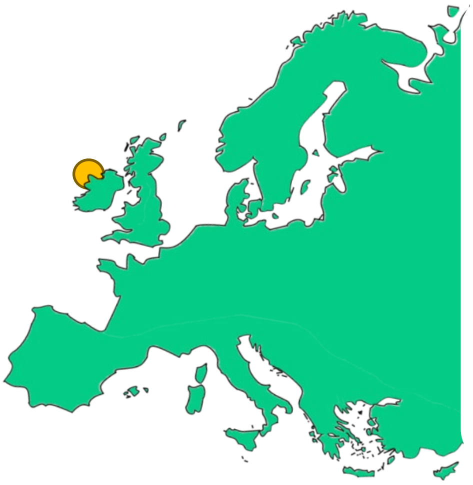
Case study



#10 Salmon in the north-east Atlantic

#11 Meagre at the Atlantic coast

#12 Seabass and seabreem in the Western Mediterranean and south Atlantic

Species background and economics

Farmed salmon (*Salmo salar*) is the most important aquaculture product in Europe (including Norway, Iceland and the Faroe Islands). Total production values across Europe was 1.46 million tonnes in 2017 (Eurostat) but while the industry has expanded greatly in Norway since 2010 (85% of Europe's total production in 2017), salmon aquaculture production within the EU28 has increased only marginally.

As Atlantic salmon are anadromous, the production cycle has both fresh water (hatchery and nursery) and marine phases (on-growing to harvest). In fresh water hatcheries, fertilised eggs hatch as alevin and grow into parr.

The parr undergo a process known as smoltification (that requires physiological, morphological and behavioural changes) that enable them to survive in sea water. Smolts are "put to sea" 6 to 18 months after they hatch, after reaching a weight of 60 to 150 g. These fish reach a typical harvest size of 3 – 5 kg after 12 to 18 months of growth at sea (Ellis et al. 2016).

One of the objectives of CERES is to determine the potential impact of climate change on the salmon aquaculture production and how the industry can adapt (and potentially benefit) in the future. This report will focus on the grow-out phase in marine systems.

Furthermore, CERES will focus on Norway and Ireland as they are the two leading countries in both industrial and organic production.

Figure 1 Lough Swilly salmon farm, Donegal, Ireland *Copyright MOWI*

Aquaculture operations in Norway are distributed along the entire coastline of Norway, except around the Oslo fjord and a few other areas due to the presence of other industries or environmental protection.

The most important production region is the coast of Nordland, followed by the northern adjacent county Troms and the more southern located regions Hordaland and Sør Trøndelag (Figure 2). The vast majority of salmon produced is exported; for example, 81% of total production (1 million tonnes) was exported in 2016. Of this amount, 75% was sold to the EU with the main importers being Poland and France.

Although the sector is characterized by a high degree of consolidation, with 6 large companies accounting for 61% of total revenues in 2016 (Ernst and Young 2018), there are currently more than 1300 companies holding licenses for salmon and trout (eurofish.dk).

Within CERES, models were based on a typical grow-out farm site located in the county of Nordland and with 3680 tonnes of production (NO-SAL-3680) (Figure 2).

Despite being a much smaller producer of only 16,300 metric tonnes in 2016, Ireland is EU's leading producer of organic salmon (Eurostat).

There are 16 grow-out production units and seven smolt licences in 2016, with the majority of production taking place in the north-west of the country (Donegal).

Other significant production regions are located along the west coast (Mayo, Galway) and in the south-west (Cork) (BIM Annual Aquaculture Survey 2017).

The vast majority of salmon farms in Ireland are owned by Mowi Ireland, however a number of smaller independent units also exist. Such sites are typically located in more peripheral rural areas along the north, west and south-west coasts of Ireland (Grealis et al. 2017).

The whole of Ireland's salmon is produced according to organic standards following a diet of organic approved feed, low stocking densities and being mostly located at high energy exposed sites (for EU organic certification see EC 834/2007, EC 889/2008).

The value of the Irish salmon production for 2016 was estimated at €105 million (BIM Annual Aquaculture Survey 2017; DAFM Report, 2017, Mid-Term Assessment National Strategic Plan for Sustainable Aquaculture Development) and the majority is exported (65% in 2017), mostly to France, Germany and recently a high market share went to Poland, whereas imports originate largely from the UK (EUMOFA database: eumofa.eu).

The Irish salmon typical farm defined in CERES is located in Donegal and produces 1540 tonnes (IE-SAL-1540) (Figure 2).

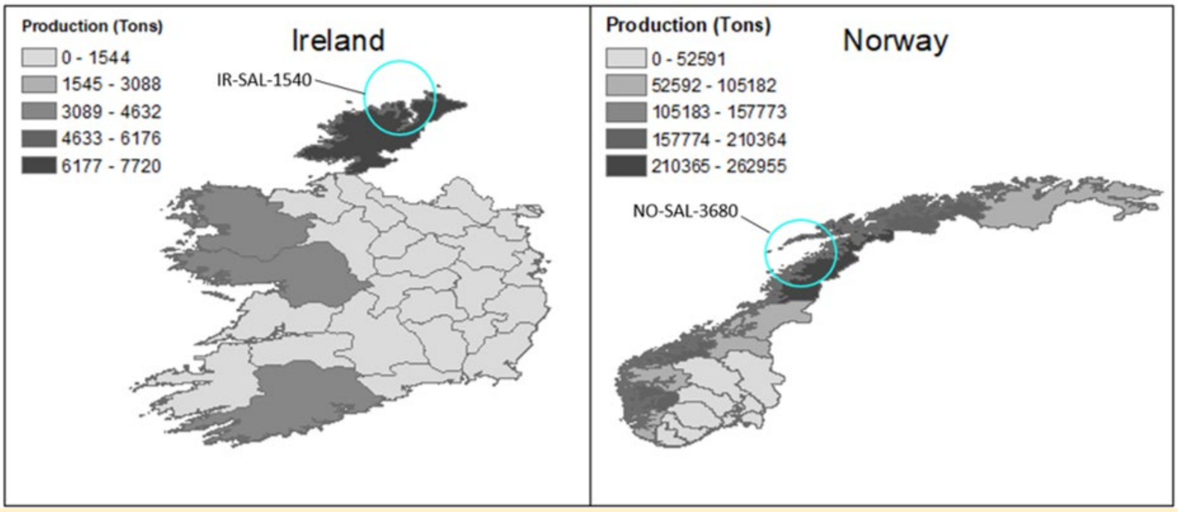


Figure 2 Atlantic salmon regional production in tonnes for the year 2016 in Ireland and Norway. Location of typical salmon farms are indicated by the open circles and labelled with a country-species-yearly production code (tonnes, e.g. IR-SAL-1540 for Ireland, salmon, 1540 tonnes). Data course: Ireland's Seafood Development Agency (BIM) and Norwegian Directorate of Fisheries.

Expected projections under climate change

Sea surface temperatures for Ireland are projected to increase over the 21st century by less than 1°C under a moderate emissions scenario (RCP 4.5) and 1.0 to 1.5°C under a high emissions scenario (RCP 8.5) (Figures 3 & 4).

For the southern part of Norway (Figures 3 & 4) the projected rise is about 1.5°C under RCP 4.5 and 2.0 to 2.5°C under RCP 8.5. These values have relatively high uncertainty because modelled temperatures for Ireland are influenced by the position of the Gulf Stream in global climate models, which varies considerably from model to model.

These higher-resolution model projections of increase in temperature generated from CERES are at the low end of projections made by lower resolution, global climate models for this region

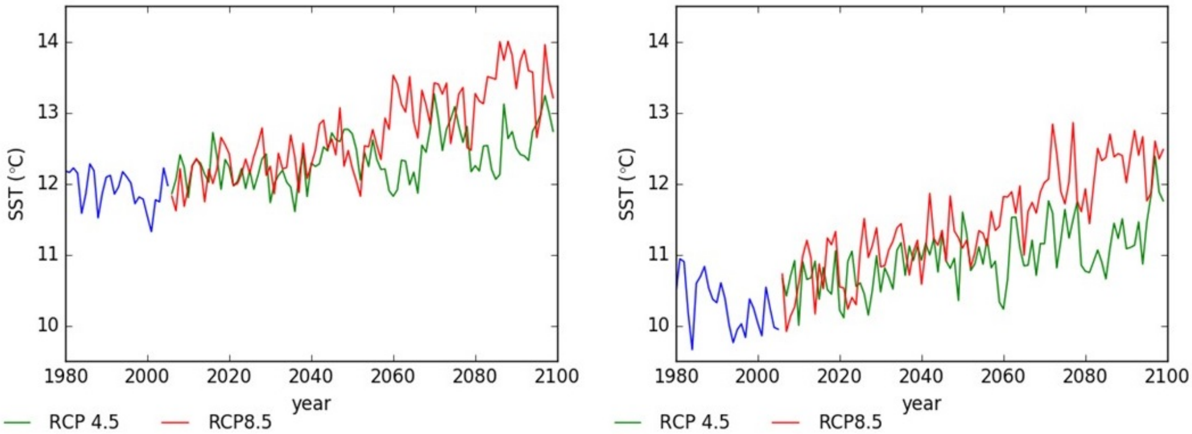


Figure 3: Annual mean sea surface temperature for Ireland (left) and Norway (right)

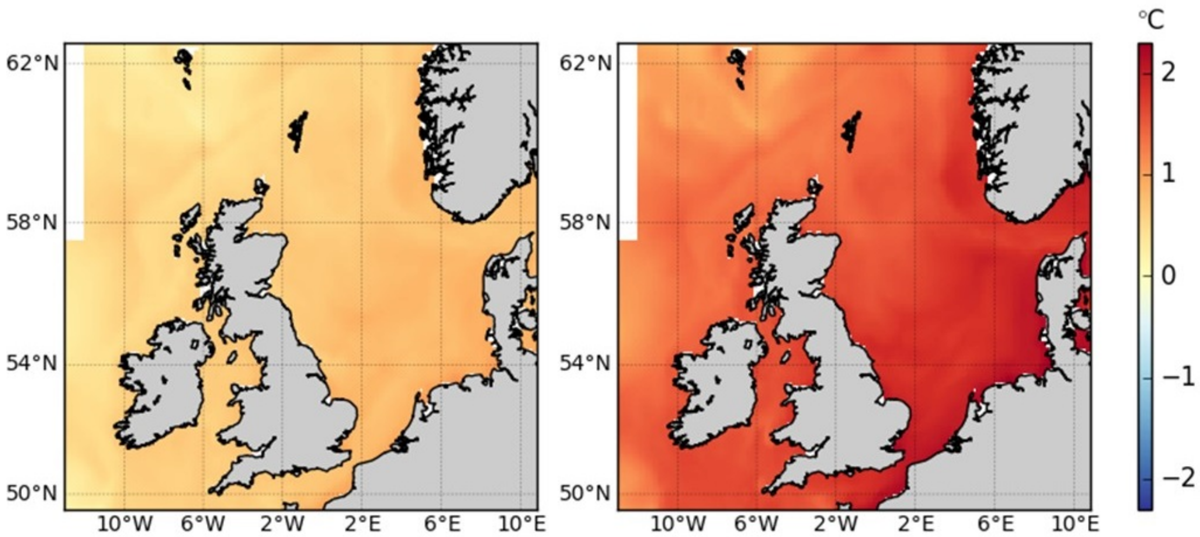


Figure 4 Sea surface temperature for Ireland/Norway difference between 2080-2099 and 2000-2019 under RCP 4.5 (left) and RCP 8.5 (right).

Assessing the proportion of days within a year where water temperatures are predicted to be in the optimal growing range for salmon suggests a greater amount of difference in the suitability between the two countries, with Ireland predicted to have 64% of days in the optimal temperature threshold whereas Norway will have 53% of days (Tables 1 & 2).

Under both RCPs the suitability is predicted to increase, however whilst the predicted increase is similar for both countries under RCP 8.5, with 7.8 and 7.4% for Ireland and Norway respectively, there is a larger predicted difference under RCP 4.5 at 8 and 4.6% respectively (Table 2).

Country	Average national present-day water temp	Average national 2050 water temp – RCP4.5	Average national 2050 water temp – RCP8.5	Percentage change in national average water temperature in 2050	
				RCP 4.5	RCP 8.5
Ireland	11.44°C (SD= 0.73°C)	11.89C (SD= 0.73°C)	11.940C (SD= 0.75°C)	3.97%	4.36%
Norway	10.45°C (SD= 0.31°C)	10.930C (SD= 0.33°C)	11.120C (SD= 0.28°C)	4.58%	6.46%

Table 1 Average predicted water temperatures in case study countries and predicted change under RCP 4.5 and 8.5

Country	Present day proportion of optimal	Present day proportion of optimal	Present day proportion of optimal	Annual national average change in temperature suitability for Atlantic Salmon in 2050	
				RCP 4.5	RCP 8.5
Ireland	0.64	0.69	0.68	8.01%	7.80%
Norway	0.53	0.55	0.57	4.62%	7.40%

Table 2 Predicted annual proportion of days in which water temperatures are predicted to be in the optimal growing temperature range for Atlantic Salmon (10-16°C) under current climate and predicted percentage change under RCP 4.5 and 8.5 projections

Global mean sea level rise for 2081-2100, compared to 1986-2005, is projected to be in the range 0.32-0.63 m for RCP 4.5 and 0.45-0.82 m for RCP 8.5 (medium confidence).

Sea level rise in Europe is projected to be slightly higher than the global mean for the Atlantic and up to 30% lower for the most northerly regions of Europe, including Norway.

Projections of changes in storminess have high uncertainty; according to IPCC Assessment Report 5 (IPCC, 2013) there are some indications of an increase in extreme wind speeds in Norway (medium confidence).

Storm surges are projected to increase in Ireland (except in the south) and Scotland.

Scenarios describing future society and economy

CERES uses models to estimate economic developments in Europe's fishery and aquaculture based on select, pre-defined physical and socio-economical future scenarios. These future scenarios were specified by industry partners and stakeholders in the first year of CERES (e.g. fish prices, fuel prices, technological advancements, regional policy issues, etc.).

'World Markets'	'National enterprise'
• Personal independence, high mobility and consumerism • Reduced taxes, stripped-away regulations • Privatised public services • High fossil fuel dependency • Highly engineered infrastructure and ecosystems	• National isolation and independence • Protection of national industry • High resource intensity and fossil fuel dependency • Low investment in technological development and education • Low priority for environmental protection
'Global sustainability'	**'Local stewardship'**
• High priority for welfare and environmental protection • Cooperative local society • Intense international cooperation • Increased income equality • Low resource intensity and fossil fuel dependency	• Promotion of small scale and regional economy • Less attention for global (environmental) problems • Moderate population growth • Income of industrialised and developing countries converge • No overarching strategy to manage ecosystems

Table 1 Outline of the four social-political scenarios developed by CERES partners and stakeholders

Socio-economic effects

Short-, medium- and long-term developments in governance, social, technological and economic drivers may be just as important to aquaculture as climate-driven changes in habitats and species. CERES uses four imagined future socio-political scenarios in all bioeconomic modelling exercises.

These scenarios are imagined, yet plausible 'futures' that can be optimistic or pessimistic, and are based on future political situations, environmental attitudes, markets, and potential technological innovations.

Scenarios go beyond a single best estimate, or a 'high' and 'low' projection, and explore a number of different, logically-coherent pathways.

The four scenarios are: World Markets (WM), National Enterprise (NE), Global Sustainability (GS) and Local Stewardship (LS). Under World Markets (RCP 8.5) people aspire to personal independence, material wealth and greater mobility, all of which have a negative effect on wider societal and environmental goals. Pressure grows to reduce taxes and strip away regulation. Under National Enterprise (RCP 8.5) there is increased national isolation and independence.

Long-term economic growth is limited by government policies that limit international competition and protect national industries. Under Global Sustainability (RCP 4.5) people aspire to high levels of welfare and a healthy environment.

The best way to achieve this is through international cooperation. Under Local Stewardship (RCP 6.0) public policies aim to promote economic activities that are small scale and regional.

There is an important focus is on using technology and new ideas to make the best use of local and regional resources. For CERES, the biological and economic projections for the salmon aquaculture industry are viewed through these four lenses (scenarios).

Key research needs

There is a large uncertainty surrounding many of the potential direct and indirect impacts of climate change on salmon aquaculture.

For example, despite studies on fish growth (Elliott and Elliott 2010; Brett et al. 1969; Brett and Groves 1979; Elliot and Elliott 2010) and industry based models, there is uncertainty on how post-smolt salmon will respond to long term exposures to increasing temperatures (Tromp et al. 2018; Hvas et al. 2017; Antilla et al. 2014).

Generally, it is considered that the optimal temperature range for salmon is between 15-18°C and that that 18.9°C is above optimum for growth and development in seawater (Handeland et al. 2000).

Yet, the picture is much more complicated as salmon are farmed in areas where average water temperatures approach upper thermal limits for the species (e.g. in Tasmania summer water temperatures can average over 19°C over several weeks, Nuez-Ortín et al. 2018). In terms of indirect effects, similar long-term studies to examine trends for well-established threats and/or limited data on new and emerging threats exist.

For example, while sea lice are the most important parasite problem in Norwegian aquaculture and hampers the growth of the industry, there are relatively few climate change studies on sea lice. However, a recent study by Samsing et al. (2016) clearly demonstrates that sea lice follow the universal model of temperature dependence as described for other marine ectotherms (Gillooly et al. 2001; Samsing et al. 2016) and therefore, sea lice develop faster into the infective copepodid stage as sea temperature increases (Samsing et al. 2016).

The effects of such temperature dependence on larval dispersal, mortality, and population connectivity needs to be examined. In terms of diseases, Pancreas disease (PD) has for a long time being the most important viral disease for salmonids in Norway and Ireland. Then in 2018, cardiomyopathic syndrome (CMS) has emerged as increasingly important in Norway, Ireland, Scotland and the Faroes.

Infectious Salmon Anemia (ISA) and Heart and Skeletal Muscle Inflammation (HSMI) remains viral diseases of major importance (Hjeltnes et al. 2019). Amoebic Gill Disease (AGD) has emerged as one of the most significant health challenges in marine salmon in northern Europe.

Despite the identification of risk factors for AGD such as high water temperature and high salinity, there remains a dearth of knowledge on the factors that have led to this dramatic increase in prevalence and impact (Oldham et al. 2016). In Norway, AGD has emerged, but not to a high level, as previously feared.

In terms of other risks, there are also no jellyfish time series to examine whether the most harmful jellyfish species to the salmon aquaculture industry, e.g. Pelagia noctiluca, are increasing in the North Atlantic and limited research to show the effectiveness of proposed mitigation measures (e.g. bubble curtains) or models to forecast jellyfish blooms.

There are also very limited studies on the interaction of changing biofouling cleaning methods, parasites, environment (in particular temperature and salinity) with marine aquaculture finfish species.

Finally, future projections of climate change impacts that take into account both these direct (e.g. physiological) and indirect (ecological) effects are needed.

CERES research

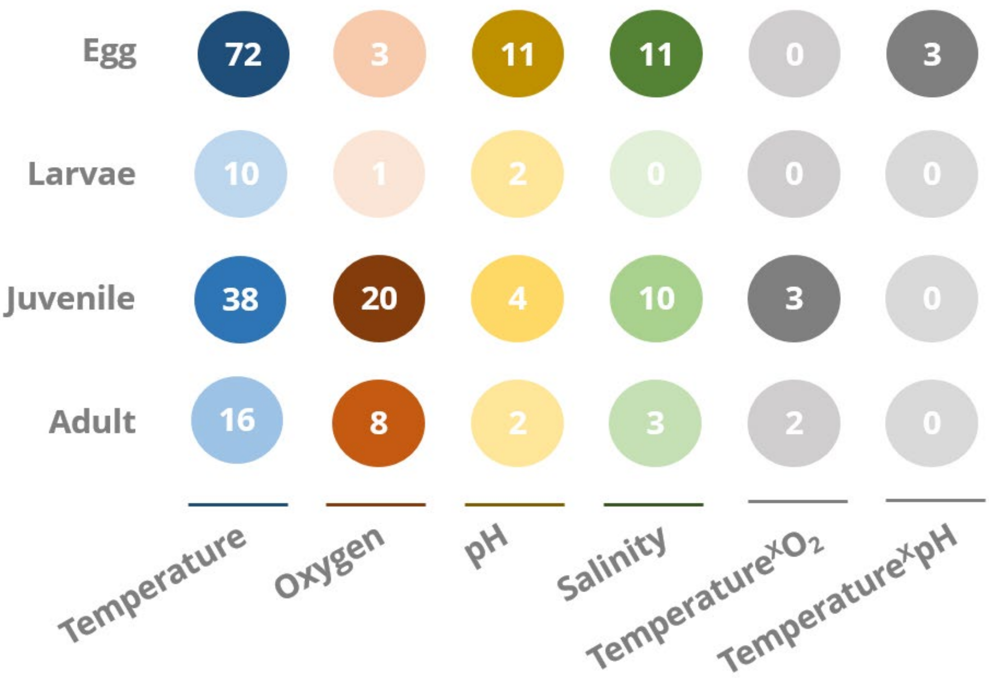
The key activities carried out in CERES on salmon aquaculture in both Ireland and Norway were:

- Calibrated two existing models to provide projections of the biological impacts of future environmental changes associated with RCPs 4.5 and 8.5 at the individual (physiological) to farm (production) levels. The growth performance of individual salmon was determined by means of a net energy balance model using the modelling software WinFish that used water temperature to drive the model (Ferreira 2013). Scaling of individual based models to populations used the FARM model software (Ferreira et al. 2007) which integrates a combination of physical, biogeochemical and salmon growth models to determine production under the different climate scenarios.
- Explored the bioeconomic consequences for CERES social-political scenarios on the future profitability of salmon cage farming based on typical farm data for Ireland (organic) and Norway (industrial).
- Demonstrated that a habitat suitability modelling approach using the best available knowledge of a salmon’s environmental requirements in combination with modelled temperature can be used to assess the suitability of habitat to predict the likely abundance and distribution of pathogens under future scenarios.
- Conducted a Gap analysis of knowledge on the direct effects of climate (changes in temperature, pH, salinity and dissolved oxygen) on European aquaculture targets comparing across species (including salmon) and regions.
- Constructed a risk map (BowTie analysis) for climate change impacts on the aquaculture of salmon via engagement with representatives from Norwegian, Scottish, Irish, Australian and Chilean salmon aquaculture industry.
- Review and analyses of changed impact of major disease problems, viral, bacterial and parasites, in the light of increased temperatures, and migrating wild species in the environment surrounding the fish farms.
- Performed a climate vulnerability assessment comparing salmon and other key European aquaculture targets including species-level exposure and sensitivity and the industry’s adaptive capacity.

The following additional activities were mostly carried out in Ireland:

- Conducted extensive stakeholder engagement with the salmon aquaculture industry in Ireland to determine their main concerns, establish the industry's understanding of climate change.
- Examined historical trends in the indirect effects of climate change on salmon aquaculture including field time series data on jellyfish blooms, including one of the most harmful jellyfish species in the NE Atlantic (Pelagia noctiluca).
- Constructed a probabilistic model for the weather-driven occurrence of harmful jellyfish in a specific bay in Ireland as a test case for creating early-warning estimates useful for salmon farms.
- Tested the effectiveness of bubble curtains for protecting salmon cages against contact with jellyfish blooms.

Results



- Salmon ranked 5 out of 28 European fish and shellfish genera reviewed here (18 studies).
- A strong regional bias was observed. 14 studies in the NE Atlantic were from Norway.
- All studies included growth measurements.
- The most common stressor studied was temperature (9), followed by oxygen (5).
- 9 studies were performed on juveniles, no studies on larvae were found

Biological

A literature review of potential direct effects found the following:

- Increased sea temperatures may lead to faster growth rates of salmon in certain areas. However, prolonged periods of warmer summer temperatures may cause thermal stress (Gubbins et al. 2013) which reduces growth potential, and may make fish more susceptible to disease.

- Increased sea temperatures may open up new areas for salmon aquaculture production at higher latitudes (e.g. in Norway, Iceland), but equally may reduce production in more southern areas that are already on the temperature limits for this species. Thus, overall there may be a shift from current production areas to areas further north, and may drive production further offshore.
- Changes in the frequency and strength of storms may pose a risk to industry infrastructure, e.g. salmon pens may be dislodged from seabed (Callaway et al. 2012). There is a strong need for more robust technical solutions.
- Independent of climate change, but due to the need to decrease the environmental footprint development of new systems such as closed or semi-enclosed cages, and offshore aquaculture systems are initiated. At present, one farm is operated offshore (Salmar, outside the Froan islands). More projects have been proposed and are in the process of realization. A legislative and management framework for offshore aquaculture in Norwegian waters is being developed. An initial mapping and suitability study of Norwegian offshore waters for aquaculture purposes was recently published (Fiskeridirektoratet 2019)
- Adverse weather events may also temporarily limit production (e.g. by reduced feeding) and health management practices (i.e. removal of mortalities, health treatments). In addition, increased strength of storms can lead to physical skin damage to the fish, which can then be prone to secondary bacterial infections.
- With climate change it is predicted that winds will increase in intensity and storminess (Hinder et al. 2012), so harmful jellyfish species such as Pelagia noctiluca or Muggiaea atlantica may be swept into coastal waters of the North East Atlantic more frequently, which can cause fish health issues.

A literature review of indirect effects found the following:

1. Increased temperatures may increase the geographic range of some diseases (northern spread) and increase the occurrence of as yet unknown or emerging diseases.
2. Sea lice, Amoebic Gill Disease (AGD), Pancreas Disease and Infectious Salmon Anaemia are some of the main challenges for the industry in sea water. As the life cycle of parasites is directly related to sea water temperatures, it is therefore possible that the impact of sea lice and AGD will increase with warming seas (Johansen et al. 2011; Oldham et al. 2016; Rittenhouse et al. 2016).
3. White spot (caused by the protozoan parasite Ichthyophthirius multifiliis) is an important disease for freshwater Atlantic salmon stages, and the parasite life cycle is also directly associated with water temperature (Karavonen et al. 2010), which may increase as temperatures increase.
4. Increased incidence of AGD and sea lice may lead to an increase in the number of disease treatments. Bath treatments used for AGD, and sea lice, include pumping fish into wellboats or enclosing cages in tarpaulins and adding freshwater, hydrogen peroxide or other pharmaceutical compounds. Higher water temperatures may increase risk of fish losses during bath treatments due the higher oxygen requirements during treatment, fish stress and increased toxicity (i.e. hydrogen peroxide). Hydrogen peroxide treatment is not recommended above 13.5°C and higher sea temperature may limit this treatment as an option. Periods of low rainfall in particular in areas where hydroelectric power plants have altered the freshwater supply, as in most Norwegian fjords, may also limit access to freshwater. Mechanical treatments, the removal of lice using brushes,

water pressure or hot water for example, are increasingly used to treat sea lice infections but can pose a risk to fish health and welfare if done too often or if fish are predisposed through other conditions such as subclinical infections or poor gill condition. Exact threshold levels are poorly defined but warmer temperatures can increase the risk posed by crowding and treatments, as well as necessitating more frequent treatments.

5. Lumpfish (Cyclopterus lumpus) and wrasse (Labrus bergylta) are used as a biological control for sea lice in Atlantic salmon aquaculture. These fish eat sea lice to lower the concentrations. However, lumpfish are cold water species and increasing sea temperatures may lead to thermal stress, which may reduce efficacy and result in lower efficiency, as well as predisposing the fish to diseases. However, the use of lumpfish and/or wrasse as cleanerfish potentially pose health risks as both carry diseases and therefore cohabitation with salmon may increase risk of disease (Brooker et al. 2018). Increased hatchery outputs for both species are needed to protect wild stocks (Brooker et al. 2018). Furthermore, the high (up to 100%) mortalities of both lumpfish and wrasse, when used as cleanerfish, have caused great concern regarding fish welfare. In general, cleanerfish is viewed as an interim solution, not sustainable in the long term.
6. Fish mortalities due to jellyfish are more frequently reported in Ireland, with Pelagia noctiluca being the most harmful species to the aquaculture industry.
7. Gill health is one of the main health challenges for the industry, and gill disease can be caused by infectious and non-infectious agents. Increasing temperatures, leading to increased pathogen load, and increasing phyto- and zooplankton blooms may increase impact and prevalence of complex gill disease cases.
8. The biofouling hydroid Ectopleura larynx is the predominant fouling organism on salmon nets in the North Atlantic (Blöcher et al. 2013). Increased abundances of this species (either through increased growth rates, or a prolonged season for growth) will result in added production costs due to increased frequency of cleaning or changing of nets. The costs associated with such biofouling are substantial (Floerl et al., 2016) and the blasting of such hydroids into the water can directly sting and injury the salmon (Baxter et al. 2012).
9. Some other potential impacts, not be related to climate change specifically but relevant in the overall context, relate to management of the industry. The current inflexibility to implement adaptive changes to sites, technology and management practices, without the need long and complex license changes, hinders adaptive change, especially in Ireland. Also, if certain locations can no longer support salmon production due to climate change, scaling up production in other areas to offset the loss of business and reduced supply is not a simple or short task, and thus food security may become an issue.

Jellyfish research

Predicting harmful jellyfish species: An empirical model, based on the sequence of wind speed and direction of wind in the bay (Raine et al. 2010), was successfully applied to predicting the occurrence of a harmful jellyfish bloom in Bantry Bay, Ireland.

Results indicate that an exchange event in Bantry Bay which coincided with fish mortalities and an increase in the harmful jellyfish (Muggiaea atlantica) was successfully hindcasted.

Notably, there is a 'flip flop' event (water exchange) in early October with negative axial winds plus a wind index value approaching -10 m s-1 (Figure 5 a & b) which coincides with a significant increase in fish mortality (Figure 5 c). The prediction is supported by Figure 5 d which shows an increase in sea temperature and abundances of the harmful jellyfish Muggiaea atlantica only approach the critical level of 300 individuals per meter (levels known to cause fish mortalities, Baxter et al. 2012) after the exchange event.

While this model successfully hindcasted a salmon mortality event associated with harmful jellyfish it requires testing in real-time under varying environmental conditions to validate its operation.

Jellyfish time series: The first time series for Pelagia noctiluca in the North East Atlantic was produced (Figure 5). Spatially, there is considerable inter-annual variation in the distribution of P. noctiluca. At its most extreme, P. noctiluca was found throughout Irish shelf waters in 2016 but was entirely absent in 2018.

Whereas in other years, P. noctiluca can be restricted to the north, west or southwest. However, abundance estimates suggest that the majority of the P. noctiluca tend to be in one region.

For example, from 2009-2013, P. noctiluca has a more central distribution off the west and northwest coasts, whereas in 2014-15 and 2017, P. noctiluca is more abundant off the west and southwest coasts.

Further work is being carried out on this dataset to model the advection of this species into Irish shelf waters from further west and south (manuscript in preparation).

Bubble curtain trials: In September 2017, a bubble curtain was installed around a six-cage salmon array in Donegal, Ireland. The bubble curtain consisted of 2 cm diameter perforated tubing that was ~800 m long and was supplied with air from a Compair C200TS compressor.

The tube was installed 5 m below the surface using the anchoring network around the cages as attachment points. In order to test the effectiveness of the bubble curtain, plankton tows were sampled both inside and outside the bubble curtain during 12 days in September 2017.

The jellyfish species Muggiaea atlantica and Clytia hemisphaerica accounted for the majority of the hydromedusae present during the test (48 ± 29 and 31 ± 25 %, respectively). Importantly, there was no significant difference in the mean abundance of jellyfish inside (36 ± 19 indiv. m-3) and outside (42 ± 18 indiv. m-3) the bubble curtain ($t(40) = -1.047$, $p = 0.3$), suggesting that the bubble curtain did not act as an effective barrier to harmful jellyfish species.

However, as there were considerable technical problems maintaining the bubble curtain during the testing, and the conditions were far from ideal, the results cannot be considered unequivocal (manuscript in preparation).

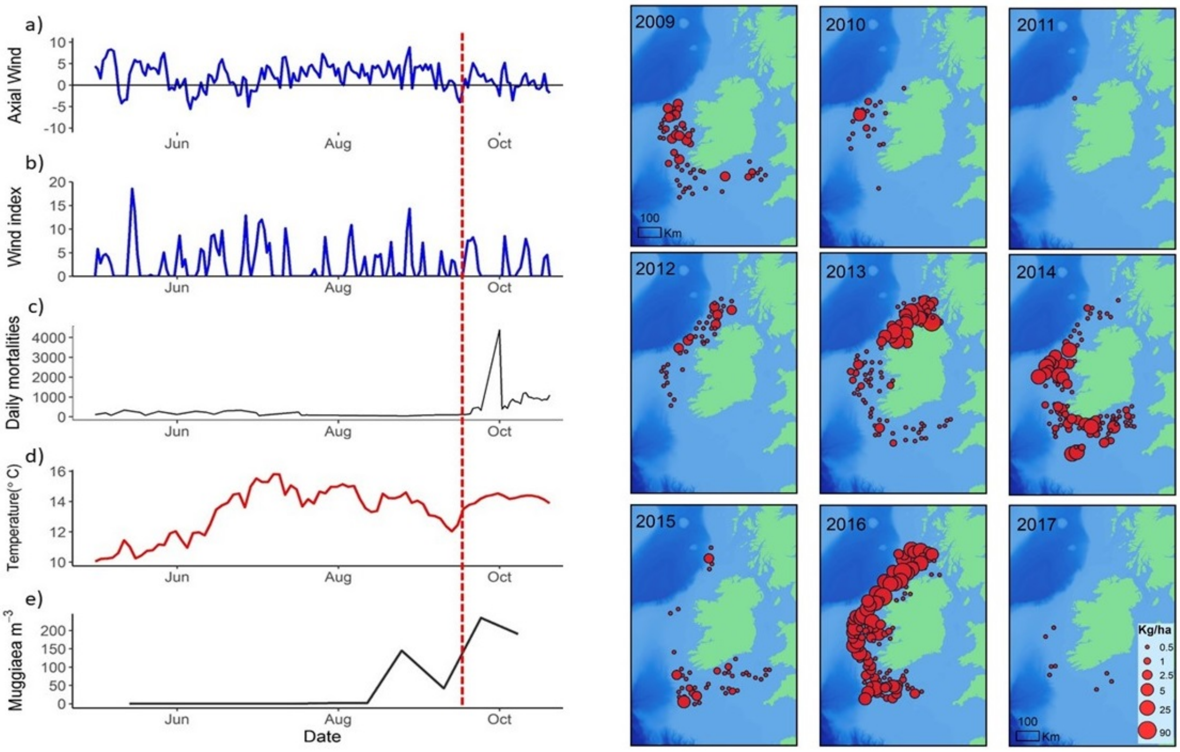


Figure 5 Left) Bantry Bay time series for 2009, with axial wind (a), wind index (b), daily mortalities of fish at salmon farm (c), temperature (d) and mean Muggiaea atlantica abundance (e). Vertical red dash line indicates exchange event predicted by flip-flop event in bay (negative axial wind component in (a) + wind index value approaching -10 m s^{-1}). Right) Catches of Pelagia noctiluca from the Irish Groundfish Survey conducted from 2009 until 2017. Bubble size represents the abundance in kg Hectare ^-1. 2018 data not shown because no jellyfish were caught.

Individual fish growth model and FARM production models:

The salmon growth model and the FARM production model were validated against current conditions at both locations to match reported growth and production estimates practices (Table 3, Figure 6 and Figure 7). The validated models were used to simulate present (2000-2019), mid-century (2040-2059), and late-century (2080-2099) conditions under two emission scenarios: RCP 4.5 – more conservative, and RCP 8.5 – more severe.

Country	***Ireland***	***Norway***
Location	55° 10' N, 7° 33' W	67° 11.26 N, 14° 23.6 E
Leased area (m^2)	169,950	40,500
Cultivated area (m^2)	18,970	8,010
Culture cycle (days)	529	590
Stocking density (ind. m^{-2})	21.5	78.3
Mortality (% over cycle)	30	5
Juvenile cost (€ per thousand fish)	797	1,250
Feed cost (€ kg^{-1})	1.51	1.11
Farmgate sale price (€ kg^{-1})	6.0	5.5

Table 3 Comparison of culture practice for the typical salmon farm in Ireland and Norway. This data was used to run the FARM model under current conditions and different climate change scenarios.

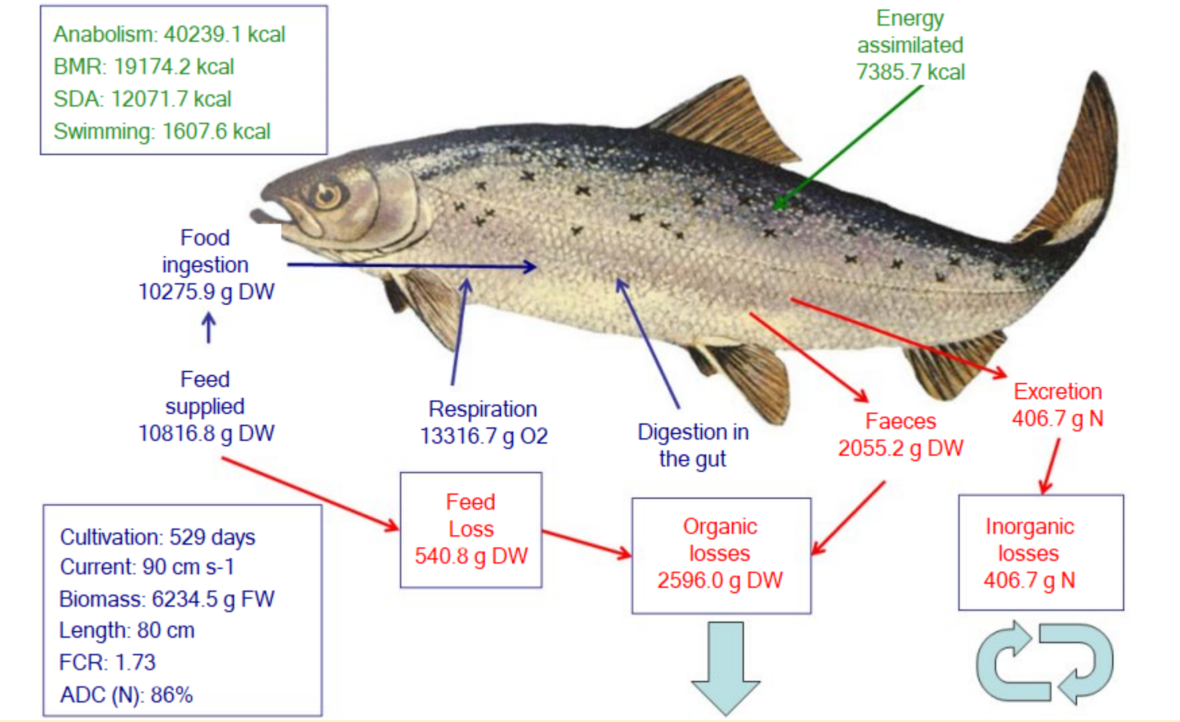


Figure 6 WinFish mass balance results for an individual salmon over a full growth cycle at the typical open water farm in Ireland. DW (FW): dry (fresh) weight; BMR: basal metabolic rate; SDA: specific dynamic action; FCR: feed conversion rate.

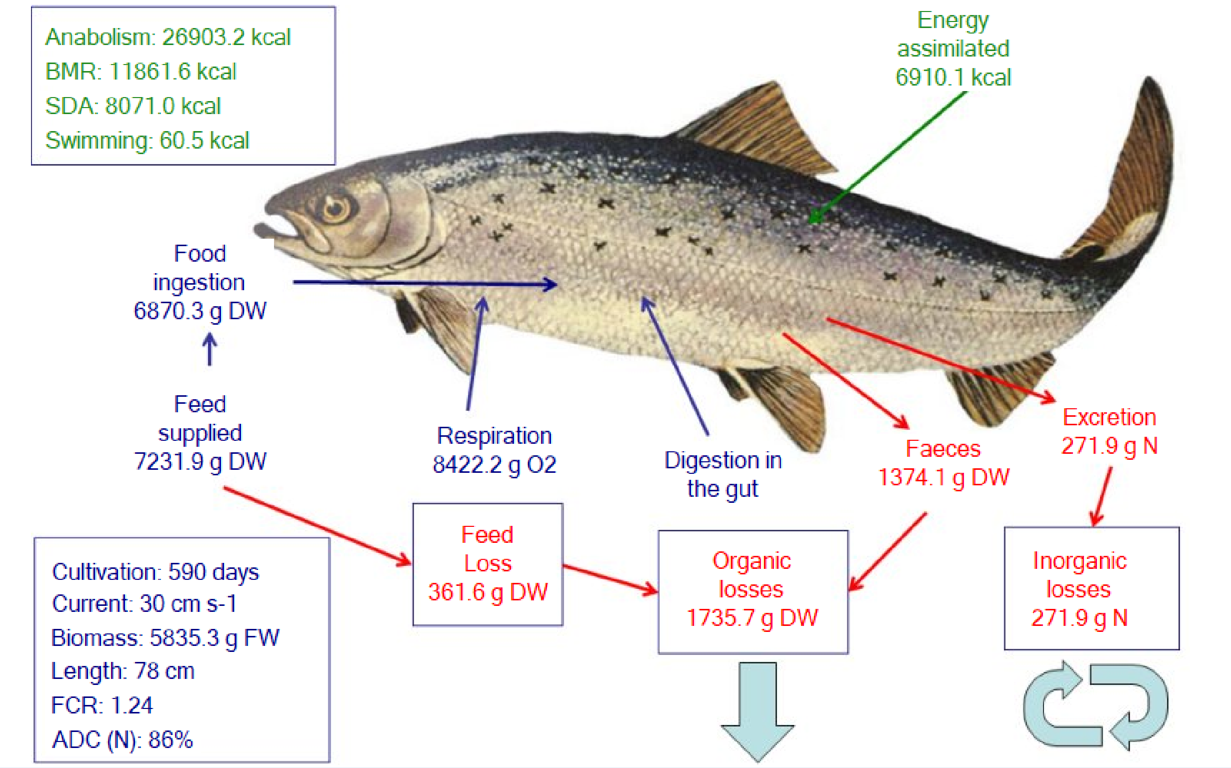


Figure 7 WinFish mass balance results for an individual salmon over a full growth cycle at the typical open water farm in Norway. DW (FW): dry (fresh) weight; BMR: basal metabolic rate; SDA: specific dynamic action; FCR: feed conversion rate.

FARM modelling results for the typical salmon farm in Ireland and Norway under climate change scenarios (in the absence of technology change and attempts to mitigate climate change): In Ireland, salmon size at harvest would increase as climate change progresses, except for the last-century high-emission scenario when temperature would be too high for salmon and growth would slow down (Figure 8 a).

This improvement in growth is not reflected within the profits which decrease over time; this decline is especially important in the last-century high-emission scenario (Figure 8 b) (Note: the FARM model results here provide projections of the biological impacts of future environmental changes on current profits in contrast to the Typical Farm analysis below [Figs 12 and 13] which explores the effect of social-political scenarios and environmental changes on the future profitability of salmon farming).

The feed conversion ratio (FCR) for Irish salmon worsens over time, with no differences between low and high emission scenarios (Figure 8 c). This is also reflected in the greater amount of feed and dissolved oxygen consumed by the fish as climate change progresses (Figure 8 d and 8 e).

In Norway, due to colder baseline (current) temperatures and the abscence of RCP 8.5 scenarios, we do not reach such high temperatures as to observe a negative effect on salmon growth (Figure 9 a). Growth and profit increase in the mid-term scenario and stagnate in the long-term scenario (Fgure 9 a and b).

For Norwegian salmon all parameters follow the same pattern: as climate change progresses they increase in the mid-term scenario and then stagnate in the long-term scenario as temperature rises (Figure 9 a-e).

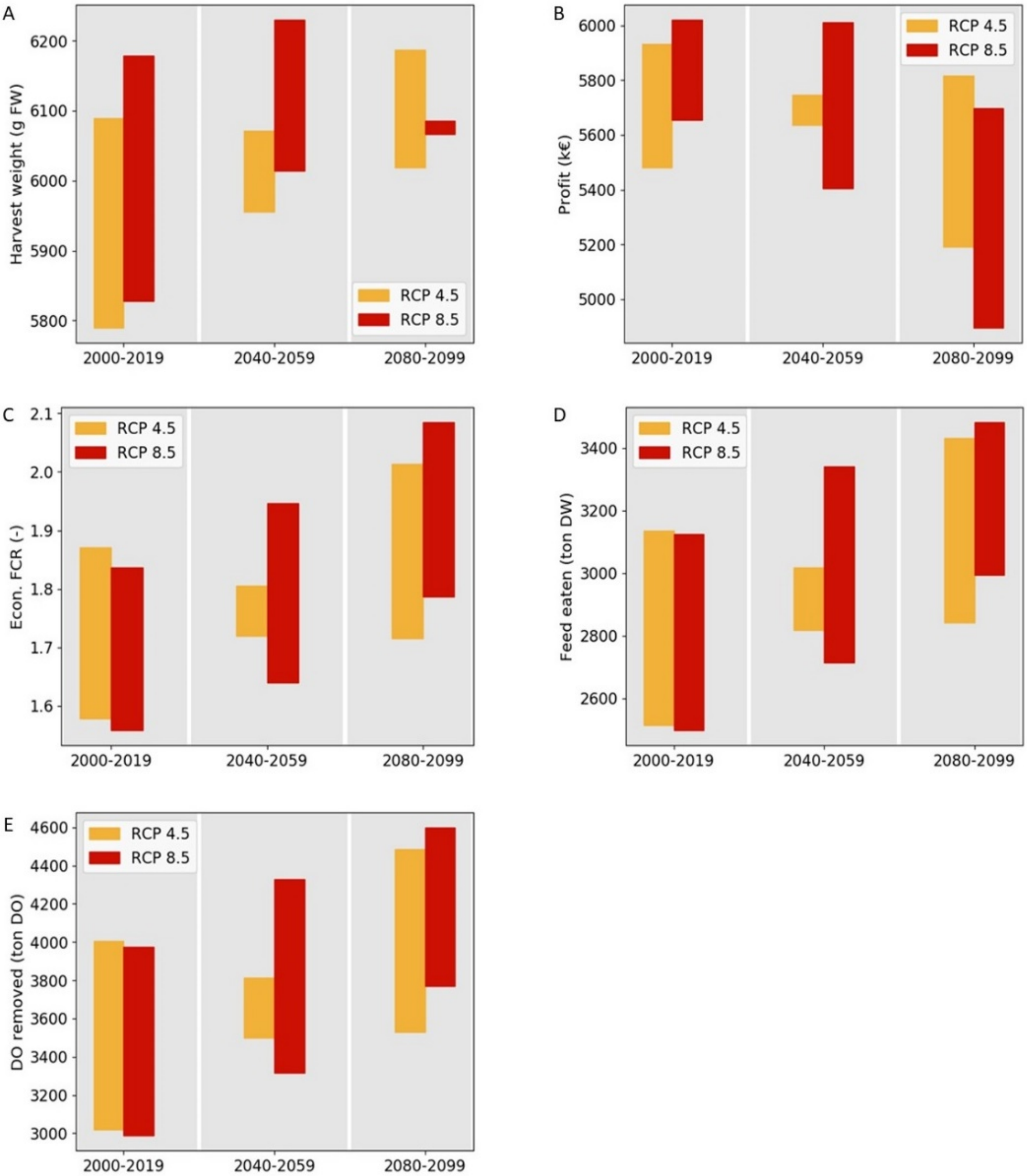


Figure 8 Range of FARM outputs for the typical salmon farm in Ireland under the different climate change scenarios. Orange and red bars represent the range (spread) of simulation values for the low- and the high- emission scenario, respectively. The drivers for the different climate change scenarios were obtained from the POLCOMS model as detailed in the text. LW: live weight; DO: dissolved oxygen.

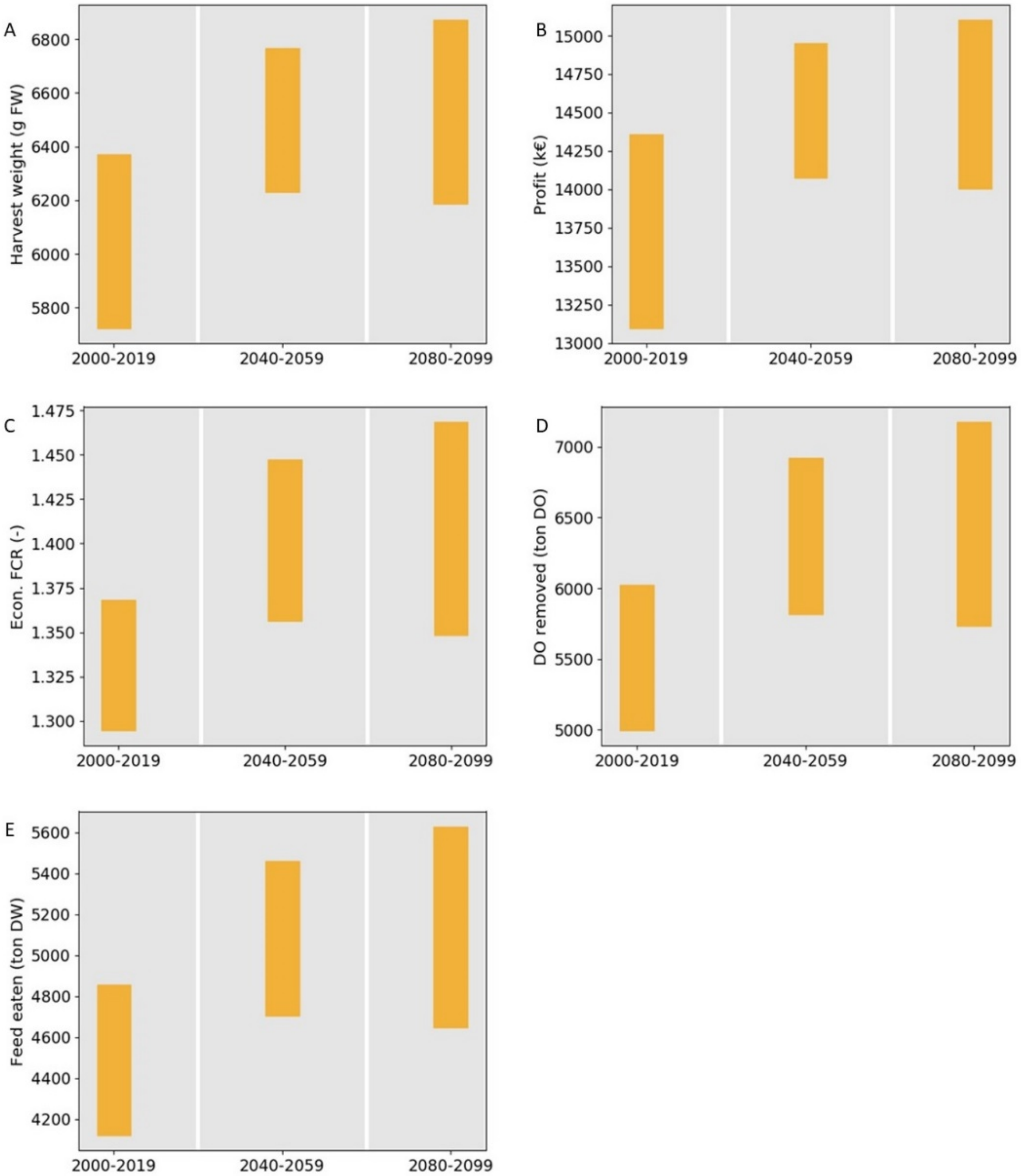


Figure 9 Range of FARM outputs for the typical salmon farm in Norway under the different climate change scenarios. Orange bars represent the range (spread) of simulation values for the low-emission scenario. The drivers for the different climate change scenarios were obtained from the POLCOMS model as detailed in the text. LW: live weight; DO: dissolved oxygen.

Indirect effects of CC: A risk mapping approach was taken to determine the 'number of days' water temperatures across the study areas are likely to be within the permissive temperature range for each of the pathogens studied.

These pathogen suitability values were developed to represent changes in the proportion of days of an average year in a time period that the most optimal infection temperatures occur across key taxa, using literature sourced disease temperature thresholds and predicted water temperature changes in the year 2050 under RCP 4.5 and 8.5.

Suitability analysis for Atlantic salmon suggest around 11% more days are within the optimal growth range in Ireland compared to Norway (64% vs. 53% of days in the year, respectively) (Tables 4 and 5).

Suitability for salmon will increase in both countries under both RCP's, but the largest increase would be in Ireland under RCP 4.5 (8%). In both countries, the biggest increase in temperature suitability is likely to be for Vibriosis. However, due to the high temperatures required for this bacterial disease, its current likelihood is low (>2%) and Amoebic Gill Disease (AGD), which is already a significant problem, is likely to be of far greater concern in both countries under either RCP.

Species / disease	Temperature threshold (°C)	Mean proportion of days per year (period: 2000-2020) that temperatures fell within the species or pathogen temperature thresholds	2050 change (%) in suitability under RCP 4.5	2050 change (%) in suitability under RCP 8.5
Salmon	10-16	0.64	8	7.8
ISA	10-15	0.59	4	4.4
AGD	12-20	0.44	10.98	11.39
Vibriosis	16+	0.02	46.87	73.19
Furunculosis	19-25	0	0	0

Table 4: Temperature suitability values for salmon and pathogens in Ireland. Values highlighted in red highlight highest the biggest increase in the suitability for a pathogen under the two climate projections.

Species / disease	Temperature Threshold (°C)	Mean proportion of days per year (period: 2000-2020) that temperatures fell within the species or pathogen temperature thresholds	2050 change (%) under RCP 4.5	2050 change (%) under RCP 8.5
Salmon	10-16	0.53	4.62	7.4
ISA	10-15	0.49	-1.19	1.95
AGD	12-20	0.37	12.96	16.44
Vibriosis	16+	0.007	181.04	232.6
Furunculosis	19-25	0	0	0

Table 4: Temperature suitability values for salmon and pathogens in Norway. Values highlighted in red highlight the biggest increase in the suitability for a pathogen under the two climate projections.

Economic consequences

Typical farm model assessments (Figure 10 and Table 8) show that the Norwegian typical farm has a much higher profit margin (27.51%) than the Irish typical farm (17.35%) today.

Feed costs are the most substantial cost for both countries although their absolute cost per kg fish is very similar (differ by 4 cents/kg). Feed costs as a percentage of total costs is 1.3 times higher in Norway than Ireland, which is due to the overall higher cash costs for Ireland.

The share of stocking costs of total cash costs is more than 2 times higher for Norway than Ireland.

However, labour costs are a lot higher for the Irish typical farm than the Norwegian farm, both in absolute costs per kg fish produced, as well as allocation of total cash costs. Although producing less than half of the production volume of a typical Norwegian farm (1540 vs. 3680 tonnes), the Irish farm has more labour and 19 times greater labour costs per kg fish produced due to less opportunities to contract services, but also a lower level of automation.

However, the Norwegian farm has 16 times higher diesel costs and higher licence costs.

Veterinary costs are important and similar for farms in both countries. It should be noted that the data used in the mode is a snapshot from 2016.

The industry is highly dynamic, thus the picture is changing both in terms of fish feed composition, the impact of different pathogens, and the consumption of fuel/transfer to electric propulsion.

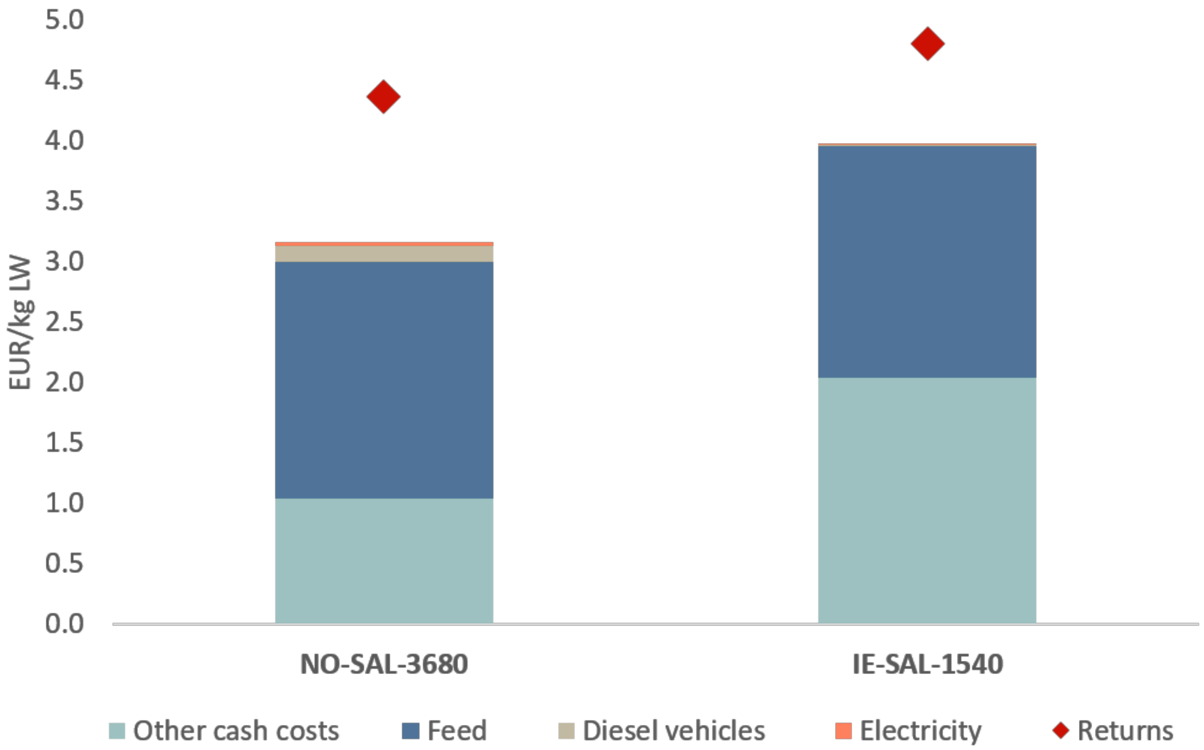


Figure 10 Costs and returns from typical Atlantic salmon farm models showing stacked costs and returns. The distance between the red returns point and the top of the stacked costs represents the short-term profit/loss.

IR-SAL-1540	2016	NO-SAL-3680	2016
Operating earnings (€/kg)	0.83	**Operating earnings (€/kg)**	1.20
Most prominent costs in % from operational costs		**Most prominent costs in % from operational costs**	
Feed	48.29	**Feed**	62.03
Other variable costs	18.85	**Other variable costs**	11.90
Labour	7.86	**Labour**	9.00
Veterinary	6.64	**Veterinary**	6.11
Stocking	5.22	**Stocking**	4.02

Table 5 Operating earnings and most prominent costs in percent from overall operational costs for all typical salmon farms analysed in CERES.

Under future price scenarios, Irish salmon farms are likely to suffer reduced profits under Global Sustainability (GS), National Enterprise (NE) and Local Stewardship (LS) scenarios, with the reductions being most severe under GS (-62%; Figure 11).

Norwegian salmon farms are also predicted to experience reduced profitability under the GS scenario though the impact is predicted to be around half that as predicted for Ireland (-24%).

Profits are predicted to increase in Norway under the NE and LS scenarios. Farms in both countries are predicted to have increased profits under the World Market (WM) scenario (Figure 11).

This is due to the most favourable combination of future feed price and returns (fish price) under these scenarios. Feed costs are lowest under the WM scenario for the Irish production compared to the other scenarios, and lowest under GS and WM (13% difference to GS) for the Norwegian. Therefore, the better fish price forecasted under WM explains why this is the most favourable scenario.

Feed costs are dependent on future price developments and demand of ingredients as well as on the assumed availability of substitutes for fishmeal and fish oil, which trace back to the technological development and trade opportunities under the four CERES scenarios with best opportunities under the two global scenarios GS and WM. However, when effect of climate is factored into the future projected prices (i.e. changes in harvest weight and FCR from the biological model), the profitability of Irish salmon under WM observed in Figure 11, is only relevant under extreme cold years, whereas extreme warm years lead to a profit loss for the WM scenario as well (Figure 11).

Furthermore, when considering future potential price variation (error bars in Figure 12), the Norwegian farm shows a higher probability of remaining profitable when considering all scenarios, whereas for the Irish farm, half of the scenarios include the risk of not being profitable. In general, the socio-economic impact is more pronounced than the climate effect and it is only under the WM and NE scenarios that there are big differences between extreme cold and warm years.

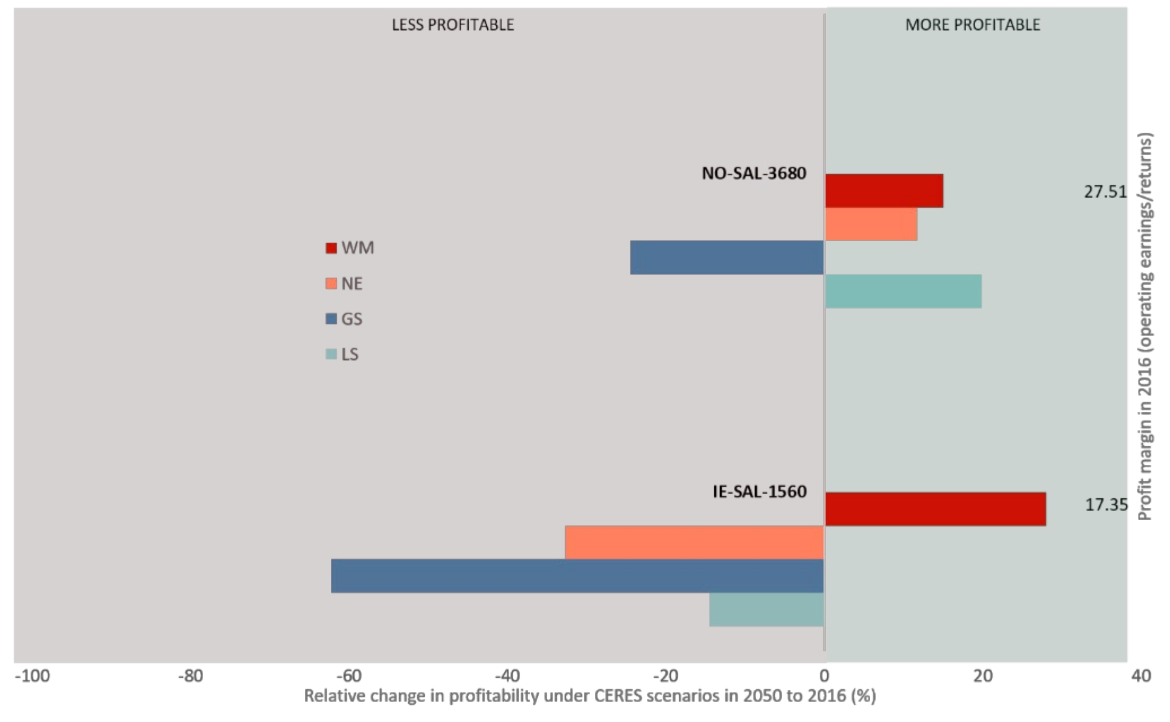


Figure 11 Relative change in profitability under the four CERES scenarios in 2050 compared to 2016 profit margin for all typical salmon farms without considering future harvest weight and FCR. World Market = WM, National Enterprise= NE, Global Sustainability= GS, Local Stewardship = LS.

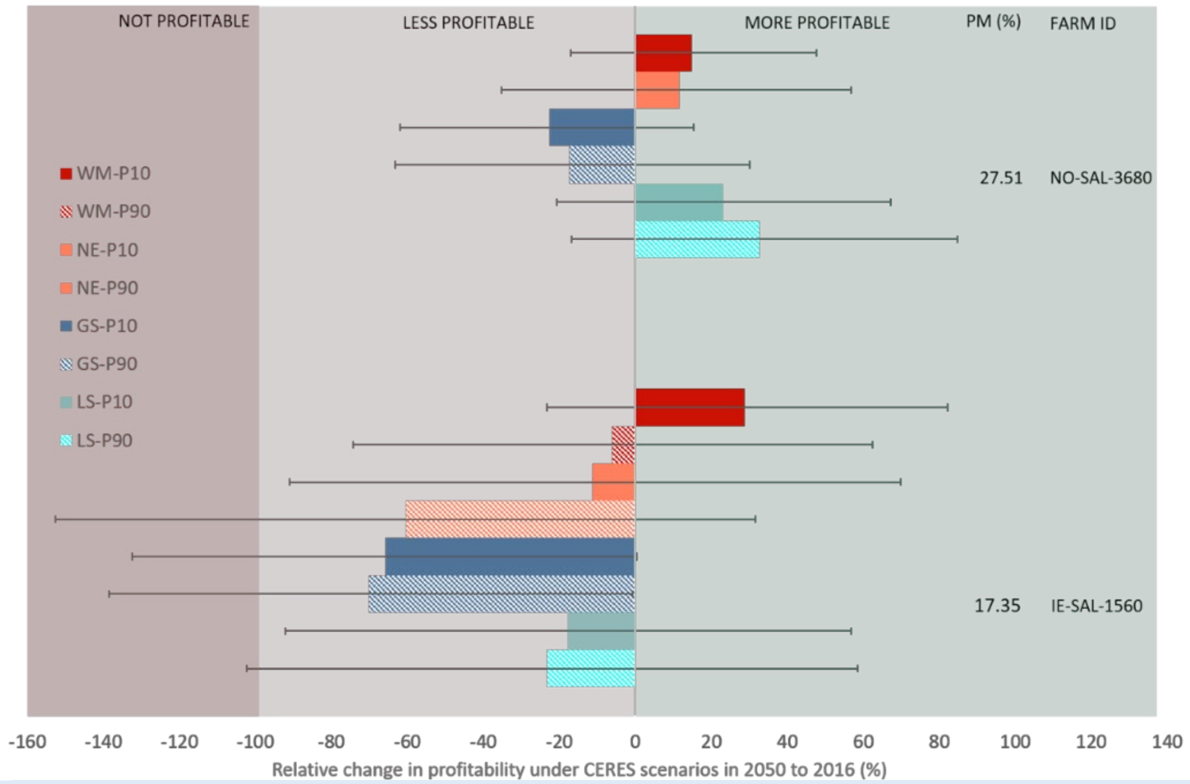


Figure 12 Relative profitability change under the 4 CERES scenarios in 2050 compared to 2016 for the typical salmon farms. World Market = WM, National Enterprise= NE, Global Sustainability= GS, Local Stewardship = LS. P10 = extreme cold year, P90= extreme warm year. Note that for Norway there was no RCP 8.5 model and thereby extreme warm /cold year analysis for the WM and NE scenario was included. Error bars indicate 95% upper and lower probability ranges from Monte Carlo simulation. PM = Profit Margin in percent.

Opportunities

Atlantic salmon currently constitute the most important European aquaculture species in terms of volume produced, and though currently a highly profitable industry, there are many challenges moving forwards.

Though there is a large export market for Atlantic salmon and few countries in Europe are able to produce salmon (due to a lack of suitable coastline or environmental conditions, but developments in RAS technology may change this), there is increasing competition in terms of supply from outside of Europe.

To overcome this challenge, the European industry will need to adapt to future changes to ensure sale prices remain competitive and its costs sufficiently low to retain good profitability.

Considering the general shift in public consciousness towards the global issues of climate change and biodiversity loss, there will be increasing consumer pressure for industry to be sustainable and to have lower carbon footprints.

Salmon aquaculture has the potential to market itself as a more sustainable option to traditional protein sources such as pork and beef, as salmon has is on a par with chicken as one of the most efficient forms of animal protein (Fry et al. 2018).

Climate-ready solutions

Compared to future price trends, local climate effects have little meaningful influence on the profitability of a site, though they may affect a sites viability.

The direct temperature effects associated with climate change are however still important and the positive side of climate change is the predicted increase in number of optimal growing days for both Norway and Ireland, which may help shorten production cycles and improve profitability.

However, this change in temperature may also increase disease risks and impact, and in open cage systems the adoption of effective preventative biosecurity measures against waterborne transmission of pathogens and harmful jellyfish blooms is challenging. Key to dealing with some of these issues may the development of closed or semi-enclosed cages, RAS and offshore aquaculture systems which may help mitigate some disease concerns, however, these measures may have limited effect against harmful jellyfish blooms. There is also great uncertainty in terms of the inter-annual abundance of harmful jellyfish species but CERES has now shown that Pelagia noctiluca can be extremely widespread in Irish coastal waters in some years but may be completely absent in others.

Another concern associated with increasing temperature is that though there may be an increased number of optimal growing days, the likelihood of exceeding the maximum physiological threshold for salmon becomes a possibility. This possibility may also be higher for the inshore waters, fjords, lochs and loughs in which production is predominantly based, obviously moving production offshore and into deeper waters may help this. Fuel costs are also a significant cost, especially in Norway, however conversion to electric energy and non-fossil fuel sources is a priority in Norway and across Europe.

Though transitioning to this technology is likely to incur significant initial investment costs, it will make the industry less susceptible in to changes in global oil prices. In Ireland labour costs are more important than Norway, due to less external services available as the industry is a lot smaller and expansion of the industry could mitigate such costs. However, any measures adopted in Ireland would need to be carefully evaluated to ensure they do not jeopardize the organic status associated with their product as this is an important marketing tool for the Irish sector allowing them to achieve good market prices.

Under the current scenario, feed constitutes the dominant cost to the sector and as a consequence, the overall profitability of a farm is greatly influenced by respective price changes. Whilst the projections made here generally show these costs to go up, besides considering the market influence of fish meal and fish oil alternatives according to the different scenarios, it was assumed there would be no change in the composition of feeds in general.

Indeed, substituting marine ingredients with alternatives such as insect meal, single cell protein, animal protein or marine algal oil as well as gene modified plant oil, is conceivable (and in some cases is already happening) and may help curb prices. However, challenges associated with new ingredients include consumer acceptance, the ability to produce the quantities required and assure their provenance, to ensure any labelling or certification standards the salmon industry wishes to adhere to are not affected. This is particularly relevant to Ireland which has the organic farming standards which have special stipulations on feed.

Mitigation measures

Feedback from the industry (Figure 13) suggested the following mitigation measures to deal with direct (increased temperature and storminess) and indirect (increase frequency of diseases and harmful jellyfish blooms) impacts from climate change:

- Move farm locations further north.
- Selective breeding for thermal tolerance e.g. salmon stock in Tasmania is already operating at predicted upper temperatures projected in climate change scenarios for southern Ireland and they are doing extremely well.
- Functional feeds to protect salmon from infections.
- Prophylaxis must always be improved, especially against various diseases but also against parasites.
- Identify high risk sites and move biomass to safer locations.
- Develop semi-closed and closed systems.
- New infectious and production diseases will emerge as aquaculture develops and resources and investment will be required to investigate and counter these challenges.
- Changing how nets are cleaned.
- Increased monitoring (water quality parameters and pathogens).
- Expansion of semi-closed systems and offshore aquaculture to protect from diseases.

Climate vulnerability

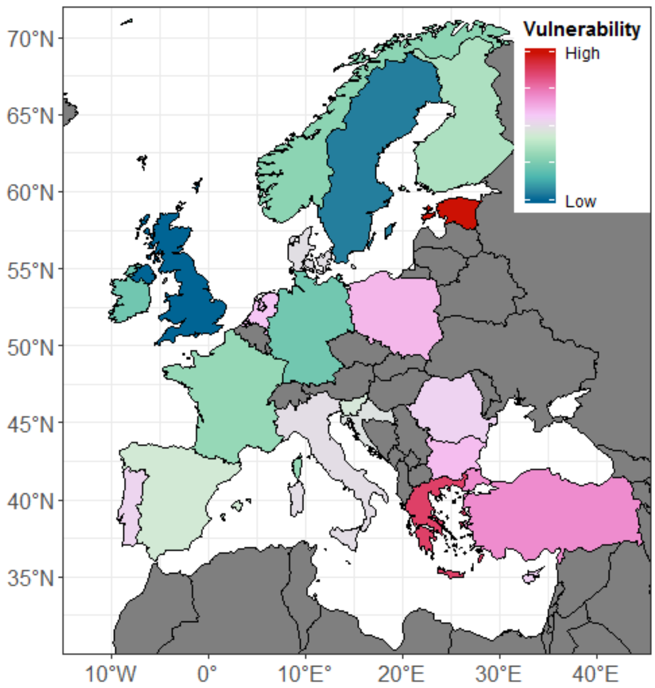


Figure 6 Climate vulnerability assessment for Europe. Colour scale is linear in the value of the corresponding score, but is presented without values, as they have little direct meaning. *Picture credit: Myron Peck*

- A climate vulnerability assessment (CVA) was conducted on the European aquaculture sector using the FAO model of Exposure + Sensitivity + Adaptive Capacity.

- The CVA included the physiological and farming methods of seven species (Atlantic salmon, sea bass, sea bream, trout, carp, mussels, oysters and clams) representing > 95% of the value for the region.
- Based on available economic data, the vulnerability of 22 countries – the top producers in the Europe28 as well as Norway and Turkey – was ranked and relative values are shown (right)
- By 2050 in RCP8.5, warming caused slight increases in the suitability of culture conditions for Atlantic salmon in NW Europe. The potential impacts of warming on sea lice and disease vector and other potential indirect impacts of climate change were not included in this analysis.
- The capacity for technological innovation (associated with larger firm sizes) decreased the vulnerability score for nations growing salmon (such as Ireland, the UK and Norway). Most countries growing salmon have also made good progress implementing climate adaptation plans and have relatively strong national economies.

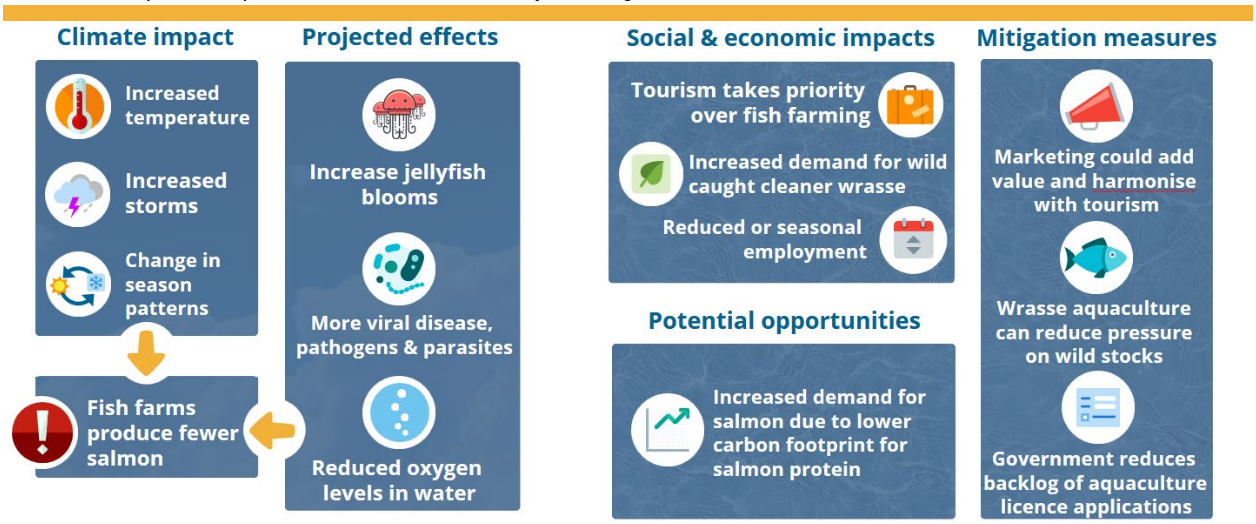


Figure 11 Bowtie analysis for salmon in the NE Atlantic based on 7 responses to the CERES online survey and feedback from 18 stakeholders (Norwegian, Scottish, Irish, Australian and Chilean salmon experts) attending a Gill Pathologies Symposium. All full BowTies available http://bit.ly/CERESbowties2020

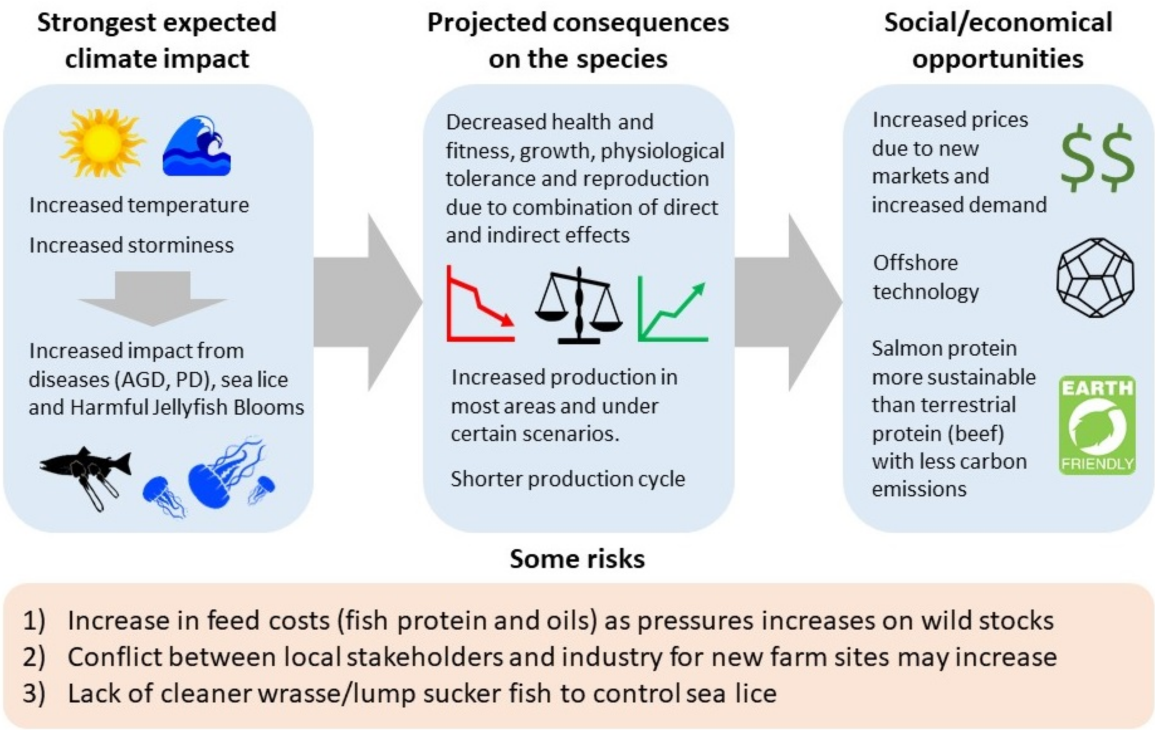


Figure 12 Projected main effects of climate change on the salmon aquaculture industry.

Policy recommendations

- Incentivisation of the practice of Integrated Multi-Trophic Aquaculture (IMTA) to reduce some of the environmental impacts. IMTA has the added benefit of additional products and jobs and will improve the reputation of the industry. The need for IMTA in a specific area is however dependent on the eutrophication situation.
- More appropriate flexible licensing systems need to be realised to allow the industry to adapt to changing environmental conditions e.g. if certain locations can no longer support salmon production, or the pathogen situation are changing. Scaling up production in other areas to maintain production levels should be a more dynamic process.
- Further large-scale trials on bubble curtain systems designed by engineers in collaboration with biologists need to be carried out to fully determine their effectiveness. Median scale trials in this study were inconclusive for small jellyfish but with showed promise for larger harmful species.
- Development of a legislative and management framework that allows and regulates offshore aquaculture.
- Development and increased use of closed or semi-closed cages in order to limit pathogen exchange and release of particulate organic matter to the environment, and to increase control of temperature within cages.

Further reading

References:

Anttila, K., Couturier, C.S., Øverli, Ø., Johnsen, A., Marthinsen, G., Nilsson, G.E. and Farrell, A.P. (2014) Atlantic salmon show capability for cardiac acclimation to warm temperatures. Nature Communications, 5:4252

Amundrud TL, Murray AG (2009) Modelling sea lice dispersion under varying environmental forcing in a Scottish sea loch. Journal of Fish Diseases 32 (1): 27–44.

Baxter, E., Sturt, M., Ruane, N., Doyle, T., and McAllen, R. 2012a. Biofouling of the hydroid Ectopleura larynx on aquaculture nets in Ireland: implications for finfish health. Fish Veterinary Journal, 13: 17-29.

BIM Annual Aquaculture Survey (2017)
http://www.bim.ie/media/bim/content/publications/aquaculture/BIM-Annual-Aquaculture-Survey-2018.pdf

Brett, J.R., 1967. Swimming performance of sockeye salmon (Oncorhynchus nerka) in relation to fatigue time and temperature. Journal of the Fisheries Research Board of Canada 24, 1731-1741.

Brett, J.R., Groves, T.D.D., 1979. Physiological energetics. In: Hoar, W.S., Randall, D.J., Brett, J.R. (Eds.), Fish Physiology, Vol. VIII. Academic Press, New York, 279-352.

Brooker, A.J., Papadopoulou, A., Gutierrez, C., Rey, S., Davie, A., and Migaud, H. (2018) Sustainable production and use of cleaner fish for the biological control of sea lice: recent advances and current challenges (2018) Vet Rec. 183(12):383.

Brooker AJ, Skern-Mauritzen R, Bron J. Production, mortality, and infectivity of planktonic larval sea
lice, Lepeophtheirus salmonis (Krøyer, 1837): current knowledge and implication for epidemiological
modelling. ICES J Mar Sci. 2018.

Blöcher, N., de Nys, R., Poole, A. J., and Guenther, J. 2013. The fouling hydroid Ectopleura larynx: a lack of effect of next generation antifouling technologies. Biofouling, 29: 237-246.

Callaway, R., Shinn, A.P., Grenfell, S.E., Bron, J.E., Burnell, G., Cook, E.J., Crumlish, M., Culloty, S., Davidson, K., Ellis, R.P. et al. (2012). Review of climate change impacts on marine aquaculture in the UK and Ireland. Aquatic Conserv. Mar. Freshw. Ecosyst., 22, 389–421.

DAFM Report (2017), Mid-Term Assessment National Strategic Plan for Sustainable Aquaculture Development.
https://www.agriculture.gov.ie/media/migration/seafood/marineagenciesandprogrammes/nspa/MidTermAss20032018.PDF

Ellis, J. and Tiller, R. (2019) Conceptualizing future scenarios of integrated multi-trophic aquaculture (IMTA) in the Norwegian salmon industry. Marine Policy 104: 198–209

Elliott, J.M. and Elliott, J.A. (2010) Temperature requirements of Atlantic salmon Salmo salar, brown trout Salmo trutta and Arctic charr Salvelinus alpinus: predicting the effects of climate change. Journal of Fish Biology (2010) 77, 1793–1817.

Ernst & Young. (2018). The Norwegian Aquaculture Analysis 2017. Retrieved from www.ey.com/Publication/vwLUAssets/EY_-_The_Norwegian_Aquaculture_Analysis_2017/$FILE/EY-Norwegian-Aquaculture-Analysis-2017.pdf

Eurofish.dk from http://eurofish.dk/member-countries/norway

Eurostat. https://ec.europa.eu/eurostat/databrowser/view/tag00075/default/table?lang=en

EUMOFA database https://www.eumofa.eu/en/web/eumofa/ad-hoc-queries3

Ferreira, J.G. 2013. Grid-based model: days of grow-out to a harvestable weight for Atlantic salmon among four salmon-producing countries. In J.M. Kapetsky, J. AguilarManjarrez & J. Jenness. A global assessment of offshore mariculture potential from a spatial perspective, pp. 117–121. FAO Fisheries and Aquaculture Technical Paper N. 549. Rome, FAO. 181 pp.

Ferreira, J.G., Hawkins, A.J.S., Bricker, S.B., 2007. Management of productivity, environmental effects and profitability of shellfish aquaculture—the farm aquaculture resource management (FARM) model. Aquaculture 264, 160–174.

Fiskeridirektoratet (2019) https://www.fiskeridir.no/Akvakultur/Tema/Havbruk-til-havs

Froehlich, H.E., Rungea, C.A., Gentry, R.R., Gaines, S.D. and Halpern, B.S. (2018) Comparative terrestrial feed and land use of an aquaculture-dominant world. PNAS 115: 20, 5295–5300

Floerl, O., Sunde, L. M., and Bloecher, N. 2016. Potential environmental risks associated with biofouling management in salmon aquaculture. Aquaculture Environment Interactions, 8: 407-417

Fry, J.P., Mailloux, N.A., Love, D.C., Milli, M.C. and Cao, L. (2018) Feed conversion efficiency in aquaculture: do we measure it correctly? Environmental Research Letters, 13: 2.

Grealis, E., Hynes, S., O'Donoghue, C., Vega, A., Van Osch, S., and Twomey, C. (2017) The economic impact of aquaculture expansion: An input-output approach. Marine Policy 81: 29–36

Gillooly, J.F., Brown, J.H., West, G.B., Savage, V.M. & Charnov, E.L. (2001) Effects of size and temperature on metabolic rate. Science 293, 2248–2251.

Gubbins, M., Bricknell, I., and Service, M. (2013) Impacts of climate change on aquaculture. Marine Climate Change Impacts Partnership: Science Review: 318-327

Handeland, S.O., Bjornsson, B.Th., Arnesen, A.M. and Stefansson, S.O. (2003). Seawater adaptation and growth of post-smolt Atlantic salmon (Salmo salar) of wild and farmed strains. Aquaculture 220, 367-384.

Hinder SL, Hays GC, Edwards M, Roberts EC, Walne AW, Gravenor MB (2012) Changes in marine dinoflagellates and diatom abundance

Hjeltnes B, Bang-Jensen B, Bornø G, Haukaas A, Walde C S (2019) The Health Situation in Norwegian Aquaculture 2018. Norwegian Veterinary Institute

Hvas, M., Folkedal, O., Imsland, A., and Oppedal, F. (2017) The effect of thermal acclimation on aerobic scope and critical swimming speed in Atlantic salmon, Salmo salar. Journal of Experimental Biology: 220, 2757-2764

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp

Johansen, L-H, Jensen I, Mikkelsen H, Bjørn P-A, Jansen P, Bergh Ø. 2011. Disease interaction and pathogens exchange between wild and farmed fish populations with special reference to Norway. Aquaculture, 315:167-186.

Karvonen A, Rintamäki P, Jokela J, Valtonen ET (2010) Increasing water temperature and disease risks in aquatic systems: climate change increases the risk of some, but not all, diseases. International Journal for Parasitology 40(13):1483-8.

Myksvoll MS, Sandvik AD, Albretsen J, Asplin L, Johnsen IA, et al. (2018) Evaluation of a national operational salmon lice monitoring system—From physics to fish. PLOS ONE 13(12): e0209949.

Nuez-Ortín, W.G., Carter, C.G., Nichols, P.D., Cooke, I.R., and Wilson, R. (2018). Liver proteome response of pre-harvest Atlantic salmon following exposure to elevated temperature. BMC Genomics 19: 133 (2018)

Oldham, T., Rodger, H. and Nowak, B.F. (2016) Incidence and distribution of amoebic gill disease (AGD) - An epidemiological review. Aquaculture 457 (2016) 35–42

Raine, R., McDermott, G., Silke, J., Lyons, K., Nolan, G., and Cusack, C. (2010). A simple short range model for the prediction of harmful algal events in the bays of southwestern Ireland. Journal of Marine Systems, 83: 150-157.

Rittenhouse MA, Revie CW, Hurford A (2016) A model for sea lice (Lepeophtheirus salmonis) dynamics in a seasonally changing environment. Epidemics 16:8-16.

Samsing, F., Oppedal, F., Dalvin, S., Johnsen, I., Vågseth, T., Dempster, T. (2016) Salmon lice (Lepeophtheirus salmonis) development times, body size, and reproductive outputs follow universal models of temperature dependence. Can J Fish Aquat. 73: 1±11.

Thorstad EB, Todd CD, Uglem I, Bjørn PA, Gargan PG, Vollset KW, et al. Effects of salmon lice Lepeophtheirus salmonis on wild sea trout Salmo trutta±a literature review. Aquac Environ Interact.
2015; 7: 91±113.

Tromp, J.J., Jones, P.L., Brown, M.S., Donald, J.A., Biro, P.A., and Afonso, L.O.B. (2018) Chronic exposure to increased water temperature reveals few impacts on stress physiology and growth responses in juvenile Atlantic salmon. Aquaculture 495 (2018) 196–204.

Waite, R., Beveridge, M., Brummett, R., Castine, S., Chaiyawannakarn, N., Kaushik, S., Mungkung, R., Nawapakpilai, S., and Phillips, M. (2014). Improving productivity and environmental performance of aquaculture. Technical Report. Instalment 5 of Creating a Sustainable Food Future. Washington, DC, World Resources Institute.

Walther S (2014) Determinants of competitiveness of agriholdings and independent farms in Ukrainian arable production. Thuenen Reports, 15, Johann Heinrich von Thünen Institute: Braunschweig, Germany