestone, calcium silicate, and feldspars, resulting in greater total alkalinity concentration in inland waters. However, it is argued that changes in water quality will be small as dominant factors affecting pH and alkalinity are fluctuations in CO_2 concentration by photosynthesis, release of CO_2 by respiration, acidity resulting from feed waste and fertiliser, and application of liming materials to ponds (Somridhivej and Boyd 2017).

Most of the following innovations fall under the category of geoengineering, which is defined as "the deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change," and are covered in a new report published by the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP 2019). However, marine and social scientists are urging a precautionary approach towards these techniques, calling for a co-ordinated framework for proposing and assessing marine geoengineering (IMO 2019).

It is likely that the first applications of alkalinity addition would be local and coastal because this would be logistically much simpler to achieve, and because of the desire to alleviate the stress on coastal resources affected by ocean acidification e.g. shellfish/corals (Albright *et al.* 2016). In any case, the duration of deployment of enhanced ocean alkalinity would need to be continuous if sustained carbon dioxide removal and/or ocean acidification mitigation are required.

26.3.1 Enhancing ocean alkalinity

Increasing alkalinity into seawater can be useful in helping counter seawater acidity such as that generated by excess CO_2, in addition to increasing CO_2 uptake and storage by the ocean. Enhanced ocean alkalinity also raises the carbonate saturation state of the oceans, which can help reverse the effects of ocean acidification, in particular countering its effects on calcifying organisms (e.g. corals and shellfish) that are central to marine biodiversity (GESAMP 2019).

Because more than 90% of the Earth’s crust is composed of alkaline minerals, determining cost-effective and safe ways of accelerating natural weathering and alkalinity generation could therefore play a major role in reducing ocean acidity on human time scales. However, such solutions should be considered high risk due to the large-scale manipulation of biogeochemical cycles, limited understanding and legal barriers they are likely to encounter.

Innovations with a potential for transformative performance improvement

Geoengineering for ocean alkalisation: Below are examples of topics currently being explored in this area.

Ocean liming - Calcination of limestone to produce lime (calcium oxide - CaO) or portlandite (calcium hydroxide - $Ca(OH)_2$) bypasses the slow dissolution rate of natural carbonate minerals (Renforth and Henderson 2017). Lime readily dissolves in the ocean and consumes ocean and air CO_2. The chemistry of this is well understood, but a major negative is the large energy and carbon footprint of conventional of conventional calcination (GESAMP 2019). A cost and energy-efficient method of liming using slaked lime produced from biogas was recently proposed (Caserini *et al.* 2019).

Electrochemical enhancement of carbonate and silicate mineral weathering - During the course of the electrolysis of saline solutions such as seawater to produce hydrogen, acids that are produced in these processes can be neutralised with carbonate or silicate minerals, which leaves un-neutralised OH-. As in the case of ocean liming, these dissolved mineral hydroxides are highly reactive with CO_2 and when exposed to air remove atmospheric CO_2, forming stable, bicarbonate-rich solutions. The air contacting and bicarbonate formation can occur away from the ocean or can occur after the hydroxide is added to the ocean. Limited experimental work has been conducted on this process (GESAMP 2019).

Coastal spreading of olivine - Olivine or other silicate mineral particles can be added to the surface ocean to effect CO_2 removal. An alternative to open ocean addition of olivine is its amendment within coastal and shelf environments where wave action and biological activity can accelerate dissolution (Montserrat *et al.* 2017).

Enhanced weathering of mine waste - Silicate and carbonate mine waste (already crushed into small particles) could be treated with microbes or spread over agricultural land to accelerate natural weathering process, and via downstream transport ultimately add to the surface ocean. Use of fine particulate mine waste avoids the extra energy and cost of mineral crushing/ grinding (Renforth and Henderson 2017).

Amending cropland soils with crushed reactive silicates - Soil pore waters are naturally corrosive, allowing in situ acceleration of dissolution kinetics and CO_2. Products of dissolution (including increased alkalinity of rainwater) are transported to the ocean via runoff, rivers and groundwater. Slow dissolution rates can facilitate further fertilisation of crops, both lowering levels the need for pesticides and potentially delivering better food security. Single column reactor experiments and several large-scale trials are taking place in the USA, Australia and Malaysian Borneo (GESAMP 2019).

Phytoremediation for shellfish - A study by a team of New England, USA researchers have demonstrated that primary production of sugar kelp can take up enough CO_2 to remediate local waters from ocean acidification, a process called “phytoremediation.” Preliminary results also suggest that shell strength of mussels and meat mass grown within kelp farms is significantly higher within this “halo” region (Island Institute 2018). Similar work has been conducted in Washington, USA for oysters and clams (Yale Climate Connections 2016).

Technology Readiness Level: 3-5; Technical risk: High

Please also refer to the section 25.9.2 on ‘Selective breeding’.

Acidification monitoring for shellfish: The Burke-o-lator is a monitoring system developed by Oregon State University professor Burke Hales that can measure multiple parameters of ocean acidification simultaneously for the shellfish industry. In addition to ocean pH, the device also measures the concentration of the mineral aragonite - a form of calcium carbonate that is critical to shell formation - as well as dissolved CO_2 gas and total carbon from non-organic sources. All these factors can affect shellfish growth. Depending on the result, hatcheries may delay oyster spawning or treat water with calcium or sodium carbonate (The Hakai Institute 2016).

Technology Readiness Level: 9; Technical risk: Low

26.4 Deoxygenation

Warmer waters (which hold less oxygen) and eutrophication have contributed to oxygen deficiency in areas of the North Sea over the last five decades. North Sea oxygen levels are expected to decline further over the next century, at rates faster than in other areas, such as the Atlantic and Pacific Oceans (MCCIP 2020). Within aquaculture, there have been some attempts to address this issue at a local level which we present here.

Innovations with a potential for incremental performance improvement

Aquaculture aeration systems: In salmon aquaculture, localised mitigation through aeration can create a more thermally-suitable water environment, with advantageous oxygen levels and the added benefit of reducing unwanted sea lice. Dutch company Bronkhorst provide the salmon industry aeration solutions with a line of remote-controlled, mass flow controllers and compressors that can be accurately timed for operation between feeds (Bronkhorst 2019).

Technology Readiness Level: 9; Technical risk: Low

Seaweed or macrophyte culture: A method to provide localised mitigation, these act as a net producer of oxygen, sequester carbon dioxide, and increase pH (Duarte *et al.* 2017).

Technology Readiness Level: 9; Technical risk: Moderate

26.5 Stratification and circulation

Prevailing winds interact with coastal topology and the earth's rotation to push surface waters offshore. These waters are then replaced with nutrient-rich deep waters (upwelled), making them some of the most productive of the world's marine ecosystems.

There is already evidence of the complex relationship between climate change and coastal upwelling, not just in terms of changes in upwelling strength, but also the timing and the geographical variability of upwelling processes. Increased sea temperature has contributed to declines in North Sea phytoplankton productivity, partly by reducing mixing of surface and bottom water layers, which stops nutrients in bottom waters reaching phytoplankton at the surface, restricting their growth and productivity. This is linked to declines in zooplankton and the fish species that predate on them, including cod, herring, haddock and sand eel, constraining fish availability (Wentworth and Stewart 2019). By 2100, climate change is also projected to reduce sea water circulation in the North Sea, causing it to become less saline and more vulnerable to eutrophication (excessive nutrient input), pollution and reduced oxygen content (Holt *et al.* 2018).

Coastal upwelling processes are poorly represented in the global climate models, and thus remains one of the larger sources of uncertainty in our knowledge of the impacts of climate change on global fisheries (FAO 2018).

Innovations with a potential for transformative performance improvement

Artificial upwelling with marine permaculture: Artificial upwelling has been suggested as a fertilisation measure by bringing deeper, nutrient-rich waters to the sunlit surface ocean, where they can stimulate phytoplankton growth and subsequently export organic carbon to depth. Artificial upwelling has also been discussed for enhancing fish production. A second effect of artificial upwelling is that upwelled deeper waters are generally colder than ambient surface waters, thereby cooling the ocean's surface and, eventually, the overlying air, thus helping counter global warming at least at local/regional scales. A number of short-term field experiments focused mainly on the technical feasibility of generating upward transport and on the supply of nutrients (GESAMP 2019).

Ocean artUp is an EU-funded research project[1] (2017-2021) exploring the potential benefits of artificially-induced uplift of nutrient-rich deep water to the ocean's sunlit surface layer. Specifically, it aims to study the feasibility, effectiveness, associated risks and potential side-effects of artificial upwelling in increasing ocean productivity, raising fish production, and enhancing oceanic CO_2 sequestration.

US-based non-profit Climate Foundation has developed a solution to restore natural upwelling and thus primary production and fisheries, particularly in dead zones. In the patent pending technology, storm-resistant platforms submerged at depths of 25m use wave and solar energy to pump nutrient-rich water upwards. Upwelled nutrients encourage plankton and kelp growth (the latter on the platform frames themselves), that will then attract other marine life. These are currently deployed in seaweed farms in the Philippines and the next phase is scaling up to 100ha offshore arrays (Climate Foundation n.d.).

Technology Readiness Level: 5-8; Technical risk: Moderate

Ocean fertilisation for stock enhancement: Proposals that large regions of offshore waters (such as eddies, ~100 km in diameter) be fertilised with nutrients such as iron, nitrogen and phosphorus to increase the areal extent for fisheries, in particular for pelagic species (GESAMP 2019). As a larger-scale version of practices commonly used in aquaculture, it is proposed that iron fertilisation will boost phytoplankton stocks in the upper ocean which will subsequently be consumed by larval and/or juvenile fish residing in surface waters of the iron-enriched region. While iron fertilisation was trialled in the North-East Pacific in 2012, ostensibly to enhance the salmon fishery, no peer-reviewed information is available on its potential impacts (GESAMP 2019).

Technology Readiness Level: 3-5; Technical risk: High

26.6 Weather and climate extremes

Weather and climate extremes (including droughts, floods, heavy precipitation events, heat waves, cold spells, tropical and extratropical storms, coastal sea level surges and ocean waves) are identified as major areas necessitating further research and have thus been

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[1] Ocean artUp: https://ocean-artup.eu/

selected as one of the World Climate Research Programme (WCRP) Grand Challenges (WCRP n.d.).

Despite limitations in modelling the location, frequency and intensity of storms, there is sufficient certainty for the IPCC to conclude that for the North Atlantic basin, where fisheries productivity is high, that the frequency of the most intense tropical storms has increased since the 1970s (IPCC 2013). For UK whitefish, pelagic and shellfish capture fisheries, storminess was identified as a priority risk (Garrett, Buckley, and Brown 2015).

Understanding how storms interact with fishery social-ecological systems can inform adaptive action and help reduce the vulnerability of those dependent on fisheries for life and livelihood (Sainsbury *et al.* 2018).

There are still significant gaps on climate change-related storm and flood forecasting, and vulnerability assessments are required to determine exposure, sensitivity and adaptive capacity of fleets and shoreside operations (personal communication; Marshall 2019).

26.6.1 Modelling of extreme events

Innovations with a potential for transformative performance improvement

Extreme event modelling and prediction: An international consortium of researchers has elaborated the scientific challenges related to elucidating large-scale drivers and local-to-regional feedback processes leading to extreme events. They argue a better understanding of the drivers and processes will improve the prediction of extremes and will support process-based evaluation of the representation of weather and climate extremes in climate model simulations. Challenges can be addressed by focusing on short-duration (less than three days) and long-duration (weeks to months) extreme events (Sillmann *et al.* 2017).

Technology Readiness Level: 3-5; Technical risk: Moderate

26.6.2 Fisheries

According to a Seafish/MCCIP report (Garrett, Buckley, and Brown 2015), proposed short-term adaptation responses for offshore fleets included keeping an industry-led watching brief on climate change and potential responses via horizon scanning and learning from others. In the long-term, a review of fishing seasons and assessment of vulnerabilities across the EU were suggested for government and researchers, respectively.

Innovations with a potential for transformative performance improvement

Extreme weather event modelling for enhanced fisheries safety planning: One Canadian study investigated the underlying relationships between extreme weather events and fishing safety and how the spatial distribution of fishing incidents may change due to climate change effects in Atlantic Canada. A mathematical model based on historical data was run using storm projections from 2081-2099. Results indicated that the exposure of fishing vessels to strong storms might decrease over time due to advances in weather forecasting technology and potential improvements in fishing safety practices. The potential for significant interannual variability of risk levels is especially important in short-term and tactical planning, such as search and rescue resource allocation. Information on the hot spots of incidents may enhance preparedness to improve safety and lower search and rescue costs (Rezaee *et al.* 2016).

Technology Readiness Level: 6-8; Technical risk: Low

26.6.3 Aquaculture

For aquaculture, adaptation to weather and climate extremes is focused on determining the feasibility and resilience of co-cultures or integrated multi-trophic aquaculture (IMTA) systems and on the use of certain species can favourably protect others from environmental extremes (D'Abramo and Slater 2019).

Innovations with a potential for transformative performance improvement

Vertical farming: Also known as 3D ocean farming, it consists of horizontal ropes on the water's surface, anchored to hurricane-proof floats, that connect to lines underwater supporting seaweed crops and interspersed with hanging net enclosures to grow scallops and mussels. Clam and oyster cages, also connected to the surface ropes, sit on the seafloor. Thimble Island Ocean Farm, which occupies 40 acres of the Long Island Sound, Canada, raises two types of seaweed, mussels, oysters and scallops. The farm provides significant non-edible benefits as well: it serves as a storm-surge protector and as a habitat for marine wildlife (TED 2017)**.**

Technology Readiness Level: 9; Technical risk: Moderate

Living breakwaters: In some cases, aquaculture itself may be used as a means to achieve storm resilience. In 2013, following Superstorm Sandy, the U.S. government launched the Rebuild by Design (RBD) competition to promote a design-led approach to proactive planning for long-term resilience and climate change adaptation. One of the winning proposals was the Staten Island Living Breakwaters Project, which proposed a layered resiliency approach to promote risk reduction through erosion prevention, wave energy attenuation, and enhancement of ecosystems and social resiliency. Included in ecological enhancement was the restoration of commercial oyster reefs and fish and shellfish habitat and particularly rocky / hard structured habitat that can function much like oyster reefs. Construction for the $60 million project is scheduled to commence mid-2020 (New York State 2020).

Please also refer to chapter 10 ‘Production and handling technologies’.

Technology Readiness Level: 6-8; Technical risk: Moderate

Climate change insurance: Pilot aquaculture insurance programmes provide examples of policy and practice to enhance national adaptation. Insuring small-scale farms, which are particularly vulnerable, can be included in social security policies to help farmers recover quickly from disasters and relieve the strain on government budgets (Barange 2018). Lessons from pilot programmes in China and Viet Nam include: 1) insurance schemes can be tailored to farmers’ circumstances; 2) farmers can improve their perception of risks, leading to faster adoption of climate-smart management practices; 3) with government support insurers have devised mutually beneficial schemes with farmer organisations that make aquaculture insurance a viable and sustainable business; and 4) government has backed political decisions with policy, institutional and financial support (Pongthanapanich, Nguyen, and Xinhua 2016).

However, the business viability of aquaculture insurance depends on aquaculture becoming more efficient and lower risk. In a recent letter to *Nature Climate Change*, the authors cautioned that policy-makers cannot rely solely on climate risk insurance in their climate adaptation plans, but that these must be complemented by adaptation actions in coastal ecosystems, such as establishing pre-storm preparation plans and investment in less vulnerable fishing boats and gear (Sainsbury *et al.* 2019).

Technology Readiness Level: 6-8; Technical risk: Low

26.7 Harmful algal blooms

Harmful algal blooms (HAB) occur when algae produce toxic or harmful effects on people, fish, shellfish, marine mammals, birds, or other aquatic organisms. Blooms occur in marine and freshwater environments throughout the world, with damaging ecological, social, and economic effects. Warmer water, higher carbon dioxide levels, changes in salinity and rainfall, sea level rise and coastal upwelling – all predicted impacts of climate change – can lead to higher incidence of HAB events (US EPA 2013).

26.7.1 Marine algal blooms

Innovations with a potential for transformative performance improvement

Clay treatment: After being scrapped in the early 2000s due to public protest, the Woods Hole Oceanographic Institution in the USA is reinstating research on the potential application of clay for the control of toxic red tide in Florida (Tampa Bay Times 2018). This time, the institution will draw on the expertise of Chinese researchers to develop a modified clay mineral that, when dispersed into the ocean surface, binds with red tide cells and the toxins they produce and carries them to the seafloor (Woods Hole Oceanographic Institution n.d.).

Technology Readiness Level: 6-8; Technical risk: Moderate

Please also refer to the section on sea pen aeration in relation to jellyfish.

Innovations with a potential for incremental performance improvement

Detection and early warning systems: Technologies come in a wide array of methodological bases and with a huge diversity of costs, usability, and downstream data products. A combination of these technological approaches, platforms and products are needed to meet recommendations set forth by national and international entities. Current existing and near-commercial technologies used for detection of biomass, taxa, or the toxins produced by HAB species include remote sensing, in situ sensing, image-based, molecular and chemical variations (Stauffer *et al.* 2019). French biotech company Microbia Environnement[1] has developed biosensor-based solutions to anticipate toxic microalgae blooms in brackish and sea waters, as early warning systems for optimised sustainable water management.

Please also refer to the 'ultrasound treatment' innovation below.

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[1] Microbia Environnement: https://www.microbia-environnement.com/en/services/early-warning-of-toxinogen-cyanobacteria-blooms/

Technology Readiness Level: 9; Technical risk: Low

26.7.2 Freshwater algal blooms

A global increase in algal bloom intensity in lakes has occurred over the past 40 years, according to a 2019 *Nature* study. Rising temperatures and increased nutrient input, like nitrogen and phosphorous, were suggested as the causes (Ho, Michalak, and Pahlevan 2019). Current treatment strategies involve the use of copper sulphate and aluminium sulphate.

Innovations with a potential for transformative performance improvement

Ozone nanobubbles: As an alternative an environmentally sustainable method has been developed to eliminate harmful freshwater algae and their toxins using nanobubble ozone technology (NCCOS 2018). Generators are placed in the water and release stable, ozone-filled nanobubbles that damage algal cell walls and break down toxins. Furthermore, ozone breaks down into oxygen and improves water quality by replenishing the oxygen stolen from animals by algae. Following successful pilot studies, Moeller has partnered with Green Water Solutions, LLC, a water purification company to scale up the technology to treat larger bodies of water (Environmental Health News 2020).

Technology Readiness Level: 6-8; Technical risk: Low

Ultrasound treatment: Dutch company LG Sonic offers ultrasonic algae control devices emitting specific ultrasonic parameters in order to control algae and biofouling in lakes, reservoirs, and industrial applications. Recently, satellite remote sensing has been employed for the detection and monitoring of the quality of larger surface water bodies at higher spatial and temporal coverages (LG Sonic 2016).

Technology Readiness Level: 9; Technical risk: Low

26.8 Jellyfish

At their poleward (southern) edge, some range-extending species may be considered pests, most notably jellyfish. Furthermore, a number of harmful viruses, bacteria and microalgae have caused significant economic harm globally in the last decade. Monitoring is currently inadequate to detect such pests until they become established. A more prepared industry, plus anticipatory monitoring based on the likelihood of an outbreak, could reduce risks.

Multiple human-driven impacts, such as ocean warming, over-fishing and eutrophication are regarded as interacting causal agents linked to recurring proliferations of jellyfish. In Scotland, fish farmers have developed strategies and cage designs to avoid or reduce jellyfish-related problems, such as sites for cages being kept out of tidal eddies or such, monitoring and warning systems, deploying mesh screens, suspending feeding, increasing oxygen by aeration, etc. (Scottish Government 2011). Below we present innovations to address increased jellyfish populations due to climate-driven changes.

For information on other types of pests, such as sea lice, please refer to chapter 9 'Pest and disease management'.

Innovations with a potential for incremental performance improvement

Sea pen aeration (air bubble curtains): The operating principle of bubble curtains is creating a bubble barrier that rises continuously from the bottom of the water to the surface. Sea pen aeration has been employed in Scotland and Chile to protect fish from swarms of jellyfish and algal blooms, respectively. Kaeser Compressors has developed a protoype compressor designed specifically for the harsh environments of the aquaculture industry (Food Processing Australia 2020).

Technology Readiness Level: Various; Technical risk: Low

Jellyfish monitoring: JellyX[1] is an advanced web mapping tool offered by AquaX for the large-scale monitoring of jellyfish swarms and their drift, based on oceanographic data provided by Copernicus Marine Service, to forecast outbreaks in order to activate loss minimisation strategies. In 2018, a team from the Technical University of Denmark applied for EU funding to develop an early warning system using a new underwater imaging system based on Time of Flight Laser cameras. The camera will be combined with a machine learning algorithm allowing autonomous early detection of jellyfish species (e.g. polyp, ephyra and planula stages). The outcome of the application remains unknown (Mariani 2018).

Technology Readiness Level: Various; Technical risk: Low

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[1] JellyX: https://www.aquaexploration.com/jellyx-demopage/

Jellyfish exploitation: An alternative strategy to addressing the challenge of jellyfish is to exploit them. The EU H2020-funded GoJelly[1] project is exploring new uses for jellyfish, such as in fish feeds, fertilisers, or as microplastic filters.as a food source. One Italian study, as part of the EU-funded programme CERES[2], found that jellyfish consumption attitudes were impacted by gender, age, and travelling habits. Individuals with the highest propensity to accept jellyfish as food are young people, familiar with the sea environment, with high education level or students, and frequent travellers. Food neophobia and sensitivity to disgust are confirmed as personality traits able to strongly impair the acceptability of a novel food (Torri *et al.* 2020).

Technology Readiness Level: 3-5; Technical risk: Moderate

26.9 Species-level adaptation and resilience

Climate change directly affects the distribution, abundance and health of wild fish stocks, and the viability of aquaculture processes and stocks. Findings that fish and other animals have already shifted into new marine territories (Pinsky *et al.* 2018) and of the complex biological and environmental criteria of farmed species such as Atlantic salmon (The Fish Site 2019) suggest that planning for new species or shoring up the resilience of existing species is prudent.

26.9.1 Fisheries

Innovations with a potential for incremental performance improvement

Gear selectivity for alternative species: As one of the key adaptation actions for the UK, DEFRA identified changing gear to fish for different species, if new or more profitable opportunities to fish different species are available, especially if these are not yet covered by EU quota restrictions (e.g. squid) (Defra 2013).

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[1] GoJelly project: https://gojelly.eu/

[2] CERES project: https://ceresproject.eu/

Please refer to the chapter: Gear Selectivity and Bycatch Reduction

Technology Readiness Level: Various; Technical risk: Low

Enhancing vessel capacity: Scaling up catch volumes should stocks of currently fished species increase, within quota allowances, was suggested in a DEFRA report (Defra 2013).

Technology Readiness Level: 9; Technical risk: Low

26.9.2 Aquaculture

Innovations with a potential for transformative performance improvement

New species selection: For situations where tolerances of potential genetic lines of a species are exceeded, the solution may reside in the farming of alternative species at existing production sites. Applied research that identifies most favourable alternative species to replace excluded species is needed. Where possible, production methods for economically viable alternative species should be fully researched and established before species shifts are put into effect (D'Abramo and Slater 2019). Please also refer to chapter 11 'Species diversification'.

Technology Readiness Level: Various; Technical risk: High

Selective breeding: Next-generation sequencing, genotyping, and phenotyping allow rapid identification of desirable traits for most cultured species. In contrast to selection for faster growth across all temperatures, few breeding programmes have explicitly selected for shifts in the optimal temperature for growth or in the whole distribution of an organism's thermal performance curve (TPC), and evidence is mixed that future selection for horizontal shifts in TPCs alone will be adequate to adapt to changing ambient water temperatures (Klinger, Levin, and Watson 2017).

A team from University of Stirling's Institute of Aquaculture (IoA), studied Sydney rock oysters in New South Wales and found that resilient strains of this oyster – generated through targeted breeding – can cope better with more acidic seawater conditions. Their research showed, for the first time, that oysters selectively bred for fast growth and disease resistance can alter their mechanisms of shell biomineralisation, promoting resilience to acidification (The Fish Site 2019). Please also refer to chapter 6 'Genetic improvement'.

Technology Readiness Level: Various; Technical risk: Moderate

Aquafeed development against stressors: There is an energetic cost for organisms acclimating under environmental or biological stressors. Diet quality and quantity have the potential to meet increasing energetic and nutritional demands associated with mitigating the effects of abiotic and biotic climate change stressors (Reid *et al.* 2019). Research efforts may be directed to determine whether formulations of manufactured aquafeeds can be developed to aid animals in overcoming physiological challenges posed by a changing climate (D'Abramo and Slater 2019). Dietary immunostimulants are being explored to enhance environmental protection under a changing climate (Wang *et al.* 2017). Please also refer to the chapter 8 'Nutrition and feeding'.

Technology Readiness Level: Unknown; Technical risk: Moderate

26.9.3 Species-specific research

Understanding the physiological responses of commercially important species to climate-driven changes is an important area to develop in order to provide the scientific basis for management strategies and climate adaptation-focused innovation activities.

Innovations with a potential for transformative performance improvement

Species-specific fundamental research: Below are examples of topics currently being explored in this area.

Atlantic salmon - Precise understanding of the thermal physiology of all major aquaculture species is essential to maintain growth and survival in warming seas. The optimal temperature range for Atlantic salmon (*Salmo salar*) is between 8 and 14°C. Increased temperature affects all forms of production parameters in the fresh water and sea water phases, including optimal dietary macronutrient composition, feeding regimes, as well as the frequency and type of bacterial, viral and parasitic outbreaks. Effects of salinity on growth and skin health are partly known for salmon, while effects on pH are less studied. Using data collected at farms along the coast of Norway, on the west coast of Scotland and along the Chilean coastline, EU-funded programme ClimeFish will develop, adapt and use biological forecasting models to secure future growth and production of Atlantic salmon until 2050 (ClimeFish n.d.).

Rainbow trout - In a case study conducted by the EU-funded programme CERES, it was found that temperature suitability for rainbow trout, according to optimal growing temperatures, will decrease for Southeast UK. Under four modelled scenarios, a best practice English trout farm with a 2016 profit margin of 11.55% was found not be profitable under the Global Sustainability scenario and would only just be profitable under the three other scenarios. Adaptation measures will increase operational costs (e.g. energy costs to increase aeration) and, if these measures are not sufficient or exceed profit, relocation of aquaculture with reduced local employment could be the consequence (CERES 2019).

Blue mussel - In the first large-scale examination of natural variation in biomineralisation in ecologically and economically important Atlantic mussel species *Mytilus edulis* and *M. trossulus*, researchers tested their ability to vary the production and composition of their calcareous shells. In lower salinity and cooler waters of higher latitudes, mussels produce thinner shells but with an increase in organic content, which helps protect the carbonate part of the shell from dissolution. Conversely, in lower latitude, warmer waters with higher salinity, the mussel shells have more calcified and thicker shells. While stronger, their shells will be particularly vulnerable as ocean waters become more acidic. These results are indicative of a compensatory mechanism, which can potentially provide a previously unexpected resilience in these species to global environmental change (Telesca *et al.* 2019).

Toxin elimination dynamics of shellfish - Findings from an EU-funded programme study indicate that increasing seawater temperature and acidification impact the accumulation/elimination dynamics of paralytic shellfish toxins in the mussel *Mytilus galloprovincialis*. Likely consequences were identified as lower toxicity values but longer toxic episodes. This study can be considered as the first step to build models for predicting shellfish toxicity under climate change scenarios (Braga *et al.* 2018).

Nephrops - The Norwegian lobster (*Nephrops norvegicus*) fishery is the most valuable crustacean fishery in Europe. Historic episodes of hypoxia on the west Swedish coast led to local extinctions, however these areas were repopulated from surrounding areas. Global changes are not forecasted to allow future repopulations. While invertebrate early life stages are generally considered to be more vulnerable to ocean acidification, there has been little research carried out on brooding species such as Nephrops where the parent is able to offer some regulation of the environment, nor of the ecologically relevant interactive effects with other climate change linked abiotic factors (Wood, Styf, and Eriksson 2014).

Tilapia - Single sex populations, especially all-male, have long been favourable for tilapia producers, as their culture results in higher and more uniform growth rates. Monosex is customarily achieved through hormonal treatments, but evidence from Chinook salmon and tilapia studies suggests that the use of steroids and testosterone can impair immune function. With emerging diseases such as tilapia lake virus (TiLV) of growing concern, more natural interventions (genetic selection and temperature) implemented by hatcheries such as the Netherlands' Til-Aqua, may provide an edge in disease resilience (The Fish Site 2020).

Jellyfish - In 2015, the jellyfish species *Dipleurosoma typicum,* was identified as the cause of farmed Atlantic salmon die-outs in Norwegian waters. The jellyfish is often found in the North Atlantic and is thought to have a boreal-circumpolar range, but this was the first observation in Norwegian waters. This raises the question of how jellyfish populations will respond to climate change. There are key spots - such as Norwegian fjords - where jellyfish populations are drastically increasing. If companies can predict when and where a bloom is likely to strike, they can avoid operating farms there in the first place (Hakai Magazine 2018). See also section 26.8.

Technology Readiness Level: 3-5; Technical risk: Moderate

26.10 Assessments and other tools

Fundamental research identifying the vulnerabilities of fisheries and aquaculture to climate change-associated stressors is crucial for formulating adaptation strategies. All interviewees for this chapter confirmed significant knowledge gaps in research, and one cautioned against kneejerk adaptation measures without a sufficient evidence base. The following section covers examples of key tools and research themes under exploration.

Innovations with a potential for transformative performance improvement

Vulnerability assessments: A framework for evaluating climate impacts over a broad range of species with existing information. These methods combine the exposure of a species to a stressor and the sensitivity of species to the stressor. These two components are then combined to estimate overall vulnerability. Notable studies include a climate vulnerability assessment on 82 fish and invertebrate species in the Northeast U.S. Shelf including exploited, forage, and protected species (Hare *et al.* 2016).

Technology Readiness Level: 9; Technical risk: Moderate

Trait-based climate vulnerability assessments: Assessments based on expert evaluation considering how the biological traits underlying sensitivity and adaptive capacity influence the response to climate exposure have emerged as a rapid tool to assess biological vulnerability, when it may be infeasible to develop detailed correlative and mechanistic analyses for all relevant species within an ecosystem. This approach was used to determine the vulnerability of 36 fish and invertebrate stocks in the eastern Bering Sea (Spencer *et al.* 2019).

Technology Readiness Level: 6-8; Technical risk: Moderate

Global inland finfish, fisheries and aquaculture assessment framework: To date, there are few comprehensive assessments of how climate change affects inland species and sectors globally compared to their marine counterparts. In order to help guide decision making and funding priorities, an international panel of researchers have identified key gaps in the knowledge including tolerances of inland fisheries to changes in temperature, stream flows, salinity, etc., and the adaptive capacity of fishes and fisheries to adjust to these changes (Paukert *et al.* 2017).

Technology Readiness Level: 3-5; Technical risk: Moderate

Long-term environmental monitoring studies: Critical to the development of responsive management strategies, gaps in the knowledge persist. An example is the assessment of long-term changes in alkalinity of inland waters (Somridhivej and Boyd 2017).

Technology Readiness Level: 9; Technical risk: Moderate

Marine spatial planning (MSP): The complex nature of temperature and precipitation shifts under global warming scenarios highlight the importance of enhanced interaction with marine spatial planning and modelling. Planning for offshore aquaculture (> ~20 m depth) represents a prime opportunity for MSP. Optimal siting of offshore aquaculture is a complex MSP problem requiring comprehensive (balancing existing and emerging sector objectives), co-ordinated (planning multiple emerging sectors simultaneously), and strategic planning (optimised using an analytically defined objective function that explicitly considers the objectives) across the seascape (Lester *et al.* 2018). Furthermore, spatial plans for aquaculture continue to ignore decadal climate variability, with strong impact on profitability both temporally and spatially (Sainz *et al.* 2019). Please also refer to chapter 16 ‘Habitat, environment and ecosystem impact’.

Technology Readiness Level: 6-8; Technical risk: Moderate

Changing stock distribution: Findings that fish and other animals have already shifted into new marine territories (at times across national and other political boundaries) at a rate averaging 70 km per decade, and with such shifts expected to continue or accelerate, point to the potential for conflict over newly shared resources. Local, national, regional, and international fisheries are substantially underprepared for geographic shifts in marine animals driven by climate change over the coming decades, and thus will require further preparations in ocean governance (Pinsky *et al.* 2018).

Technology Readiness Level: 9; Technical risk: Low

Species distribution projections: Species distribution models (SDMs) are important tools to explore the effects of future global changes on biodiversity. One study employed the rarely used multi-model approach to assess biogeographic shifts at the global scale across 802 species of exploited fish and invertebrate species to assess global patterns of change in species richness, invasion, and extinction intensity in the world oceans. Averaged global hotspots of invasion and local extinction intensity were found to be robust and coincided with high levels of agreement (Jones and Cheung 2015). In a study of fish in the North Sea, generalised additive models (GAMs) trained on a rich species data set, coupled with climate projections predict that future distributions of demersal fish species over the next 50 years will be strongly constrained by availability of habitat of suitable depth. This will lead to pronounced changes in community structure, species interactions and commercial fisheries, unless individual acclimation or population-level evolutionary adaptations enable fish to tolerate warmer conditions or move to previously uninhabitable locations (Rutterford *et al.* 2015).

Technology Readiness Level: 9; Technical risk: Moderate

Real-time monitoring: Real-time information can alert farmers to the presence of deleterious conditions that may not be obvious until the onset of behavioural or clinical symptoms in the stock. Monitoring is routine for parameters such as oxygen and temperature in many aquaculture sectors, but in the USA, capacity can be increased with near real-time water quality data through ocean condition monitoring networks (e.g. Integrated Ocean Observing System) (Reid *et al.* 2019). For species where, observation of the onset of environmental stress is difficult e.g. shellfish, microsensor technology is being explored. Researchers in Australia have trialled this technology to monitor shellfish heart rates, as a means to assess real-time response to environmental or biological stressors (Hellicar *et al.* 2015).

Please also refer to the sections on HAB and jellyfish

Technology Readiness Level: 3-5; 9; Technical risk: Low

Innovations with a potential for incremental performance improvement

Epigenetics: The epigenetic response potential of fish and marine suggests some level of adaptive capacity to climate change, but there are significant knowledge gaps, especially with regards to acidity. Plastic responses in aquaculture, particularly in early life stages, suggest that greater environmental control during early rearing may help direct adaptive epigenetic responses. Hatcheries are already well positioned to use this strategy (Reid *et al.* 2019).

In capture fisheries, epigenetic mechanisms may be particularly important for the evolutionary potential of “K-strategist” species with long maturation times and low reproductive potential, particularly when faced with rapidly changing environmental conditions. Researchers studying the winter skate (*Leucoraja ocellata*) in Atlantic Canada have discovered that the population has been able to adapt to a 10°C higher water temperature over short evolutionary time (7,000 years), dramatically reducing its body size (by 45%) and other adaptations in life history and physiology. An epigenetic basis for these adaptations was demonstrated and it was argued can enable survival and adaptation of K-strategist species to different environments in light of future climate change (Lighten et al. 2016).

Technology Readiness Level: 3-5; Technical risk: Moderate

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27 Climate change mitigation

Contents

From the SIF Executive Board

The method applied in this review has generated numerous examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently happening. It is recognised that there are existing innovations and research areas that are not included here, and new areas where future innovations may occur. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

27.1 Overview: climate change mitigation

What is the challenge in the UK?

The UK seafood sector is responsible for nationally significant emissions of greenhouse gases, primarily through fuel consumption in fishing activities or through feed usage in aquaculture. Fuel consumption and feed usage also represent major variable costs in a sector where profit margins are often tight. There is therefore an urgent environmental and economic necessity to develop technologies and approaches for climate change mitigation for the UK seafood sector.

What are the most promising innovation categories?

- Carbon dioxide conversion for feed production.
- Integrated farming of seaweed and shellfish.
- Use of IoT technology and big data analytics for aquaculture.

Where are their important knowledge gaps?

- Centralised collection of granular fuel consumption data for fishing activities.
- Approaches to reducing consumer waste of seafood.
- Standardised and efficient methods for estimating the carbon footprint of seafood products

Note: This chapter discusses the greenhouse gas emissions resulting from fishing and aquaculture activities and presents innovations that can support a climate change mitigation approach. For discussion of the impacts of climate change on fishing and aquaculture activities, please refer to chapter 25 on ‘Climate change adaptation’.

Climate change mitigation is a human intervention to reduce the sources or enhance the sinks of greenhouse gases (United Nations 2014). Global wild catch fisheries consumed 40 billion litres of fuel in 2011 and generated a total of 179 million tonnes of CO_2 emissions (Parker et al. 2018). Aquaculture activities are also linked to significant Greenhouse Gas (GHG) emissions, primarily through the production of feed.

In 2019 the UK Government enacted a legally binding target to achieve net zero greenhouse gas emissions by 2050 (Department for Business, Energy & Industrial Strategy 2019). One of the first examples of how this target is influencing UK industrial policy is in the draft of the Fisheries Bill (Lord Gardiner of Kimble 2020), which contains a ‘climate change objective’. The objective states that the UK must ensure that “the adverse effect of fish and aquaculture activities on climate change is minimised, and fish and aquaculture activities adapt to climate change.” Once passed, the Fisheries Bill will create the legal foundation for ‘climate-smart’ fishing and aquaculture policy in the UK.

The concept of ‘climate-smart’ food production systems originates in agriculture and suggests that attention should be given to the development of food production systems that help to reduce or remove greenhouse gas emissions, help build resilience to future climate-driven changes, and have potential for increased productivity and income generation (FAO n.d.). Some seafood production systems will be naturally closer to meeting these requirements that others. The small pelagic fisheries of the UK have been identified as potential climate smart source of seafood products (Sandison 2015). Other products, such as farmed mussels may be low impact in terms of greenhouse gas emissions but may be more susceptible to future climate-driven changes, such as increasing ocean acidity (see the ‘Climate change adaptation’ chapter for further discussion of resilience to climate-driven changes). Many of the current seafood products produced in the UK will require changes to the way they are fished/farmed, processed and transported to make them more ‘climate smart’.

A key part of developing more climate smart seafood products is to identify the current ‘hotspots’ - the phases of the product lifecycle and specific activities that are dominant in terms of a product’s total GHG emissions. Whilst the hotspots will vary from product to product, from fishery to fishery and from farm to farm, analysis of a number of life cycle assessment studies reveals some typical patterns, which are presented in Table 27-1.

From Table 27-1 it can be seen that for wild-capture products, the fishing activity is a hotspot for GHG emissions. The cost of fuel is a major contributor to costs meaning that the industry is sensitive to price fluctuations. For instance, the average fuel price increased has increased from 34 pence per litre in 2016 to 50 pence per litre in 2018. The fleet expenditure on fuel has increased accordingly from £95 million in 2016 to £136 million in 2018 - representing 18% of total income in that year (Seafish 2018). Fuel-intensive fishing gears, such as beam trawlers are particularly vulnerable to rising fuel prices. In 2018, fuel costs accounted for 48% of income North Sea beam trawlers over 300 kW whilst overall operating costs were 110% of total income in this fishery (Ibid). There is therefore an urgent need to identify ways to reduce fuel consumption, both as a climate change mitigation strategy and to ensure the economic sustainability of many UK fisheries.

Table 27-1: Typical GHG emissions hotspots for wild-capture and aquaculture products. Key: +++ Major source of GHG emissions, ++ Moderate source, + Minor source.

	Wild-capture	**Aquaculture**
Primary production	+++ Fuel consumption +/++Leakage of refrigerants + Fishing gear and vessel production	+++ Feed production + Well boat/service boat activities
Processing	+ Processing yield + Additional ingredients (where applicable) + Packaging	
Transport	+++ Air freight (where applicable)	
Customer	++ Waste	

For aquaculture, feed production is the major hotspot for GHG emissions and is also the main variable cost, contributing around 46% of total production costs for Scottish salmon according to one source (Shepherd, Monroig, and Tocher 2017). This has driven innovation in the industry to improve feed conversion ratio and identify lower cost ingredients whilst still maintaining productivity and the nutritional quality of the final product, particularly in terms of Omega-3 content. Identifying feed ingredients that meet these existing challenges that also have a lower impact in terms of GHG emissions is therefore very difficult.

For both wild-capture and aquaculture products transportation can be a major hotspot, particularly when air freight is used. This is often the case when transporting live crustaceans to Asian markets, which is a significant market for UK shellfish producers.

This chapter presents a range of innovations that help to reduce the GHG emissions associated with fuel consumption and feed production as well as the other significant contributors identified in Table 1.

Three significant knowledge gaps relevant to climate change mitigation were identified through interviews with experts. The first is the lack of a standardised methodology and accompanying tools for performing rapid carbon footprints of seafood products. Whilst it was noted that

Seafish and Dalhousie University developed the 'Seafood CO_2 Emissions Profiling Tool'[1] some years ago, this tool was intended a pilot to assess the engagement from industry stakeholders. One expert interviewed proposed that a standardised methodology for the carbon footprinting of seafood products should be developed through engagement with industry stakeholders and should then be formalised within a tool that could be made available for use by industry. Such an approach has proven successful in the agriculture sector in which the Cool Farm Tool[2] has been developed through an alliance of major producers, retailers and experts.

The second knowledge gap is the lack of granular fuel consumption data available for fishing activities. Some data is available in terms of annual fuel consumption and these data are used at a macro-economic level to understand the cost structures competitiveness of fisheries. Several studies have identified that there are significant variations in fuel consumption per tonne of catch between fisheries and between vessels in the same fishery – with up to 40% differences in some cases. This suggests there is significant scope for improvement – by raising all fisheries and vessels up to the level of best practice. However, the data available does not have sufficient granularity to understand and explain the variability between fisheries and vessels.

The third knowledge gap concerns the difficulty in engaging consumers in behaviours that support seafood waste reduction. It is estimated that 40-47% of the edible U.S. seafood supply goes uneaten, with over half of this waste attributed to consumer behaviour (Love et al. 2015). Innovations to reduce consumer waste of seafood would therefore appear to have significant potential as a climate change mitigation strategy.

As a final point, it must be recognised that climate change mitigation is just one aspect of the overall sustainability performance of the UK seafood. Other dimensions of sustainability performance may be equally important or more important depending on the nature of the product. For further discussion of the sustainability impacts of wild-capture fisheries, please see the chapter 16 on 'Habitat, environment and ecosystem impacts'. An overview of the

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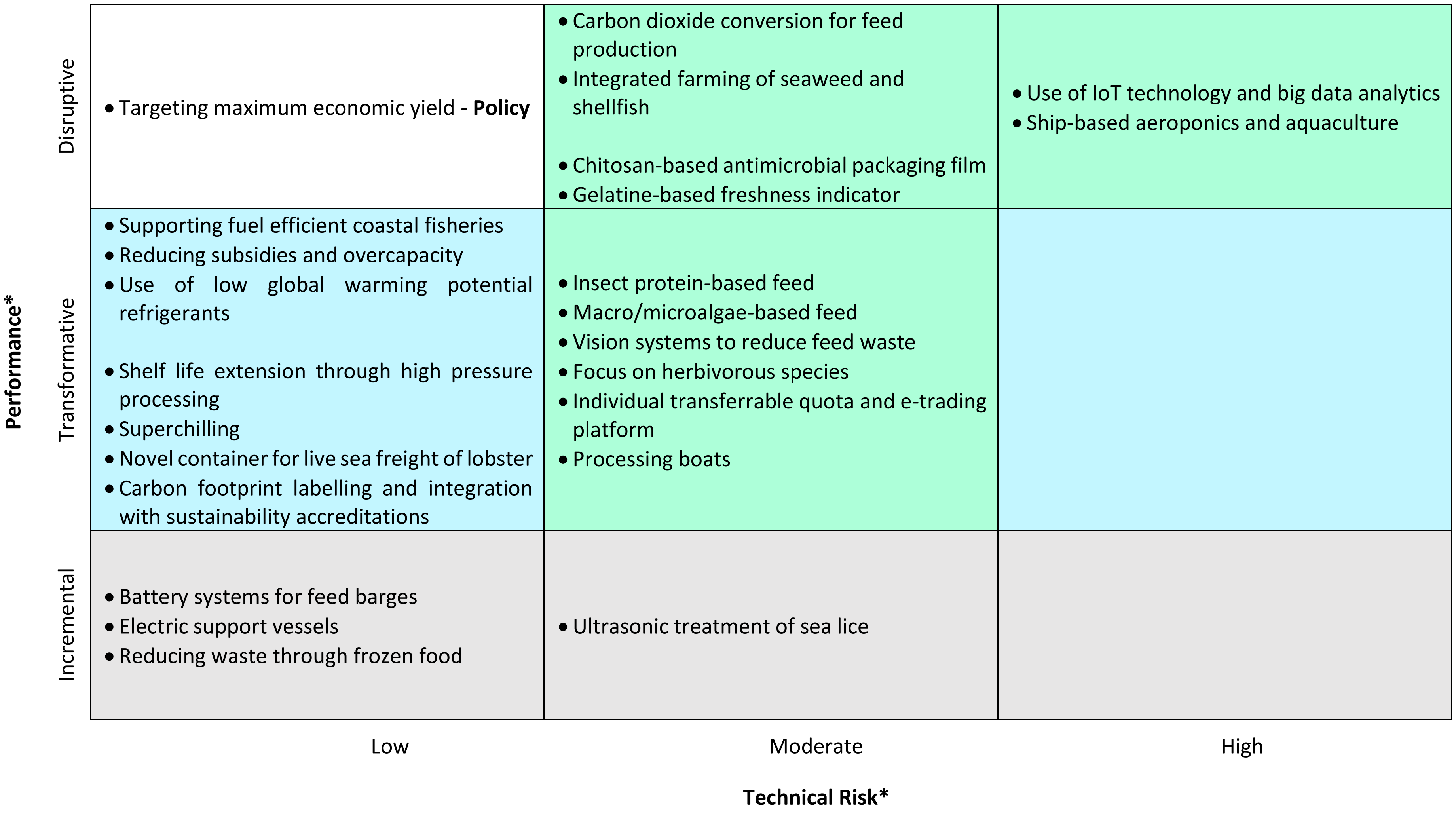
[1] Seafood CO_2 Emissions Profiling Tool: https://www.seafish.org/article/seafood-co2-emissions-profiling-tool

[2] Cool Farm Tool: https://coolfarmtool.org/

potential performance improvement rating of recent (2015-2019) innovations in climate change mitigation technologies are outlined in Figure 26-1.



Performance*	Low	Moderate	High
Disruptive	• Targeting maximum economic yield - **Policy**	• Carbon dioxide conversion for feed production • Integrated farming of seaweed and shellfish • Chitosan-based antimicrobial packaging film • Gelatine-based freshness indicator	• Use of IoT technology and big data analytics • Ship-based aeroponics and aquaculture
Transformative	• Supporting fuel efficient coastal fisheries • Reducing subsidies and overcapacity • Use of low global warming potential refrigerants • Shelf life extension through high pressure processing • Superchilling • Novel container for live sea freight of lobster • Carbon footprint labelling and integration with sustainability accreditations	• Insect protein-based feed • Macro/microalgae-based feed • Vision systems to reduce feed waste • Focus on herbivorous species • Individual transferrable quota and e-trading platform • Processing boats	
Incremental	• Battery systems for feed barges • Electric support vessels • Reducing waste through frozen food	• Ultrasonic treatment of sea lice	

Technical Risk*

Figure 27-1: Performance and technical risk rating of innovations in climate change mitigation.

**See section 4.4 for definitions of the performance and technical risk rating scales.*

27.2 Primary production: aquaculture

In aquaculture, the main source of GHG emissions associated with the primary production of carnivorous fish species is the feed. For example, a comprehensive study of Norwegian salmon farming found that 75-83% of the GHG emissions from salmon delivered to the wholesaler were due to the feed (Winther et al. 2020). The breakdown of the emissions reveals that GHG emissions associated with the soya protein concentrate content of the feed were over three times higher than that of the fishmeal content, despite making similar contributions to the mass of the feed (21% soya protein, 17% fishmeal). The disproportionate impact of soya protein concentrate was mainly due to the impact of land use change, whereby mature forests in Brazil are cleared for soya bean production. So whilst the salmon farming industry has been under pressure to reduce the use of fish meal and fish oil in salmon feed – and has made significant progress against this objective (Salmon Facts 2016) – the unintended consequence may well have been an increase in the carbon footprint of farmed salmon due to increased use of soya protein.

The main focus of this section is therefore on reducing the GHG emissions associated with aquaculture feeds. General innovations in aquaculture feed are discussed in chapter 8 'Nutrition and feeding'. Innovations to support reduced energy use and GHG emissions linked to aquaculture farm operations are also presented.

In the section, the focus is solely on innovations in relation to climate change mitigation and some of these are covered in greater extent in other chapters. Where this is the case, these chapters are referenced below e.g. for further innovation examples for different aquaculture feeds, please refer to the chapter: Nutrition and feeding.

Innovation with a potential for disruptive performance improvement

Carbon dioxide conversion for feed production: Kiverdi, a California-based company, have developed a protein-rich feed for aquaculture that they claim is 'nutritionally comparable to traditional fishmeal' and yet is produced from carbon dioxide, nitrogen, hydrogen, water and nutrients. The 'CO_2 aquafeed' uses single-cell organisms ('hydrogenotrophs') in a bioreactor, where these different elements are converted into biomass. The process is powered by renewable energy sources and the carbon dioxide used in the process can come from any industry source once it has been cleaned to food grade. Kiverdi has not released details of the carbon footprint of the feed or how it compares to traditional fishmeal and feed, but it does claim that production of CO_2 Aquafeed requires 10,000 times less land and 2,000 times less water compared to soya protein. The feed producer Skretting has pledged to invest $2 million in trials of CO_2 Aquafeed over the course of 2020 (The Fish Site 2019).

Technology Readiness Level: 6-8; Technical risk: Moderate

Use of IoT technology and big data analytics: Marine aquaculture operators are using an increasing range of sensors to capture data about water quality, feed requirements, and pen conditions to inform farm management operations. However, data collection activities still often require on-site operations involving staff and vessels. A number of initiatives are beginning to explore how ‘Internet of Things’ (IoT) technology and big data analytics could be used within aquaculture to improve the efficiency of data collection and inform better decision making. R3-IOT and Censis in Scotland are collaborating on the development of an energy-efficient, satellite-based IoT system that can be used for aquaculture management. The technology is still in development, but plans are being formulated for field trials in Scotland (Censis 2019). Meanwhile in New Zealand, a NZ$13 million collaborative research project led by Victoria University of Wellington is aiming to apply big data analytic methods to enable low-carbon aquaculture (Victoria University of Wellington 2020). The project will develop evolutionary and statistical learning techniques to optimise the farming of Greenshell™ mussels and finfish in open ocean farms.

Whilst the sensing and communication technologies that make up these platforms will actually increase direct energy consumption a small amount, the potential savings in terms of avoided service vehicle journeys, increased yield, reduced mortalities and increased feed conversion ratio should lead to significant overall reductions in GHG emissions.

Technology Readiness Level: 3-5; Technical risk: High

Integrated farming of seaweed and shellfish: GreenWave[1] in the USA have developed a ‘3D ocean farming’ model, based on integrated multi-trophic aquaculture principles, which involves growing kelp amongst vertically strung mussel socks, along with scallop, oyster and clam cages. The kelp absorbs carbon dioxide during photosynthesis, which helps to reduce the acidity of the surrounding water. This creates ideal growing conditions for the shellfish.

GreenWave have suggested that the system could be scaled up by having up to 50 farms located around a centralised processing facility. They estimate that the farming 5% of US

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[1] GreenWave: https://www.greenwave.org/

waters could sequester 135 million tonnes of carbon, along with 10 million tonnes of nitrogen whilst producing protein equivalent to 3 trillion cheeseburgers.

Technology Readiness Level: 9; Technical risk: Moderate

Innovation with a potential for transformative performance improvement

Insect protein-based feed: There has been considerable research and commercial interest in the potential of insect-based protein to support food production, either as a feed source or for direct human consumption. Whilst insect protein is generally viewed as an efficient approach to protein production, life cycle assessments have shown that the sustainability benefits of insect-based feeds are highly dependent on the feed source for the insects. Smetana et al (2016) found that feeding black soldier fly on ryemeal resulted in higher sustainability impacts (resource consumption, ecosystem impacts and human health) than fishmeal produced from fish processing waste. It was only in scenarios that employed waste streams (cattle manure, dried distillers' grains or municipal waste) that the insect protein showed reduced sustainability impacts. Similarly, Le Féon et al (2019) found that the carbon emissions of trout fed with a feed containing up to 30% mealworm as a replacement for fishmeal increased from 1.2 kg CO_2e per kg to 1.72 kg CO2e per kg. Insect protein should not therefore be seen automatically qualifying as a more sustainable alternative to fishmeal without evidence of the sustainability of the feed source and the lifecycle impacts.

There are at least two companies targeting large scale production of insect-based fish feeds. AgriProtein[1], based in South Africa, are producing ‘MagMeal’ and ‘MagOil’ products on a commercial scale using black soldier fly larvae fed on food waste. The company is expanding into the North American market, with a 4,000 tonne per annum capacity facility for protein meal production being developed in California (IntraFish 2019).

Protix[2] are using black soldier fly, locusts, crickets and mealworm ingredients to produce a range of feeds for fish and poultry. The fish feed is not available to buy directly but is currently

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[1] AgriProtein: https://agriprotein.com/

[2] Protix: https://protix.eu/

being used by a sister company, Friendly Fish[1], that is producing aquacultured salmon, trout and shrimp. For further examples, please refer to chapter 8 Nutrition and feeding.

Technology Readiness Level: 9; Technical risk: Moderate

Macro/microalgae-based feed: Various forms of seaweed have been studied as a low carbon footprint source of protein that is high in nutritional value, notably omega-3. There are already commercial suppliers of macroalgae-based animal feeds, such as Ocean Harvest Technology[2] based in Ireland. However, the natural concentrations of protein in seaweed are generally too low for direct use in carnivorous fish feed. Seghetta et al (2017) have overcome this challenge by first farming seaweed (Laminaria digitate) before drying it and performing a enzymatic hydrolysis stage to produce sugars (glucose and mannitol) which are then used in a bioreactor with micro algae Chlorella protothecoides. Through this process, 1000kg of seaweed results in 147kg of high-quality protein. The temporary sequestration of carbon from the growth phase of the seaweed results in a net carbon footprint of -1230 kg CO_2e per hectare of sea. An additional benefit is that the filtering effect of seaweed growth helps to reduce marine eutrophication. For further examples, please refer to the chapter 8 ‘Nutrition and feeding’.

Technology Readiness Level: 6-8; Technical risk: Moderate

Vision systems to reduce feed waste: One strategy to reduce the GHG emissions associated with aquaculture feed is to reduce feed waste. Whilst software models can often be used to estimate feed requirements, the appetite of fish can vary on day to day basis due to a variety of external (Zhou et al. 2018). This can lead to feed waste if a surplus of feed is delivered. To help prevent this, vision systems can be installed that monitor fish behaviour to track the movements in individual or groups of fish that indicate satiation. Machine learning techniques have been applied to enable automatic detection of fish satiation. When the majority of the population are displaying signs of satiation, the feed system can be stopped. A variety of vision systems are available that support fish satiation detection and can also be used for applications including fish counting, mass estimation, health and welfare monitoring, gender detection etc (Antonucci and Costa 2019).

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[1] Friendly Fish: https://friendlyfish.nl/

[2] Ocean Harvest Technology: https://www.oceanharvesttechnology.com/

Further examples of innovations to support feed waste reduction are presented in chapter 12 ‘Waste management and valorisation’.

Technology Readiness Level: 9; Technical risk: Moderate

Focus on herbivorous species: Increasing production of herbivorous specious of finfish and filter feeders has been proposed by the FAO as a climate change mitigation strategy that could help to reduce the GHG emissions linked to feed production for carnivorous species (FAO n.d.). In the UK, aquaculture of species such as carp and tilapia exists but in the case of carp is focused on restocking of angling ponds (Hambrey and Evans 2016) and in the case of tilapia is focused on fry production for export markets (The Fish Site 2017). For further discussion of the challenges and options for species diversification in the UK please refer to chapter 11 ‘Species diversification’.

Technology Readiness Level: 6-8; Technical risk: Moderate

Innovation with a potential for incremental performance improvement

Battery systems for feed barges: Whilst the production of feed is the primary source of carbon emissions, the feeding process can also make a non-negligible contribution. Feed barges for marine aquaculture often rely on diesel generators to provide power for feed distribution systems. These generators must be sized for peak power demand but often run at low power for most of the day – which is inefficient. To address this issue, Tesvolt have developed battery systems that are adapted to the demands of aquaculture. The system has a maximum output of 120 kW and is charged by running the diesel generators for three hours at their most efficient level. The system has been implemented by Kvarøy in Norway. There they claim that the system has led to a 60% reduction in diesel consumption, saving €150,000-200,000 over the course of an 18-month grow-out cycle. The system can be controlled from land and the reduced duty cycle of the diesel generators saves ten working days and €10,000 each year in generator maintenance.

Technology Readiness Level: 9; Technical risk: Low

Electric support vessels: With many marine aquaculture sites now located a significant distance from shore, the GHG emissions from support vessels to transport staff, feed and other supplies to the farm site can be significant. Norwegian company, Salmar Farming have introduced the world’s first electric support vessel into their farming operations. The 13.5-metre-long catamaran uses an electric motor and battery system developed by Siemens and is being used to make the 50-minute journey to their Kattholmen farm at a speed of 8.5 knots. It should be noted that the GHG emissions factor for the Norwegian electricity grid is very low at 0.011 kg CO_2e per kWh due to the very high proportion of renewable energy sources. The UK GHG emissions factor is 0.2773 kg CO_2e per kWh, some 25 times high than Norway, meaning that the climate change mitigation benefits of electric support vehicles would be less pronounced unless a low-carbon source of electricity is used to recharge the batteries. For further vessel related innovation examples, please refer to chapter 13 ‘Fishing effort and fuel consumption’.

Technology Readiness Level: 9; Technical risk: Low

Ultrasonic treatment of sea lice: In a study of Norwegian salmon farms conducted by Winther et al (2020), pest and disease management was found to contribute to GHG emissions in two ways. First, mortalities due to pests and diseases and delousing procedures resulted in reduced economic feed conversion ratio, and as feed production is the primary contributor to the overall carbon footprint of the finished product, this makes a noticeable difference. Secondly, operations related to pest and disease management, including operation of delousing equipment and use of service vessels to deliver medication, where found to have a small but not insignificant impact.

LiceSonic is an ongoing project that aims to develop a system to remove sea lice from farmed salmon by combining ultrasound technology with water quality and fish monitoring (LiceSonic n.d.).The project’s first feasibility study resulted in a reduction of 60% in attached sea lice to salmon. Different ultrasonic sound wave frequencies will be used to ensure that sea lice develop no resistance to the ultrasonic control method (World Fishing & Aquaculture 2018).

Further examples of innovations to support improved pest and disease management can be found in chapter 9 ‘Pest and disease management’.

Technology Readiness Level: 3-5; Technical risk: Moderate

27.3 Wild-capture fisheries

Fuel cost is often the largest variable cost in fishing (Ziegler and Hornborg 2014) and so reducing fuel consumption is a high priority for fishers as well as a necessity for climate change mitigation. Studies of fuel consumption in wild-capture fishing have noted that there are often significant variations between fisheries and gear types (Suuronen et al. 2012) and even between vessels utilising the same gear within the same fishery (Sandison 2015). This suggests that there are significant opportunities to reduce fuel consumption across and within fisheries. Technological measures to reduce fuel consumption include improved vessel design, improved fishing gear design, and more efficient engines. It has been noted that increased fishing pressure within a fishery will tend to lead to increased fuel consumption due to declines in abundance (Ziegler et al. 2013). There is therefore an important role for fisheries management policy in supporting reductions in fuel consumption.

A variety of innovations to directly enable reductions in fuel consumption for wild-capture fisheries are described in the 'Fishing effort and fuel consumption' chapter. This section therefore focuses on factors that contribute to the climate change impact of wild-capture fisheries but are not directly linked to fuel consumption, specifically fisheries management and use of refrigerants.

Innovation with a potential for disruptive performance improvement

Targeting maximum economic yield: Fisheries management policies in the EU have generally targeted the 'maximum sustainable yield' – the maximum level at which a stock can be exploited without long-term depletion. The 'maximum economic yield' refers to the level of catch maximises the profit per unit of landings – which is lower than the maximum sustainable yield. In a modelling study of the Tasmanian southern rock lobster fishery, a scenario of targeting maximum economic yield rather than maximum sustainable yield decreased the carbon footprint by 80% or 10 kg CO_2e per kg of lobster at capture (Farmery et al. 2014). Whilst there are no significant technical barriers to implementing maximum economic yield-based quota systems, the political and socio-economic barriers are likely to be significant due to the reduced fishing effort that would be necessary compared to the current situation.

Technology Readiness Level: 9; Technical risk: Low

Innovation with a potential for transformative performance improvement

Supporting fuel efficient coastal fisheries: Ocean in Balance is a Danish social enterprise focused on sustainable coastal fishing in the Skagerrak Sea. Ocean in Balance works with independent fishers and groups of fishers to enable them to purchase fuel efficient vessels equipped for low impact fishing methods (gillnets and Danish seine) that result in high-quality catches without damaging the rich ecosystem of this region (Ocean in Balance 2018). In 2017, the Danish Parliament enabled the transfer of fishing quotas from the open quota market into this type of protected small-scale and low-impact fishing scheme. The policy also provides for annual increases in quota for smaller vessels (under 15m length) using low impact gear.

Technology Readiness Level: 9; Technical risk: Low

Individual transferrable quota and E-trading platform: Historically**,** quota systems have often inadvertently led to significant discards as fishers try to maximise financial returns by discarding bycatch and low value specimens or are forced to discard catches due to landing restrictions imposed by the quota system. Discarded catches represent a significant waste of fuel as well as the obvious waste of fish. Individual transferrable quota systems aim to address some of these issues by allowing fishers to trade some or all of their quota with other fishers. In Sweden, an individual transferrable quota system has been implemented along with an e-trading platform, known as ‘FishRight’. The platform provides a simple, fast and transparent means to trade quota allocations between fishers and is accessible 24 hours per day through any Internet-enabled computer or mobile device. This means that hauls containing large quantities of non-target species that previously might have been discarded can now be retained as incidental catch and be landed under a quota obtained through the FishRight platform (Kosviner 2018). For other examples of innovations to reduce bycatch, please refer to the ‘Selectivity of gear and avoidance of unwanted catches’ chapter.

Technology Readiness Level: 9; Technical risk: Moderate

Reducing subsidies and overcapacity: In 2011 it was estimated that the size and capacity of the EU fleet was around 2 to 3 times above the sustainable level in a number of fisheries (Pew Charitable Trust 2011). Despite similar situations in many fisheries globally, capacity-enhancing subsidies were estimated at USD 22.2 billion in 2018 (Sumaila et al. 2019). Other forms of subsidy include tax-emptions on fuel costs (Ziegler and Hornborg 2014). Such subsidies reduce the attractiveness of investments in fuel efficient vessels and onboard technologies. There have therefore been calls for governments and the World Trade Organisation to identify strategies to reduce overcapacity and phase out subsidies (FAO n.d.; Cisneros-Montemayor and Sumaila 2019). As with other fisheries management policies described here, whilst there are no technical barriers to the implementation of this approach, the social and political barriers are likely to be significant.

Technology Readiness Level: 9; Technical risk: Low

Use of low global warming potential refrigerants: Refrigerant leakages from cold chain technologies can make a significant contribution to GHG emissions of wild-capture fisheries. This is due to the very high ‘global warming potential’ of certain refrigerants. For example, 1 kg of R22 refrigerant has a global warming potential of 1820, meaning that it has the same impact on global warming as the emission of 1820 kg of carbon dioxide. A 2015 study of the Scottish mackerel fleet found that, were R22 was used on some older vessels, the refrigerant leakages could increase the carbon footprint of the fishing activity by up to 250% (Sandison 2015).

The use of refrigerants with a high global warming potential, such as R22 and HFC 404A, have now been phased out within the EU through legislation designed to tackle ozone depletion. Modern vessels use ammonia or other 'climate neutral' refrigerants but these require systems designed for operation at higher pressures. For older vessels, this means replacing the entire refrigeration system. To avoid this cost, some vessel owners have sought to use 'drop-in' replacements for R22 and HFC 404A but many of these alternative refrigerants also have very high global warming potential.

It is not clear how many vessels in the UK fleet are currently using high global warming potential refrigerants are what the rates of leakage from these systems might be as no centralised data is collected on this topic. However, data from the Norwegian fleet collected in 2017 estimated that around 16 tonnes of HFC refrigerant was released through leakages by the fleet in that year, which made a significant contribution to the overall carbon footprint of the fishing activity (Winther et al. 2020). Finding 'drop-in' replacements for R22 and HFC 404A for existing systems is challenging as, whilst there are many alternatives that have significantly lower global warming potential, finding a replacement that offers similar refrigeration performance (temperature range and coefficient of performance), is compatible with the current lubricant and seal and does introduce health and safety concerns (flammability or toxicity) is very challenging. A brief search of secondary sources did not identify any drop-in replacements for R22 refrigerant for marine applications although R-1234ze, which has a global warming potential of 1, has been identified as a potential replacement in some non-marine applications (Amrane 2016). HFC 449A is a potential replacement for HFC 404A (Gluckman Consulting 2016) and has a global warming potential of 1273 (versus 3922 for HFC 404A).

For new vessels, there are now a range of low global warming potential refrigerants available. Ammonia (R717) is now commonly used for marine applications and has a global warming potential of zero, although does increase risks due to its flammability and acute toxicity.

A key task for operators of both old and new vessels is to ensure good maintenance and regular inspection of refrigeration systems to avoid leaks, thereby improving safety, saving costs and avoiding climate harmful emissions (Wilhelmsen 2016).

Technology Readiness Level: 9; Technical risk: Low

27.4 Processing

The climate impact of seafood processing are generally considered to be relatively low and have often been overlooked in carbon footprint analyses. However, a study of Alaskan Pollock products (frozen battered-and-breaded fillets and frozen crab-flavoured sticks) sold in the USA found that secondary processing was actually the largest contributor to the overall carbon footprint at 0.56 – 0.66 kg CO_{2eq} per kg of product versus 0.34 – 0.35 kg CO_{2eq} per kg of product for the fishing activity (McKuin et al. 2019). This was mainly due to the impact of the non-marine ingredients, such as wheat, in the manufacturing of the product.

Other studies have highlighted the significance of waste, process yield and the utilisation of co-products as having a significant influence on the carbon footprint of the primary product. Processing and packaging innovations that enable shelf life extension can contribute to climate change mitigation in several ways. First, by reducing food loss and waste across the supply chain. Secondly, by enabling the switch from high carbon (air freight) to more sustainable (sea or train freight) modes of transport.

The energy consumption related to cold chain technologies in land-based processing is generally not a primary contributor to GHG emissions in the seafood supply chain. Even for frozen fish, the increased energy use for the refrigeration system is offset by gains in packing efficiency as more product can be shipped per unit of volume compared to chilled products that require layers of ice (Ziegler et al. 2013). In fact, frozen products are preferable in many cases as they result in less waste (discussed further in the ‘Consumer aspects’ section) and the considerable shelf life extension offered by freezing means that products can be shipped to export destinations by less carbon-intensive transport modes e.g. sea freight instead of air freight (discussed further in the ‘Transportation’ section) (Ziegler et al. 2013).

Innovations related to each of the aforementioned aspects are presented here.

Innovations with a potential for transformative performance improvement

Shelf life extension through high pressure processing: High Pressure Processing (HPP) is a food processing technology that is primarily used to improve food safety and extend shelf life without use of heat or preservatives. The process, sometimes referred to as ‘cold pasteurisation’, involves placing the produce in a pressure vessel that is filled with water and then subjected to very high pressures (up to 600 MPa), killing any bacteria, viruses or pathogens present.

A variety of studies of the microbial load reduction in fish muscle have shown that HPP can offer significant microbial load reduction (0.5 to 5 log reduction in total viable count), enabling an extension in shelf life of 6-10 days for hake, 2-19 days in salmon, and 0-7 days in sea bass (Truong et al. 2015).

For further examples of shelf life extension innovations please refer to the 'Quality and food safety management systems and accreditations' chapter.

Technology Readiness Level: 9; Technical risk: Low

Superchilling: A method that makes ice (accounting for up to 20% transport weight) redundant in cooling and storing fish by using new technology to cool fish to -1° to -2°C, on the borderline of being frozen, but cooling it beyond what can be achieved with ice. A Norwegian study on farmed salmon confirmed that superchilled salmon stays fresher for longer than conventionally chilled fish resulting a shelf life extension of up to a week (Nordic Innovation 2016).

Technology Readiness Level: 9; Technical risk: Low

27.5 Transportation

Transportation impacts vary significantly depending on the mode of transport. Airfreight of seafood produce results in considerably higher GHG emissions than land or sea freight. The high cost of airfreight mean that its use is generally reserved for high-value live or fresh products such as lobster and crab. In 2018, the UK exported £58 million of shellfish to China (Marine Management Organisation 2019). A significant percentage of lobster exports to China will have been air freighted. Whilst no studies on the climate impact of UK seafood airfreight activities have been identified, a study of rock lobster export from Australia concluded that switching from airfreight to sea freight could reduce transportation GHG emissions by 40-56% (van Putten et al. 2016). The focus of this section is therefore on innovations that enable reduced use of airfreight for seafood products.

Innovations with a potential for disruptive performance improvement

Ship-based aeroponics and aquaculture: An alternative approach to reducing transport related emissions would be to have a mobile production facility. Klarin et al (2019) have presented an outline feasibility study of a ship-based aeroponics and seafood production facility based on a catamaran of dimensions 180m x 40m x 28m. It is suggested that the facility would produce lettuce, tomatoes and strawberries through aeroponics and have a lobster aquaculture system on board. Renewable energy would be used to power a desalination plan and provide all other on-board power requirements, with sun-tracking technology used to maximise solar power production. The authors claim that having a mobile ship rather than a land-based facility or floating farm provides several significant benefits:

- The vessel could sail towards or away from the equator to provide optimum growing conditions in terms of sunlight and temperature throughout the year.
- The vessel can sail directly to large markets in coastal cities – resulting in very low transportation emissions.
- The vessel can be repositioned in case of storms.

The total capital cost of the facility is estimated at €33 million, with operating costs of €8.25 million and a projected payback period of 6 years.

Technology Readiness Level: 3-5; Technical risk: High

Innovations with a potential for transformative performance improvement

Novel container for live sea freight of lobster: Lobster is generally transported live by air freight (high GHG emissions) or frozen by sea freight (lower sales price). To enable maximum sales revenue for live products whilst reducing GHG emissions from transportation, CMA CGM have developed the Aquaviva shipping container[1]. The live lobsters are placed in special units that are placed in the container. A water filtration system circulates water throughout the lobster storage area throughout the journey, maintaining oxygen levels and filtering bacteria. On arrival the lobsters are unloaded, and the used sea water is filtered with UV light in order to clear the water of all living organism that might impact marine biodiversity.

An independent life cycle assessment of imports of lobster from the USA that considered the Aquaviva system as a transport scenario found that the total GHG emissions for live lobster

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[1] Aquavia container: http://www.cma-cgm.com/services/special-services-refrigerated

transported by sea using the Aquaviva system were 49% lower than the live air freight scenario (Borthwick 2019). However, the study also noted that transportation of frozen lobster by sea resulted in a 73% reduction compared to the live air freight scenario (due to the much large quantities of lobster per container compared to the Aquaviva system).

Technology Readiness Level: 9; Technical risk: Low

Processing boats: Processing boat in e.g. the salmon aquaculture industry enables the salmon to be slaughtered in a large, converted well-boats on site. Hence, there is no need to transport the fish to a slaughtering facility. Processing boats are furthermore more economic, as they are more efficient and with a smaller carbon footprint and better for disease control. The use of processing vessels shortens the down the time and with a capacity of 1000 tonne it takes seven to eight hours to empty a standard cage with pumping, stunning, killing and gutting. There are very few mortalities in this process, which means that all harvested fish are fit for human consumption (personal communication). For more information on processing boats please refer to chapter 6 ‘Farmed animal health and welfare’.

Technology Readiness Level: 9; Technical risk: Moderate

27.6 Consumer aspects

There are two main ways in which consumers can support climate change mitigation in relation to seafood products. The first is by purchasing products that have a lower carbon footprint. Given that, in most cases, marine-derived sources of protein have a lower carbon footprint than land-based sources, it has been argued that promoting increased consumption of seafood products is a climate change mitigation action (De Silva and Soto 2009). The second is by avoiding waste. If food waste was a country, it would be the third largest emitter of GHG emissions (FAO 2015). The short shelf life of many seafood products makes waste a particularly important issue for seafood. For example, a study in the USA estimated that 40-47% of the edible U.S. seafood supply goes uneaten, with over half of this waste attributed to consumer behaviour (Love et al. 2015). This demonstrates the importance of focusing on post-production food waste as an important part of climate change mitigation efforts (Ytrestøyl, Aas, and Åsgård 2015). Innovations related to these two consumer aspects are presented here.

Innovation with a potential for disruptive performance improvement

Chitosan-based antimicrobial packaging film: Scottish company CuanTec have developed an antimicrobial packaging film produced from chitosan. Chitosan has natural antimicrobial properties (Kong et al. 2010). The company is using novel bio-fermentation technology to extract chitin from langoustine processing waste, which results in higher yields and quality compared to the standard chemical process. Their deacetylation process to process chitin into chitosan involves five times less sodium hydroxide than the conventional chemical process.

The final packaging film is biodegradable and is due to be trialled by Waitrose in some of their fish products (Waitrose & Partners 2019).

For further examples of packaging innovations that enhance shelf life, please refer to chapter 20 on ‘Packaging technologies’.

Technology Readiness Level: 6-8; Technical risk: Moderate

Gelatine-based freshness indicator: Mimica Touch[1] is a temperature sensitive indicator of product freshness that helps to provide a real-world indicator of product freshness. It consists of a label or cap that is placed on the outside of the product at the point of production. Inside the label there is a layer of gelatine that covers a ridged plastic layer. When first applied, the label feels smooth but as the gelatine layer decays and breaks down the plastic ridges underneath can be felt. An advantage of this system is that it is suitable for visually impaired consumers, unlike standard labels.

The gelatine layer can be tailored to match the spoilage rate of the product. The first commercial application of the Mimica Touch will be for fresh juice products, with further applications for milk and meat expected.

For further examples of packaging innovations that enhance help to avoid consumer rejection of edible food, please refer to the ‘Packaging technologies’ chapter.

Technology Readiness Level: 6-8; Technical risk: Moderate

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[1] Mimica Touch: https://www.mimicalab.com/product

Innovation with a potential for transformative performance improvement

Carbon footprint labelling and integration with sustainability accreditations: For a number of years it has been suggested that seafood sustainability accreditation and labelling schemes should include a requirement to perform a carbon footprint and take actions to reduce GHG emissions (Madin and Macreadie 2015). The Aquaculture Stewardship Council (ASC) is the first standard to include a requirement for producers to collect and report data on the GHG emissions associated with their farm operations and feed. Whilst these data must be reported to the ASC scheme, they are not made publicly available. A different approach is being taken by the Friend of the Sea certification scheme. It has developed the ‘Seafood Carbon Footprint Calculator’ that enables customers to estimate the GHG emissions linked to transportation for the products they have purchased (Friend of the Sea 2008). The company is also offering customers the option to purchase carbon credits to offset an equivalent amount of GHG emissions.

Currently these is limited evidence of the impact that consumer education and carbon labelling schemes have on purchase behaviour (Madin and Macreadie 2015). Whilst the majority of consumers would like more information about the carbon footprint of the food products they purchase, the use of labels can cause confusion for consumers (Gadema and Oglethorpe 2011). Furthermore, a 2013 study that trialled the use of a traffic light label for carbon footprint of fresh seafood products in a US retail chain led to a 15% decline in sales, including 35% reduction in sales of ‘yellow’-labelled products (Hallstein and Villas-Boas 2013). Consumer attitudes on this topic may well have evolved in the intervening years and so the potential climate change mitigation benefits of carbon footprint labelling of seafood products are unclear at present.

Technology Readiness Level: 9; Technical risk: Low

Innovation with a potential for incremental performance improvement

Reducing waste through frozen food: Rates of food waste are generally lower with frozen foods than fresh foods, due to the extended shelf life of frozen foods. Promotion of frozen products has been proposed as a strategy to reduce seafood waste (Love et al. 2015). However, in many seafood markets, fresh, chilled products are viewed as being of higher quality and nutritional value than their frozen equivalents. These beliefs are outdated, given the improvements in freezing technology and cold chain management over the last 20 years. Consumer education programmes in the UK (Food Manufacture 2015) and Sweden (personal communication) have therefore been conducted to advice consumers on the benefits frozen foods in terms of their quality and the reduced risk of food waste. Whilst there are no data on the impacts of such schemes, the scale of the seafood waste challenge suggests that further efforts to reduce waste through consumer education are merited.

Technology Readiness Level: 9; Technical risk: Low

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28 Summary and conclusions

Contents

<u>From the SIF Executive Board</u>

The method applied in this review has generated numerous examples of innovations across a wide range of different topics. These examples highlight the main areas where innovation is currently happening. It is recognised that there are existing innovations and research areas that are not included here, and new areas where future innovations may occur. Therefore, the inclusion or exclusion of a specific innovation in this report does not determine the outcome of applications to the SIF programme.

28.1 Overview

The aim of the SIF Baseline Review was to generate an overview of the state-of-the-art technologies and innovations since 2015 that are relevant to the UK fisheries, aquaculture and seafood industries. The research involved a top-level analysis of academic, grey literature and patents as well as interviews with academics, NGOs, industry experts and thought leaders. Thus, the review is not a systematic literature review, nor does it provide an exhaustive list of innovations relevant to each challenge. The evaluation of innovations in terms of their potential impact on the UK seafood sector, Technical Readiness Level and technical risk was performed using the guidelines described in section 4.4 but was limited by the availability of information in the public domain concerning these innovations and so should not be seen as a definitive evaluation.

During interviews, it was noted that there are conflicting opinions and different ‘schools of thought’ for some of the challenges included in this review. Wherever possible, Strategic Innovation has kept an objective approach and presented findings to include diverging views, where these were expressed by the leading global experts interviewed.

The Baseline Review is designed to assist the SIF in evaluating applications, identifying innovation, providing insights and listing challenges and knowledge gaps to identify promising opportunity areas. Figure 27-1 is an overview of how identified innovations are spread across the four key themes covered in the SIF Baseline Review and demonstrates a focus towards aquaculture, perhaps reflecting the relatively recent emergence of this sector compared to the mature marine fisheries sector. In this chapter we will provide a brief summary of the findings from each topic including what are the key knowledge gaps relevant to the UK seafood sector.

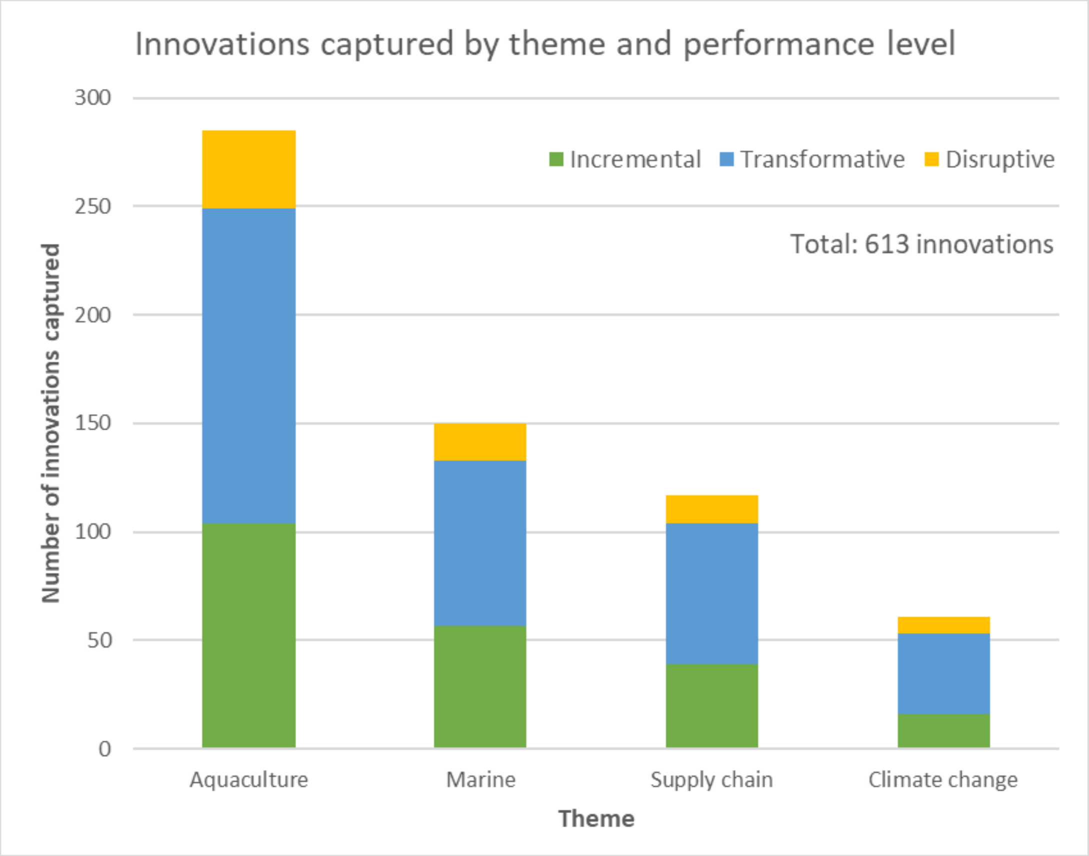

Figure 28-1: Innovations categorised by theme and by innovation type.
N.B. definitions of the innovation categories and how they were applied are found in chapter 3 'Methodology'.

28.2 Key challenges and opportunities in UK Aquaculture

Environment and ecosystem monitoring and impacts

Escapees are perhaps the most significant concern with regards to environmental impact of aquaculture. Innovations that help to reduce the likelihood of escapes include closed systems, land-based operations (e.g. RAS), and genetic modification of farmed species. Transmission of pests and diseases from farmed to wild animals is another major challenge, with innovations aiming to reduce transmission and increase monitoring. Organic and foreign material emissions from aquaculture are problematic, especially in coastal areas, non-coastal farming alternatives are attracting more attention and funding (see also refer to chapter 10 'Production and handling').

The extensive use of cleaner fish also has various impacts on the environment ranging from increased organic matter under the sea pens (due to mortalities) and the threat to the wild stock through over-fishing. Breeding and farming of cleaner fish is therefore a key consideration.

Knowledge gaps surround the precise monitoring of escapees, genetic modification and practices to minimise interaction of farmed species with the natural ecosystem. Also, novel netting materials and novel biocidal compounds with anti-fouling properties are highlighted as areas where innovation is needed.

Farmed animal health and welfare

Crowding is a fundamental challenge in intensive aquaculture as this inherently makes the fish more susceptible to pests (e.g. sea lice), viral, bacterial and fungal diseases and limits natural behaviours. Innovations addressing farming systems and their design are promising developments to improve fish welfare (e.g. current control and various stimuli to encourage natural behaviour).

Sea lice are often controlled using cleaner fish. However, the survival rates and welfare of the cleaner fish themselves are so low that their continued use in the salmon farming industry is uncertain. Separation of fish from sea lice through more extended smoltification periods on land and development of pen designs that reduce the risk of sea lice infestations are amongst the most promising innovations in order to address this challenge.

The use of improved stunning methods and processing on-site have been highlighted as key innovations for improved welfare. The most important gaps in fish welfare concern domestication of cleaner fish, stress reduction and having better metrics and monitoring technologies to understand, evaluate and recognise behavioural cues in relation to stress.

Genetic improvement

Discoveries in genetics are incrementally translating into improvements in animal health, welfare and profitability in salmonid species. Traits such as disease resistance and robustness are being achieved through genomic selection for faster/greater gains. Genome editing using the CRISPR/Cas9 system is slowly maturing and epigenetic research to improve the understanding of favourable breeding conditions is increasing. Genetic improvements in shellfish and other species have been limited in the UK, which represents an opportunity for development.

Knowledge gaps include genetic improvement of non-salmonid species and improvement of traits underpinned by polygenic genetic architecture.

Nutrition and feeding

Fish meal and fish oil (FMFO) are the primary feed input for aquaculture but have a significant impact on feedstock species and other environmental harms. Supply issues are likely to limit future aquaculture growth. Research has been conducted into plant-based alternatives, with limited success due to cost and nutritional deficiencies. Innovations are currently focused on supplemental nutrition, targeted at specific life stages.

New developments in alternative feed sources appear to suffer from limited economies of scale in comparison with current feed sources. However, such developments are likely to be in line with consumer trends towards more sustainable food production. Alternative feed companies able to overcome technical challenges may be successful if business development activities are effectively conducted and sufficient investment in production infrastructure is possible.

Key knowledge gaps surround the development of feeds and manufacturing systems to match FMFO based feed in terms of cost, scale and nutrition.

Pest and disease

Significant funding and innovation activity have focused on sea lice in salmonid aquaculture, where physical separation of the salmon and sea lice is currently attracting attention and substantial (e.g. extended smoltification periods on land and closed pen designs). Advances have also been made in vaccines together with improved administration techniques to control viral, bacterial and other parasitic diseases.

Development of new antibiotics has seen lower priority, with R&D focusing on the development of alternatives primarily through genetic improvements of farmed fish and to a lesser extent through developing immune modulating feed ingredients such as probiotics. Approaches to monitoring and rapid diagnosis of prevalent diseases has been a key focus.

Knowledge gaps include treatments and vaccines for multiple viral diseases (fish and shellfish) and fungal diseases.

Production and handling

Technologies allowing for non-coastal farming, either offshore or inland, are seen as enablers to future growth in the sector. Recirculating aquaculture systems (RAS), including aquaponics, are attracting investment and global R&D efforts. There has been little commercial activity in the UK, but as the technologies evolves globally this is considered a potential area of promising innovation. Other promising developments are in the automation and remote monitoring of fish farms, reducing labour cost and making offshore farms more viable.

Key knowledge gaps are around the design and operation of RAS systems, particularly for smolt production in the salmon industry, where the merging of computational technologies (such as AI) with fish monitoring systems needs further development.

Species diversification

Currently, a narrow range of species are farmed in the UK, due to limited consumer tastes, high production costs and regulatory restrictions. The most promising areas of innovation include farming of shellfish, seaweed and algae. Domestication of the two cleaner fish species to complement salmonid farming is a related development topic.

Knowledge gaps primarily centre around viable closed-lifecycle breeding and suitability of new species in UK waters.

Waste management

Waste feed and excreta are significant challenges for both marine and land-based aquaculture. The most promising innovations are around improvements to feed delivery systems, biofiltration of critical nutrients and the use of other species such as sea cucumbers or sea urchins for processing fish waste.

Key knowledge gaps exist around viable integrated multi-trophic aquaculture (IMTA) systems nearshore, which provide a level of recirculation and valorisation of organic nutrients.

28.3 Key challenges and opportunities for UK Marine wild-capture fisheries

Fishing effort and fuel consumption

Innovation efforts to reduce fuel consumption continue in areas such as gear, vessel and engine design. Innovations are also appearing that help skippers to improve the fuel efficiency by providing real-time data on fuel consumption and fishing performance. There are relatively few disruptive innovations in this area, although in the far future the development of offshore docking stations to refuel and resupply vessels could enable step-change reductions in fuel consumption.

Most innovation concerning fishing effort is related to finding better ways of measuring and monitoring fishing effort for specific circumstances.

Knowledge gaps are around the acquisition and use of precise data to inform fishing effort improvement activities.

Welfare of fish in marine wild-capture fisheries

Whereas in aquaculture it is possible to talk about improving welfare, fisheries will generally only impinge on welfare of the fish when caught, and improved welfare is therefore about reducing negative impact during the capture process to minimise stress and injury and the number of individuals affected. With the high survivability exemption from the EU Landing Obligation there is an increased interest in robust data on discard survival. One of the key areas of innovation is welfare education (e.g., methods of retrieval and handling) and making a case for a market pull approach - highlighting the link between welfare, quality, shelf life and sustainability. It is often difficult to implement welfare measures established in aquaculture at sea, but innovations addressing killing and slaughtering at sea are slowly appearing.

Knowledge gaps that are important to address include research on the different stressors for wild-caught fish and research to provide evidence that it is possible to promote survival of unwanted catch through handling procedures including release methods (e.g., slipping).

Ghost fishing and marine litter from fishing gear

Abandoned, lost or otherwise discarded fishing gear results in ‘ghost fishing’, estimated to cost between £10 million and £70 million per year as well as significant environmental damage. Innovations to address this challenge include spatial or temporal zoning of fisheries, use of biodegradable materials and ropeless fishing systems.

Important knowledge gaps include the understanding of economic and environmental costs and benefits of spatial/temporal zoning of fisheries. Technical solutions to mitigate the impacts of lost gear are needed.

Habitat, environment and ecosystem impact

Environmental and ecosystem impacts from wild-capture fisheries in the UK are centred around determining how to best minimise collateral damage, especially from dredging, trawling, and fisheries with high levels of bycatch. Provision of data to provide insights for policy making is improving, for example, the distribution of essential fish habitats such as cod and herring nursery grounds. Key innovations focus on development of methodologies that allow for (big) data collection, processing and analysis and ways to monitor and assess impacts in a cost-effective and time efficient manner. Whole system modelling, better tools to evaluate fisheries impact and improved acoustic instruments for identification of catch, fish and shoal-size are also high on the list of key innovations.

There are substantial knowledge gaps to address in the area of data collection, verification and data processing and in understanding impacts of fisheries on open-ocean ecosystems.

IUU (illegal, unreported and unregulated) fishing activities

Although IUU in UK waters is considered to be limited this is not a reason for complacency. The most important innovations to combat IUU fishing activities relate to image recognition systems (of vessels and for rapid species detection), the use of satellites and drones, artificial intelligence for vessel observation and data processing. Combining Vessel Monitoring System (VMS) and Automatic Identification System (AIS) data with data gathered by satellites, particularly using optical images and Synthetic Aperture Radar (SAR) is a key focus area. Regulatory mechanisms and legislation are likely to be at the forefront of avoiding IUU fish entering the UK market assisted by faster automated data analysis of images and other data sets to improve responsiveness of officials to potential IUU activities.

Key knowledge gaps exist around rapid data analysis technologies including AI/machine learning techniques for monitoring vessels and trade. Importantly, the introduction of new monitoring technologies will need to go hand in hand with regulatory mechanisms and legislation.

Onboard processing

High capital costs of state-of-the-art onboard processing means this is primarily the domain of larger, vertically-integrated companies, which are not typical of the UK industry. Such automation is particularly suited to single species processing on large vessels. Innovation is required to increase the flexibility of the equipment to deal with mixed species, reduce capital costs and operate reliably in typical UK settings.

Big data integration allowing for real-time communication between various stakeholders from harvest to market, together with selective gear, automated slaughter, grading, sorting and processing, lightweight, automated and sustainable chilling are amongst the important areas of innovation.

Selectivity of gear and avoidance of unwanted catches

Long-term health and productivity of fisheries requires overall biomass extraction rates to remain within sustainable levels, including bycatch. The ability to remove sustainable numbers of target species of commercial value is a key enabler to achieving this objective. Promising innovations include vision systems in trawls for real-time species identification, the use of lighting in combination with bycatch reduction devices and pre-catch characterisation for purse seine.

Knowledge gaps include the need to develop effective technologies to provide precise data capture on levels of bycatch and discards within UK fleet and in the area of pinniped depredation management in UK waters.

28.4 Key challenges and opportunities for UK onshore supply chains and added value production

Packaging

An estimated 23,000 tonnes of fish and shellfish purchased by UK consumers ends up as waste. There is therefore a need for novel packaging systems to help reduction of seafood waste. With the increasing pressure on retailers and manufacturers to reduce their use of plastic packaging and eliminate non-recyclable packaging there is a need for more sustainable packaging materials. Seafood packaging systems will need to improve if seafood is to compete with other sources of protein. A few promising innovation areas include the use of chitosan, gelatine-based freshness indicators and nanocomposite and nano encapsulation of antimicrobial agents.

Knowledge gaps include seafood packaging and delivery systems suitable for e-commerce, especially in direct to consumer channels.

Primary processing technologies

Advances in the UK have been limited with the exception of farmed salmon and trout. Due to high capital costs, state-of-the-art processing has been the domain of larger, vertically-integrated companies focusing on single species processing. Labour shortages and regulatory issues are likely to lead UK-based processors to seek more flexible, modular automation. Computer vision systems and water-jet cutting are examples of technologies that enable processing of a variety of species and sizes. Automated and sustainable chilling solutions lead to significant improvement in product quality from the point of harvest.

Knowledge gaps include data integration to allow for real-time communication and sharing of data throughout the production/capture, processing, logistics and retail chain. This will enable end to end traceability and matching demand with supply. There is currently minimal innovation activity in shellfish processing.

Quality, food safety management and accreditation systems

Within the UK seafood processing industry there is widespread adoption of international recognised food safety and quality management systems, such as the BRC Global Standard for Food Safety. However, the United Kingdom is now ranked 17th in the Global Food Security Index, with seafood-producing competitors such as Norway, Sweden, Finland and the USA scoring significantly higher in terms of food quality and safety. Imports of semi-processed and processed products, particularly from outside of the EU, represent a risk. New technologies for product authenticity verification, combined with blockchain traceability technology, offer a potential route to addressing import-related challenges, but there appears to be limited development and trials of such technologies in the UK to date. Promising areas of innovation therefore include smartphone-based sensors for analysis of food safety, blockchain-based traceability systems and product authenticity test such as stable isotope and trace element analysis.

Key knowledge gaps include the currently limited adoption of novel traceability technologies, such as blockchain and next-generation RFID tags, in the UK.

Sustainability accreditation and labels

An inventory compiled for the European Commission in 2009 lists 441 different schemes for agricultural products and foodstuffs marketed in the EU Member States, most of which were established during the first decade of the new century. The Ecolabel Index (2016) indicated that there were 148 public and private sustainability standards and quality assurance schemes for food and beverages available at the EU or national levels. This large number of accreditations and labels leads to confusion for sustainability and welfare conscious consumers, who are looking to make an informed purchasing decision.

The most promising innovations in this area are related to improving existing technologies for better monitoring. Whether these technologies will be used for existing certification schemes or allow the emergence of new schemes is yet to be seen.

Knowledge gaps in this area include the harmonisation of standards and labels.

Waste reduction and valorisation

The UK operates a relatively effective collection system for fish processing waste, with the majority being used for fish meal and fish oil. However, there is limited evidence of using waste in higher value products, especially for shellfish waste. Promising innovations include fish protein hydrolysates, biorefineries for processing fish waste, alternative processes of extracting chitin from crustacean waste using fermentation, and the use of crustacean waste derived chitin for plastic alternatives.

Knowledge gaps are mainly around the identification of market opportunities, where ‘waste’ materials can be converted into commercially attractive higher value products.

28.5 Key challenges and opportunities for the UK in climate change mitigation and adaptation

Climate change mitigation

Efforts to reduce the UK seafood sector’s contributions to greenhouse gas emissions are primarily through reduced fuel use during fishing, transport and chilling. The development of more sustainable feeds seeks to lower embedded carbon and feed usage in aquaculture. Promising areas of innovation include novel technologies for carbon dioxide conversion for feed production, integrated farming (e.g. seaweed and shellfish), and the use of IoT technology and big data analytics for monitoring and managing fisheries and aquaculture.

Key knowledge gaps include the centralised collection of detailed fuel consumption data for fishing activities and novel approaches to reducing consumer waste of seafood. There is a need for development of standardised and efficient methods for estimating the carbon footprint of seafood products.

Climate change adaptation in the UK

Research is ongoing to monitor and forecast the impacts of changes in temperature, weather events, sea-level rise and sea water pH. Measures to date have focused on capacity building within the sector, policy measures, building resilience through a reduction in other stressors, developing alternative markets or livelihoods and protecting critical infrastructure. Promising innovations include pen and cage designs allowing for offshore and/or mobile aquaculture solutions. Also, RAS, IMTA and other culture systems may protect against most climate-driven changes. Innovations regarding selective breeding, species diversification and aquafeed development address species-specific resilience whilst modelling and prediction is key in forecasting extreme events, safety and assessing vulnerabilities.

The key knowledge gaps are around fundamental research to understand species pH and thermal biology and vulnerability, which is critical to guide development of effective strategies.

28.6 Conclusions

The key knowledge gaps identified for each challenge are covered in the SIF Baseline Review can be contextualised using the 'Box Model' of innovation, which was introduced in chapter 4 as a framework for understanding which innovations are most likely to successfully address these knowledge gaps. The Box Model offers a holistic overview for evaluating and comparing innovations by identifying the issues that might prevent the innovation from becoming widely adopted ('blue curves') and recognising the innovations that appear to hold a strong position (potential 'red curves').

Innovations most likely to succeed are those, which positively affect the majority of the Box Model arrows, particularly those that match a trend or solve a key contradiction between the requirements of consumers, technology or business (e.g., in packaging, consumer expectation of excellent product quality, presentation and convenience vs consumer demand to eliminate single use plastics). Focusing on some of these fundamental contradictions is where the most 'disruptive' innovations are likely to be found. The overarching contradiction is that the seafood sector needs to be both commercially successful and to maintain a sustainable and productive ecosystem, with due regard to animal and human welfare.

Whilst the SIF Baseline Review has focused on the technical performance of seafood innovations the promising innovations will also have the means to execute the novel idea – with capable people, infrastructure and tools/methods and access to sufficient funding. These factors should be taken into account by the SIF when selecting the most promising innovations to fund

In the following sections we present the authors' views of where innovation is most needed within the UK seafood sector.

28.6.1 Aquaculture

In aquaculture, innovations to improve commercial returns are often in alignment with sustainability and animal welfare goals. Such technologies include practices and medicinal interventions to reduce pest and diseases, reduced escapes, genetic improvement, improvements to feed sustainability and conversion ratio, and species diversification. We conclude that such developments should continue to be encouraged.

However, production efficiency has led to intensive, single species farming. The resulting intensity and scale of production is fundamentally in contradiction with sustainability and animal welfare. There are two fundamental challenges to be addressed. First, viable alternatives need to be found to fish meal and fish oil from processing of wild captured species. The second is to reduce the farming intensity, whilst improving or maintaining commercial viability. This may require a disruptive shift in the industry towards a systems view (i.e., a holistic, multi-species approach), where the measure of the commercial outcome is at the system level and not the single species level. This may in turn allow aquaculture to move away from being a net extractive operation to being ‘regenerative’, analogous to emerging ‘regenerative agricultural’ systems that are showing promise.

Identifying ‘triple wins’ for sustainability, promoting products that provide benefits for industry, the consumer and the environment, are suggested as a priority. An example already rapidly progressing in the West is the move from using antibiotics to employing alternative strategies to increase fish health. When successful, this translates into lower ongoing overheads for the farmers, less impact on the environment and seafood products without traces of antibiotics for the consumers to purchase.

28.6.2 Wild-Capture

Innovations that reduce operational costs through increased efficiencies are often in alignment with, rather than in contradiction to, sustainability objectives. Automation, valorisation of waste, reduced energy consumption, reduced bycatch, species selectivity, shelf life extension, precise fisheries management and reduced gear loss are all largely beneficial to both business profitability and ecosystem health. We conclude that the wild-capture industry should continue in these endeavours.

However, there are several challenges in wild-capture fisheries that are not in alignment with sustainability objectives. Over-fishing, bycatch and impact on the wider ecosystem are not novel issues but remain fundamental for the industry to address and solve if wild-capture fisheries are to ensure a sustainable and healthy ocean for our future generations. Informed legislation and innovations providing data for better data capture, monitoring, and hence better understanding of fish stocks and the wider system, are key in achieving this goal.

Again, identifying triple wins for sustainability, promoting products that provide an industry, a consumer and an environmental benefit is suggested as a priority. Moving from dynamic, high impact fishing methods for cod to static methods (e.g., line-caught, pod or cage-based), alongside campaigns to educate consumers on the improved welfare of these methods, represents an important opportunity for the industry to nudge consumers to make more sustainable purchasing decisions. The industry nudge would be centred around highlighting the link between fish welfare, meat quality, increased shelf life and sustainability, which should become an essential part of the UK fisheries' marketing story.

28.6.3 Onshore supply chains and added value production

Advances in genetics, computing, telecommunications, robotics, drones, sensing and data analytics are already being adopted within the seafood sector. Many of these are enablers of disruptive or transformative innovation. One of the key functions that improves management of fisheries, the supply chain, and information to consumers is traceability and data sharing. Further improvements in traceability and data sharing will enable innovative new products and services.

28.6.4 Building capability to develop scalable businesses

During the Baseline Review research, we have become aware of innovation attempts that have failed, show limited implementation or failed to scale. This often appears to be due the 'catch 22' of insufficient scale leading to being uncompetitive with incumbent technologies.

The UK seafood sectors will require technologies that can be developed for large scale production to remain competitive. Note that there is a potential contradiction with the earlier suggestion to reduce reliance on high intensity, 'monospecies' model of production. Resolving this contradiction will require systems of production that have very low (or net positive) sustainability impacts, that are financially viable in their own right but can be easily replicated across a large number of sites/fisheries. This type of low impact, profitable and scalable approach to increasing production is already being promoted through the concept of 'climate smart agriculture'[1], with GreenWave IMTA system[2] being a good example of this type of approach in the seafood sector. Such approaches will be vital both for long term financial viability and to meet the climate change objectives of the Fisheries Bill.

We therefore conclude that efforts should be made to identify smaller organisations within the UK seafood sector involved in 'climate smart' production systems and support them to build

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[1] Climate smart agriculture: http://www.fao.org/climate-smart-agriculture/en/

[2] GreenWave: https://www.greenwave.org/toolkit

their capabilities in general business disciplines including marketing, finance and planning, alongside support for development and scale-up of core technologies and new services.

28.6.5 External and human factors

Human factors have a significant influence on innovation in the seafood sector. Consumer taste preferences, behaviours and buying patterns in the UK affect market demand. An industry-led consumer nudge should be encouraged to promote more sustainable purchasing decisions, as often consumers do care but are generally unaware of the negative impact of their food choices. For a multi-species approach to be successful, as opposed to intensive monocultures or intensive fishing for only a limited number of species, UK consumers need to adapt and be willing to eat a wider range of seafood. Governmental involvement is key in areas such as developing guidelines and recommendations for a healthy diet and raising awareness of the environmental, financial and social sustainability impact of food items. These activities can built on existing initiatives such as the 'Fish is the dish'[1] campaign by Seafish to inform consumers about the health benefits of a diet incorporating seafood and could be extended to address wider sustainability issues so that consumers can make more informed purchasing choices.

The demographics of current fishers is known to be skewed towards older generations. As these retire, they will be replaced with a younger cohort with a different world view, who are likely to be more open to disruptive and transformational innovations. Likewise, traceability and more easily accessible data on the environmental impact of consumption may give rise to a broadening in demand for a wider variety of more sustainable species and product types.

Attitudes of fishers, farmers, business leaders and policy-makers influence the behaviour of their respective organisations. Changes in human factors emerge from social, demographic and societal shifts, which are perhaps most clearly observed in inter-generational interactions and dynamics. The significant disruption of society through increased concerns over climate change and environmental issues, particularly in younger generations, combined with Brexit and the recent Covid-19 pandemic provides an opportunity to adopt more radical, transformative innovations. It is therefore highly recommended that SIF take these human factors into account when deciding priorities for innovation funding.

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[1] Fish is the Dish: https://www.fishisthedish.co.uk/health/fish-protein-super-seafood