

Climate change impacts on marine aquaculture relevant to the UK

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KEY FACTS

What is happening

- In the UK, there have been no major changes to the types or locations of species farmed due to climate change.
- At salmon farms, a link between milder winter temperatures, disease and increased fish mortality has been identified and marine heatwaves can contribute to mass mortality events.
- In Scotland, some shellfish areas have experienced poor spat settlement and mortality, but the link to climate change is not fully established.

What could happen

- Temperatures are expected to remain suitable for salmon growth until the end of the century, when aquaculture in Northern Ireland and the southwest of Scotland may experience seasonal declines due to warming.
- Ocean acidification may reduce shellfish spat settlement, although it is unlikely to affect finfish farming.
- Warming conditions will lead to a rise in outbreaks including sea lice, fish diseases (especially gill diseases) and shellfish pathogens, with subsequent increased mortality.
- The risk of mortality due to more frequent and intense heatwave events will increase in the future, highlighting the need for adaptive management.
- Facilities in sheltered coastal areas may experience more fluctuation in temperatures, salinity and OA, but be less exposed to structural damage due to potential changes in storm events, creating different challenges for farming in different areas.

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SUPPORTING EVIDENCE

INTRODUCTION

UK aquaculture

Aquaculture is an important food production sector in the UK that supports a broad workforce, including highly skilled jobs in rural communities where other opportunities are often limited (BiGGAR Economics, 2020). In 2022, marine aquaculture output in the UK was 193,000 tonnes live weight valued at \$1,184 million (FAO, 2022). There is significant potential for aquaculture to develop further throughout the UK. However, in 2022, 87.5% tonnage and 93.4% value of UK marine aquaculture was attributable to salmon production, leaving a vulnerability to disturbance to this sector.

UK marine finfish aquaculture is dominated by the production of Atlantic salmon (*Salmo salar*) in net pens off the west coast and islands of Scotland (169,194 tonnes in 2022; Munro, 2023), and a very small production from Northern Ireland. Marine rainbow trout (*Onchorhynchus mykiss*) and small volumes of other species are also farmed. In the past, sea bass (*Dicentrarchus labrax*) were farmed in a land-based recirculating system (RAS) in Wales.

Mussels (*Mytilus sp*) are the main farmed seafood product of Wales, Northern Ireland and England, and the main shellfish production species for Scotland (UK total 12,223 tonnes in 2022). Pacific oyster (*Crassostrea gigas*) is the second most widely farmed UK shellfish (2,976 tonnes), with minor production of other bivalve species (FAO, 2022). Crustacean farming remains small-scale (Capuzzo, 2022). Seaweeds are also farmed in the UK, 25 companies have capacity for 840 tonnes wet weight production (Veenhof *et al.*, 2024; Capuzzo, 2022).

In this review, we provide an update to a 2022 MCCIP report (Murray *et al.* 2022), itself an update of the more detailed Collins *et al.* (2020) report, with new information generated since the earlier reports. Following a similar structure to Collins *et al.* (2020), we consider what is already happening to aquaculture, before assessing the potential implications for future aquaculture production under climate-change projections. We will discuss these projections in the section “What Could Happen in Future”.

WHAT IS ALREADY HAPPENING?

Climate change has an impact on many different aspects of the aquaculture sector, including growth and metabolism of the species farmed, fish health through diseases and parasites, invasive species, algal and jellyfish blooms, direct damage to facilities, changes to environmental carrying capacity and food safety and zoonosis. These impacts are driven by different direct and indirect climate drivers of temperature, salinity, ocean acidification (OA), wind and waves, which synergise to create impacts on the sustainability, economic viability and future of aquaculture. Warming occurs both as long-

term trends (Cornes *et al.*, 2023) and as marine heatwave events (Berthou *et al.*, 2022), however the Atlantic coasts of the UK (where salmon aquaculture is based) may be less susceptible to heatwaves than the southern North Sea (Jacobs *et al.* 2024). Uncertainty due to climate change reduces investment in aquaculture (Zitti and Guttormsen 2023). It can be difficult to disentangle the effects of climate change on different aspects of aquaculture production and there are many knowledge gaps about the combined effects of multiple stressors (Falconer *et al.*, 2022).

Growth and metabolism of farmed species

Finfish and shellfish are poikilotherms and so growth rates are strongly influenced by temperature (Elliott and Elliott, 2010; Cubillo *et al.*, 2021), though growth is also associated with other factors such as food utilisation and health of the farmed species. For salmon, increased metabolism at warmer temperatures leads to increased food requirements (Handleland *et al.*, 2008). Warming also increases oxygen consumption, while reducing concentrations. Feed composition has changed considerably in recent years and ongoing research to develop sustainable diets that are optimal for salmon (Albrektsen *et al.*, 2022) including feeds that are appropriate for higher water temperatures and heatwaves (Mock *et al.*, 2021). Feed companies are now prioritising product development that use sustainable ingredients (associated with fewer GHG emissions) via circular bioeconomy frameworks to increase resilience in aquaculture sectors (Colombo and Turchini, 2021).

Mussel spat settlement and mortality is linked to environmental factors (Corrochano-Fraile *et al.* 2024). Current temperatures in UK waters are lower than optimal for Pacific Oyster growth (King *et al.* 2021, Palmer *et al.* 2021). Shellfish feeding depends on filtering plankton, and plankton production has a complex relationship with climate (Guyondet *et al.*, 2015), which will be explored later in this paper.

Fish, shellfish and seaweed health

Farmed animal health is critical to aquaculture sustainability both directly and through impacts on wild animals. Loss rates of salmon biomass have been increasing in recent years and a statistical link has been identified with milder winters (Moriarty *et al.*, 2020). High temperatures are one of the factors causing mass mortality events (Sajid *et al.*, 2024). However, the proportion of input salmon lost per production cycle shows no trend (Munro *et al.* 2023). Disease is a major cause of losses in aquaculture, although this is part of a complex interaction with other factors (Oliveria *et al.*, 2021, Sajid *et al.* 2024). However, climate change and OA impacts on disease (Woo *et al.*, 2020) can be expected to increase aquaculture losses.

Gill health challenges have increased in recent years (Boerlage *et al.*, 2020), some due to new pathogens, e.g., the emergence of Amoebic Gill Disease (AGD), caused by *Paramoeba perurans*, is associated with high salinities

and temperatures in regions where it is established (Sokołowska and Nowak, 2020) and environmental stressors are associated with complex gill disorders CGD (Noguera *et al.*, 2019). AGD likely emerged in Scotland and Norway following a particularly warm summer in 2006 and thereafter outbreaks follow mild winters. Other pathogens also respond to changing environments, notably sea lice populations grow faster and are more difficult to control in warmer waters (Brooker *et al.*, 2018; Fast and Davlin, 2020); despite this, lice number per fish has declined in recent years (Rabe *et al.*, 2024) owing to increased investment in control. Cleaner fish are now commonly used in the salmon industry to control lice infestations but there are also concerns about the disease challenges that affect cleaner fish species (Erkinharju *et al.*, 2020).

Shellfish diseases have also expanded their ranges into and within the UK (Murray *et al.*, 2012). The spread of OsHV-1 μ var, the virulent variant of oyster herpesvirus, since 2010 in England and Ireland has been attributed to the distribution of infected hatchery spat rather than climate (Peeler *et al.*, 2012). Nevertheless, the warming of UK waters may contribute to a situation where clinical disease is more likely given mass mortalities associated with OsHV-1 μ var occurs at $>16^{\circ}\text{C}$.

Seaweed health is sensitive to salinity, temperature and pH, through tissue blistering and increased microbial activity (Qui *et al.*, 2019; Davis *et al.*, 2022). However, conditions in UK waters are very good for many coldwater seaweed (Macias *et al.*, 2025).

Decay rates for viruses' infectivity increase with temperature (Oidtmann *et al.*, 2017) as does *Bonamia* (Arzul *et al.*, 2009), conversely, warming promotes the growth of opportunistic bacterial pathogens such as *Vibrio* (Hernroth and Baden, 2018). There is growing diversity in the number of *Vibrio* species inhabiting UK waters, which includes the recent isolation of *Vibrio rotiferianus* and *V. jasicida* from English and Welsh shellfish sites for the first time (Harrison *et al.*, 2022). *Paramoeba perurans* growth increases with temperature to 15°C in culture (Collins *et al.*, 2019) and on farms (Benedicenti *et al.*, 2019; Boerlage *et al.*, 2020). Sea lice maturation and production rates increase with temperature (Brooker *et al.*, 2018).

Salinity affects pathogen survival. Growth and survival of *P. perurans* increases at higher salinity (Collins *et al.*, 2019; Sokołowska and Nowak, 2020); survival of sea lice (Shephard *et al.*, 2016; Brooker *et al.*, 2018) and *Bonamia* (Arzul *et al.*, 2009) also increases at higher salinity. Conversely, fungi and oomycetes may increase under less saline conditions associated with runoff (Van West, 2006). The sensitivities of viruses depend on the specific virus (Oidtmann *et al.*, 2017).

Pathogens are labile under UV radiation, and RNA viruses such as ISAV may be particularly sensitive (Oidtmann *et al.*, 2017). Binding to particles associated with storms and runoff protects viruses and bacteria (Campos *et*

al., 2013). Therefore, periods wet and weather respectively increase and reduce pathogen survival and so transmission.

The environment affects the susceptibility of hosts to disease. Changes in environmental salinity and pH may affect the immune reactivity of mucosal immune molecules or may change the viscosity of mucus (Roberts and Powell, 2005), increasing adhesion ability of bacteria to host surfaces. Periods of high temperature, hypoxia and increased UV radiation will result in the production of a stress response in finfish with a direct immune suppressive effect (Tort, 2011). Treatment of sea lice is less effective, and stress associated with bath or mechanical treatments are more likely to result in host mortality, at higher temperatures (Overton *et al.*, 2019).

Invasive species

Marine invasive non-native species (INNS) including the tunicates *Didemnum vexillum* and *Styela clava* are present and spreading, although this may not be climate-change related. These INNS have the potential to smother and outcompete cultured shellfish species as well as incurring additional husbandry and product-processing costs. *D. vexillum* has been found on aquaculture sites and in an oyster hatchery in England (marlin.ac.uk), and more recently on sites in Scotland (Cottier-Cook *et al.*, 2019). Although the significance of its impacts on shellfish is uncertain in the UK, impacts have been reported on green-lipped mussel aquaculture in New Zealand (Fletcher *et al.*, 2013).

Anthropogenic introduction of INNS such as *C. gigas*, including unaided dispersal via artificial stepping stones, rather than climate change, is thought to be the primary cause of spread, though increasing water temperatures above 16°C can support their establishment and range expansion (Wood *et al.*, 2021). Populations of feral Pacific oyster, *C. gigas*, (originally considered unable to reproduce at UK seawater temperatures) are now established in many areas as a result of warming (King *et al.*, 2021).

Mytilus trossulus is a native UK ‘nuisance species’ for the aquaculture of *M. edulis* as its flesh quality is inferior and its weaker shell is prone to harvesting and storm damage. Recent research has suggested that environmental effects may influence shell strength more than previously thought (Michalek *et al.*, 2021), but further research is needed to identify if climate change has affected this.

Algal and jellyfish blooms

Algal phytoplankton is essential for food for shellfish production. Their production is a complex response to light, thermal stratification, and nutrients, which are influenced by the upwelling of deep water or inputs from terrestrial sources during floods.

Blooms of the dinoflagellates *Karenia mikimotoi* have caused mortalities of farmed fish in Scottish waters in the 1980s with impacts on the benthos

reported in the late 1990s (Davidson *et al.*, 2009). A review of the last 10 years reveals a strong regional variability in the incidence of Harmful Algal Blooms (HABs) in the UK (Bresnan *et al.*, 2020). Mechanisms of HAB impact and mitigation on fish health have recently been reviewed (Hallegraeff *et al.*, 2023), these mechanisms are influenced by temperature, salinity and hydrodynamics and so are sensitive to climate change. Modelling of HAB's impact on aquaculture is being developed in Scotland (Dees *et al.*, 2023). However, signals from climate change are difficult to disentangle from seasonality and short-term weather events (Gianella *et al.*, 2021; Whyte *et al.*, 2023; Klem *et al.*, 2022; Gianella 2023).

HABs can damage fish gills, laying them open to complex gill disorders (Noguera *et al.*, 2019). Similarly, hydrozoan biofoulers' stinging cells can damage fish skin and gills (Bloecher *et al.*, 2018).

Jellyfish blooms can be a significant cause of mortality for penned finfish (Luisetti *et al.*, 2018), mainly through exposure of gill tissue to the stingers resulting in direct traumatic damage, impaired function and triggering secondary diseases (Clinton *et al.*, 2021). Globally, most reports of jellyfish impact on aquaculture are on salmon in the North Atlantic (Bosche-Belmar *et al.*, 2021) with losses of up to \$1.3 million in Scotland and Ireland. Mortality of Irish salmon due to a *Physalia physalis* bloom was associated with a tropical storm (Mitchell *et al.*, 2021).

Seafood safety

Changes in contamination of shellfish with human or zoonotic pathogens such as norovirus and *Vibrio* are reviewed in another MCCIP report (Bresnan *et al.*, 2020). Warming relates to environmentally acquired *Vibrio* infections in human populations (Bresnan *et al.*, 2020). Norovirus (NoV) levels were positively associated with the frequency and volume of sewage discharges, river flow and storm overflow events and were negatively associated with waters >10°C (Bresnan *et al.*, 2020). Changes in temperature and pH may affect antibiotic persistence in seawater and so impact antibiotic resistance in bacterial populations. *Escherichia coli* shellfish contamination in the UK has been correlated with rainfall and suspended sediment (Campos *et al.*, 2013), which is compounded by infrastructure issues contributing to increasing instances of sewage overflows (Rangel-Buitrago *et al.*, 2024).

Some HAB species produce toxins which accumulate in the flesh of shellfish that feed on them and pose a serious risk to human health if consumed (Bresnan *et al.*, 2020); as noted above HABs have a complex relationship with the environment and hence links to climate change are uncertain. The algal toxins responsible for Paralytic Shellfish Poisoning (PSTs), Diarrhetic Shellfish Poisoning (DSTs), and amnesic shellfish poisoning (ASTs) are detected in UK shellfish with most incidences recorded in Scotland and along the south coast of England. In Ireland, in addition to PSTs, ASTs, and DSTs, concentrations of the toxin group

Azspiracids are also observed in shellfish. Dinoflagellate HABs associated with marine heatwaves have been associated with mussels exceeding permitted toxins and causing £1M losses (Brown *et al.*, 2022).

Limits to suitable sites availability

Sea-level rise can reduce suitable sites for aquaculture, e.g., intertidal mudflats for shellfish. Sediment deposition from runoff, and resuspension during storms, can affect fish and shellfish mortality, health and growth. Suspended particles can cause gill damage in fish. These climate effects can make coastal sites unavailable. Storms and waves can damage exposed fish cages, leading to escapes or predator access (Jackson *et al.*, 2015) and interact with other stressors to impact fish health (Szewczyk *et al.*, 2024). Storms can also damage or detach shellfish or seaweeds from seabed or aquaculture structures, and most present-day shellfish aquaculture is confined to sheltered areas. Furthermore, daily operations and site access can be affected by increased bad weather resulting in health and safety concerns for farm stock and the farm workers (Thorvaldsen *et al.*, 2015). Exposure limits available offshore sites, without major investment in robust structures.

WHAT COULD HAPPEN IN THE FUTURE?

Future climate scenarios as reviewed by MCCIP predict continuing increases in air and water temperatures (Cornes *et al.*, 2023). Some areas are warming faster than others, so there are likely to be some differences in the rate and magnitude of temperature change at aquaculture sites. However, increased temperature effects are likely already impacting aquaculture and so we do expect impacts to continue in the short term (10-15 years) and increase in the long term to 2100. OA is also very likely to increase (Humphreys *et al.*, 2020), although noticeable impacts may only be more long-term. Rainfall may be variable with drier summers and wetter winters, and increasing flood events (Met Office, 2022). This is reflected in reduced salinity over the long term, which is projected to drop fastest in northern areas, potential even rising in areas such as the English Chanel. Storms are likely to increase in intensity and effects could be felt in the short term.

Growth and metabolism of farmed species

In poikilotherms, feeding/growth rates gradually increase towards an optimum temperature and rapidly fall off if the temperature exceeds this optimum (Figure 1).

Salmon summer and autumn productivity in southern Scotland (e.g. the Clyde Sea) and Northern Ireland might decline particularly in sheltered

coastal waters with local temperatures substantially different from coastal means (Falconer *et al.*, 2020).

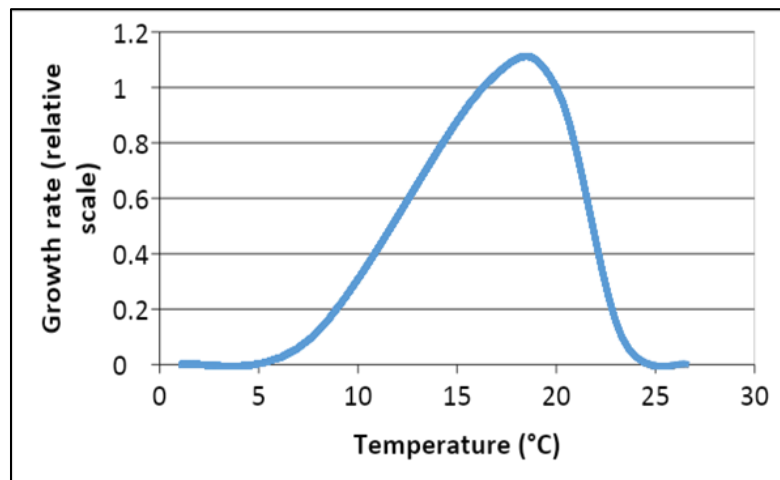


Figure 1. Relative growth rate response of Atlantic salmon to temperature (from data in Elliott & Elliot 2010).

Events associated with heat waves could cause episodes of mortality that would need to be managed (Spillman and Hobday, 2014; Brown *et al.*, 2022), and such events can be expected to increase in frequency and magnitude (Frölicher *et al.*, 2018). Sustainable densities may also reduce due to coping with lower dissolved oxygen levels, since warmer water holds less oxygen and increases fish metabolism (Vikeså *et al.*, 2016), although this can be counteracted using aeration (Burke *et al.*, 2022).

Increasing SST (sea surface temperature) makes farming of coldwater species such as cod more difficult (Ytteborg *et al.*, 2023) but improves the potential for sea bass, sea bream or other species in southern UK waters, though temperatures are still suboptimal (Besson *et al.*, 2016) even by 2100 predictions. Temperatures in southern England may become too high for cultivation of coldwater seaweed species such as *Alaria esculenta* (Macias *et al.* 2025). A systematic review of sensitivities of fish, shellfish, seaweed and other species to climate change scenarios has been developed in Norway (Falconer *et al.*, 2022; 2024), providing a guide for planning future aquaculture.

UK mussel spat falls, predominantly occurring in spring and autumn, may benefit from warming in most parts of the UK, though autumn temperatures in the south of England may occasionally be too high. Similarly, in the south of England adult *M. edulis* growth may be affected by high summer temperatures, delaying in autumn spawning. Increases of 1°C and 4°C were predicted to reduce production by 10 and 50% for *M. edulis* in Strangford Lough, Northern Ireland (Ferreira *et al.*, 2007). In the south of England, *Mytilus galloprovincialis*, with optimum larvae survival at 20–24°C (Sánchez-Lazo and Martínez-Pita, 2012), may increase its distribution, so

even if temperatures become too high for *M. edulis*, production of mussels will likely continue.

Predicted increases in UK SST may overall benefit *C. gigas* survival (King *et al.*, 2021) and growth (Palmer *et al.* 2021), but may also result in early maturation resulting in lost production. For Strangford Lough NI 2 - 5% losses were predicted under 1 °C and 4 °C warming (Ferreira *et al.*, 2007). Increasing SST may also promote the development of the native oyster *Ostrea edulis* in UK waters. New species such as abalone might be cultivatable in warmer waters which includes areas in the southern UK (Goulden, 2018).

OA is detrimental to larval shellfish (Lemason *et al.*, 2017). Metabolism and shell growth are also affected with a predicted reduction of 25% and 10% in shell growth by 2100 for mussels and oysters respectively (Gazeau *et al.*, 2007). OA affects *Mytilus* byssal threads (Dickey *et al.*, 2018), making some shellfish more susceptible to storm damage and predators. Even if shellfish reach production size, OA may impact quality and value, and increase costs of production (Mangi *et al.*, 2018).

Rising water temperatures may increase the spread of *C. gigas* feral populations, settlement predicted to reach Scotland by the 2060s (King *et al.*, 2021) with possible impacts on benthic habitats given the species' ability to form extensive reefs. Warming temperatures increase their metabolism and increased food intake could result in competition with other filter feeders (Guyondet *et al.*, 2015).

Fish, shellfish and seaweed health

Disease impact is very sensitive to the environment, so climate changes are likely to increase impacts already observed (Woo *et al.*, 2020). Some diseases have specific temperature windows of expression, this may change the time of year at which they occur, which may require changing management and surveillance, and some with cold water preferences may decline, for example, cold water vibriosis whose pathogenicity is expressed below 10°C (Kashulin *et al.*, 2017). More diseases and parasites, however, are likely to increase in prevalence and impacts with rising temperature (Woo *et al.*, 2020; Combe *et al.*, 2023), which could also include the appearance of pathogens associated with invasive species (Wood *et al.*, 2023).

In salmon, the key diseases of complex gill disorders (Noguera *et al.*, 2019) and sea lice (Fast and Dalvin, 2020) are likely to increase in impact under conditions of increased temperatures and salinities, although low salinity with higher rainfall reduces these. CGD outbreaks are driven by a range of pathogens such as *Paramoeba perurans* (Boerlage *et al.*, 2020) and microsporidians plus gill insults associated with HAB and/or jellyfish which individually, and in combination, are sensitive to changing environmental conditions. Lice numbers may continue to be reduced (Rabe *et al.*, 2024) by

new technologies, however at both financial and welfare cost (Overton *et al.* 2019). Increased gill damage may reduce options for treating sea lice, particularly in warmer waters and therefore impacts may synergise. General mortality can be predicted to continue to increase as winters get milder (Moriarty *et al.*, 2020).

The transmission of salmon lice through the environment to wild salmonids is increased at higher temperatures and lower salinity (Shephard *et al.*, 2016). Other farm fish pathogens have shown less evidence of substantial transmission to wild fish (Wallace *et al.*, 2017).

Shellfish diseases are likely to increase in their diversity and range. In Scotland, current low water temperatures reduce the impact of pathogens such as *Bonamia ostreae* and would limit OsHV should it be introduced. Under warming temperatures, these pathogens may increasingly be expressed as disease and increase in virulence (Combe *et al.*, 2023). Exotic and novel pathogens (to the UK), such as *B. exitiosa* (Longshaw *et al.*, 2013) and infectious neoplasia (Bramwell *et al.*, 2021) may emerge under warming.

Seaweed pests are increasing due to climate change in Asian waters, causing losses up to 60%, but there is a research gap regarding Atlantic seaweed pests (Gachon *et al.* 2010).

Invasive species

Climate change may increase the introduction, establishment and secondary dispersal of marine invasive species and extend ranges northwards (Cottier-Cook *et al.*, 2017; King *et al.*, 2021). Marine heatwaves may increase the ability of invasive seaweeds to outcompete native species (Atkinson *et al.*, 2020). Biofouling of fish and shellfish aquaculture structures is conservatively estimated to contribute 5–10% of aquaculture production costs (Fitridge *et al.*, 2012). Similarly, *C. gigas* recruitment to feral populations is predicted to increase (King *et al.*, 2021) which will have an environmental impact (Christianen *et al.*, 2018) and act as a reservoir for shellfish pathogens.

The introduction and establishment of INNS is a complex process influenced by both climatic factors as well as mediation by humans. There is also insufficient information on the biology of INNS and many native biofoulers. It is therefore difficult to predict how a changing climate may exacerbate their impacts on aquaculture.

Algal and jellyfish blooms

Prediction of the response of algal blooms to climate change is challenging (Bresnan *et al.*, 2020; Klemm *et al.*, 2022) but broad-scale HAB modelling studies (Gobler *et al.*, 2017) predict an increase in the occurrence of toxin-producing species in the North Sea. However, these models need to account for the complexity and differences of life cycles at a species level and

Gianella *et al.* (2021) report no year-on-year increase. Prediction of the potential for the northern expansion of HAB species in the north-east Atlantic (Townhill *et al.*, 2018) is made difficult by the complexities of modelling of plankton. However, HAB models are being refined (Dees *et al.*, 2023; Gianella 2023), which may allow more confidence in prediction in response of HAB impact on aquaculture to climate changes.

Although complex environmental factors affect jellyfish blooms (Edwards *et al.*, 2020), increasing temperatures appear to be a key factor for many species (Kennerley *et al.*, 2021). Increasing temperatures may result in greater frequencies of blooming events within the natural long-term cycles of jellyfish populations, with greater numbers of days occurring where ocean temperatures fall within the optimum physiological tolerances of several native and non-native species (e.g., Collingridge *et al.*, 2014). However, there are significant knowledge gaps in species-specific physiological information in response to each of the environmental factors thought to influence jellyfish populations (Kennerley *et al.*, 2021; Fernández-Alías *et al.*, 2024).

Seafood safety

Norovirus may decline in association with warmer conditions but is likely to increase in association with projected increases in high-intensity rainfall, and has the potential to increase the number and magnitude of Combined Sewer Overflow (CSO) releases (Younger *et al.* 2022). Runoff from agricultural areas under such events may also cause zoonotic contamination (Webber *et al.* 2021). *Vibrio* includes several zoonotic species that may increase their range and abundance under warming temperatures (Bresnan *et al.*, 2020).

As noted, prediction of HABs is problematic (Bresnan *et al.* 2020; Gianella *et al.*, 2021) but toxic blooms may increase (Gobler *et al.*, 2017) and increase toxin production (Whyte *et al.*, 2023) leading to accumulation of toxins in shellfish, further accumulation may increase under marine heatwaves (Funesto *et al.*, 2023).

It is difficult to predict if climate change and OA will result in significant changes to metal/pollutant contaminant levels in aquaculture organisms (Shi *et al.*, 2016), due to interactions between climate change effects and OA on modulating uptake, metabolism, and elimination processes.

Changes to suitable site availability

Sea-level rise may remove some shellfish production sites, but could produce new ones, it could also damage shore-based facilities. Similarly, seaweed production sites availabilities are dependent on coastal environments (Kerrison *et al.*, 2015) and increased freshwater flows may cause mortalities (Davis *et al.*, 2022).

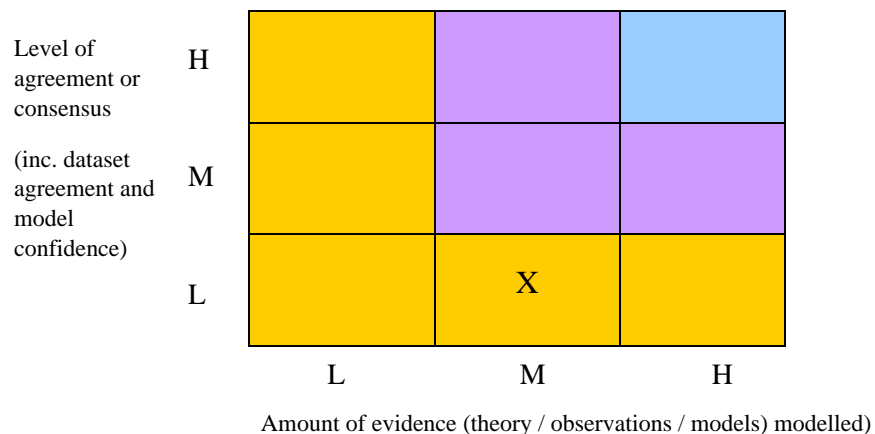
Storms may increase under rising temperatures, however, their impact on UK aquaculture is uncertain because the trajectories may also shift (Bricheno *et al.*, 2023). Storms are associated with structural damage to aquaculture facilities and resultant escapes (Jackson *et al.*, 2015). Future offshore farms may be more exposed but will be designed to tolerate storms and waves. Escaped salmon are already associated with introgression (Gilbey *et al.*, 2021), with resultant damage to wild populations.

Sea lice from farms transmit to wild salmonids, and transmission increases under warmer and more saline conditions (Shephard *et al.*, 2016) while control on farms becomes more difficult (Overton *et al.* 2019). The impact of lice on wild salmonids is a key factor for the social licence of salmon aquaculture, and hence limits farm site availability. These wild populations are likely to be impacted by other climate-change impacts (Hastings *et al.* 2020).

Increased respiration rates under higher temperatures may lead to increased anoxia in the sediments around fish farms. Rising sea levels may impact the availability of sites for shellfish production (Filgueira *et al.*, 2016) and put aquaculture shore facilities at risk. Shellfish provide broader environmental services that may be disrupted by OA (Lemasson *et al.*, 2017).

CONFIDENCE ASSESSMENT

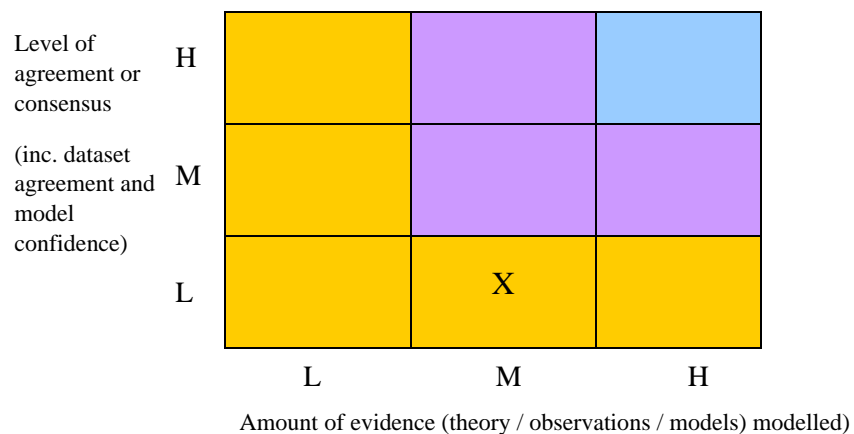
What is already happening?



We have statistical evidence (Moriarty *et al.*, 2021) of an existing association of salmon mortality with milder winters and evidence of the emergence of amoebic gill disease in UK waters in association with warm summers and persistence with mild winters. There is also the association of HABs and jellyfish with warmer seasonal conditions. The spread of invasive species can be anthropogenic or climate-related; establishment of feral *C gigas* is related to warming and it may act as a reservoir for disease in

farmed shellfish. Increased zoonotic infections via shellfish are associated with warmer and wetter conditions. Escapes and equipment damage relate to storms, but evidence for trends is lacking. So, we can have confidence that there are impacts on aquaculture related to climate and some at least relate to climate change. Confidence is not high as only a few factors link directly to climate change, as opposed to seasonality. However, the evidence has increased since Murray *et al.* (2022) leading to Moderate confidence. There have been no major shifts in species farmed or evidence of links of changed production to climate. So confirmed impacts of climate change are relatively Low compared with changes associated with economic and technical developments.

What could happen in the future?



The existing impacts of climate on finfish may be expected to continue, this includes mortality in salmon, particularly relating to gill disease. Drivers for increased sea lice impacts in warming conditions, and greater difficulty in control without side effects are strongly associated with warming conditions. This could make salmonid aquaculture less sustainable, or lice control more expensive, particularly if sea lice control and gill health problems synergise. Future control depends on research to develop new technologies and further investment to apply existing technologies. Salmon growth rates are likely to increase, although in the long term they could decline in areas such as Northern Ireland. UK waters are expected to remain suboptimal for new species such as sea bass.

Shellfish aquaculture may benefit from increased growth rates in warmer waters, although diseases may increase in impact. This could particularly affect Scotland as water, currently too cold for pathogens to express disease, warms, e.g. *Bonamia*. OsHV could spread as feral *C. gigas* populations are predicted to spread into Scotland mid-21st century. Zoonotic pathogens can be expected to continue to increase in the marine environment, exposing shellfish to contamination. Ocean Acidification may reduce mussel smolt

settlement. New species of shellfish such as abalone might be farmed in southern UK waters.

Seaweed aquaculture has considerable potential to expand, but this potential might be reduced under a warming climate. There is a need for more research on increasing resilience of seaweed in response to climate change, with an eye on future cultivation.

Other impacts of climate change remain highly uncertain. HABs and jellyfish are found in warmer waters, but blooms depend on complex ecosystem behaviour, making long-term response to climate change very difficult to predict (Bresnan *et al.*, 2020; Gianella, 2023). Climate changes themselves are uncertain, for example, UK coastal waters display greater variability than the overall NE Atlantic region (Cornes *et al.*, 2023). Rates of climate change have different projected changes between regions of the UK. Farmed species have different sensitivities and plasticities to climate changes (Crozier and Hutchings, 2014).

Overall, we have Moderate confidence that there will be impacts from climate change on both finfish and shellfish aquaculture, disease impacts will be negative but may be mitigated by investment in technological developments, while growth rates are likely to increase, so the net impacts on productivity may be Low. However, the dependence of aquaculture value on one species, *Salmo salar*, does leave UK aquaculture vulnerable to a worst-case scenario.

KEY CHALLENGE FOR DEALING WITH CLIMATE CHANGE

From this review we identify key scientific challenges to address to minimise climate changes impact on aquaculture.

- Understanding synergies between different pathogens and environmental drivers in fish health's response to climate changes, such as CGD.
- Understanding the synergistic effects of climate change and OA (and the effect of fluctuating, compared to continuous, exposure to these impacts) on settlement (shellfish), growth and survival of aquaculture species.
- Identifying the potential impacts of climate change on environmental conditions at aquaculture sites e.g., the assimilative capacity of receiving water bodies, including offshore.
- Identifying what impacts of climate change favour the establishment and spread of INNS.

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