Climate change impacts on marine aquaculture relevant to the UK and Ireland

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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 strong link between milder winter temperatures, disease and increased fish mortality has been identified.
- 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 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.
- Offshore facilities may be more exposed to structural damage due to potential changes in storm events, with an increased risk of farmed species escaping.

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SUPPORTING EVIDENCE

INTRODUCTION

UK aquaculture

Aquaculture is an important food production sector in the UK, with a wide supply chain that supports a broad workforce, including highly skilled jobs in rural communities where other opportunities are often limited (BiGGAR Economics, 2020). Figures from 2018 reveal the Scottish aquaculture sector supported 11,700 jobs and had a turnover of £1.5 billion and salmon was the UK's largest food export (BiGGAR Economics, 2020). In 2020, marine aquaculture output in the UK was valued at £1,348,707.2 (USD 1000), with a production of 211,025.9 tonnes live weight (FAO, 2022). There is significant potential for aquaculture to develop further throughout the UK. However, in 2020, with 91.5% tonnage and 96.7% value of UK marine aquaculture attributable to salmon production, this low species diversity leaves the overall aquaculture industry vulnerable to any disturbance to salmon production.

UK marine finfish aquaculture is dominated by the production of Atlantic salmon (*Salmo salar*) off the west coast and islands of Scotland (192,129 tonnes in 2020; Munro, 2021), and a very small production from Northern Ireland. Marine rainbow trout (*Onchorhyncus 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. Though this facility is now used for cleaner fish production.

Mussels *(Mytilus sp*) are the main farmed seafood product of Wales, Northern Ireland and England, and the main shellfish production of Scotland. Pacific oyster (*Crassostrea gigas*) is the second most-farmed UK shellfish, with minor production of other bivalve species. Crustacean and macroalgal farming remain small-scale (Capuzzo, 2022).

The previous MCCIP report on aquaculture (Collins *et al*., 2020) provided an overview of the available information on UK aquaculture and climate change. A notable development since then was the publication of the Seafish report on climate change adaptation on domestic and international aquaculture supply chains of importance to the UK (Garrett *et al*., 2021). This report outlined key impacts, risks, and adaptation responses that were identified following a review of available evidence and a series of stakeholder engagement events.

In this review, we provide a brief update to the 2020 MCCIP report by Collins *et al*. (2020), by supplementing new information that has been generated since the last report. 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.

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) and wind, which synergise to create impacts on the sustainability and future of aquaculture. 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), 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). 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).

In Scotland, some shellfish areas have experienced poor spat settlement and mortality, thought to be caused by environmental factors (Munro, 2022), however, there are insufficient long-term datasets at present to link this to climate change. Higher temperatures were one of the factors that Ashton (2020) linked to oyster mortality events in Lough Foyle, which lies between Northern Ireland and the Republic of Ireland. 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 and shellfish health

Farmed animal health is critical to aquaculture sustainability both directly and through impacts on wild animals. Disease is a major cause of losses in aquaculture, although this is part of a complex interaction with other factors (Oliveria *et al*., 2021), although some pathogens such as oyster herpes virus (OsHV) can cause mass mortality (Rodgers *et al*., 2018). Climate change and OA impacts on disease (Woo *et al*., 2020) could affect aquaculture. A strong statistical link between increased mortality in salmon farms with milder winter temperatures has been identified (Moriarty *et al*., 2020).

Gill health challenges have increased in recent years (Borelage *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 (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 (Hall and Murray, 2018) 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 µvar 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 have contributed to clinical disease where mass mortality occurs at >16°C.

Decay rates for viruses increase with temperature (Oidtmann *et al*., 2017) as does larval 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). 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; Skołowska 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 protects viruses and bacteria (Campos *et al*., 2013).

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, they 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 may support their establishment (Wood *et al*., 2021). Populations of feral Pacific oyster, *C. gigas*, (originally considered unable to reproduce at UK seawater temperatures) have successfully bred 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). Over this relatively short time scale, signals from climate change are difficult to disentangle from short-term weather events (Whyte *et al*., 2014).

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.

Food safety and zoonosis

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).

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 Azaspiracids are also observed in shellfish.

Limits to 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. Storms and waves can damage exposed fish cages, leading to escapes or predator access (Jackson *et al*., 2015). Storms can also damage or detach shellfish 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).

WHAT COULD HAPPEN IN THE FUTURE?

Future climate scenarios as reviewed by MCCIP predict continuing increases in air and water temperatures (Tinker and Howes, 2020) and OA (Humphreys *et al*., 2020). Rainfall may be variable with drier summers and wetter winters, and increasing flood events (Met Office, 2022).

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).

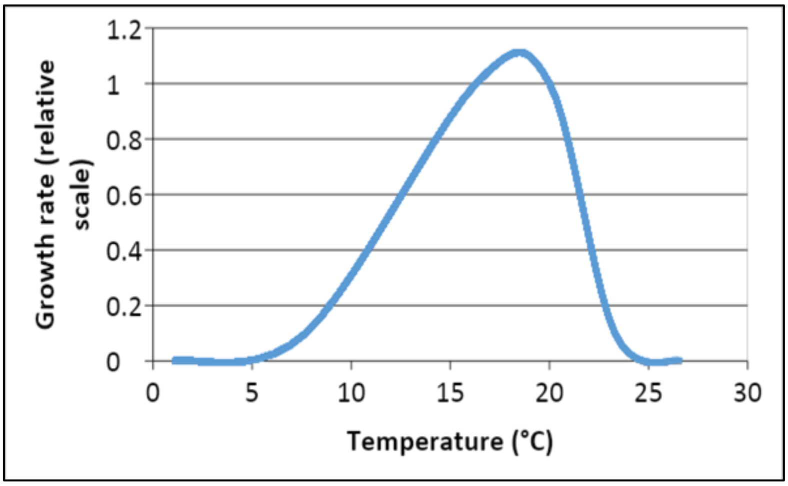


Figure 1: Relative growth rate response of Atlantic salmon to temperature (from data in Elliott & Elliot 2010). *Figure 1. Relative growth rate response of Atlantic salmon to temperature (from data in Elliott & Elliot 2010).*

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).

Events associated with heat waves could cause episodes of mortality that would need to be managed (Spillman and Hobday, 2014), 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).

Increasing SST (sea surface temperature) makes farming of coldwater cod and halibut more difficult (Björnsson and Tryggvadóttir, 1996) 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.

UK spat falls, predominantly occurring in spring and autumn, may benefit most parts of the UK, though the highest autumn temperatures in the south of England may be suboptimal. Similarly, in the south of England adult *M.*

edulis growth may be affected by high summer temperatures, with an associated delay in autumn spawning. Increases of 1°C and 4°C were predicted to reduce production by 10 and 50% for *M. edulis* and 2 and 5% for *C. gigas* respectively 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 benefit *C. gigas* survival (King *et al*., 2021) growth, but may also result in early maturation resulting in lost production. 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).

Increased incidences of high precipitation and freshwater runoff during winter and drought and higher UK SSTs in summer may have a greater impact on oyster and mussel growth respectively.

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 on final quality and value, and increase costs of production (Mangi *et al*., 2018).

Warming water temperatures may allow *C. gigas* to increase the spread of feral populations and to expand northwards with settlement thresholds reaching 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 and shellfish 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 at temperature 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).

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, and numbers may be restrained at cost by new control technologies. Increased gill damage may reduce options for treating sea lice, particularly in warmer waters (Overton *et al*., 2019) 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 stocks is increased at higher temperatures and lower salinity (Shephard *et al*., 2016). Other farm fish pathogens show 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 (Murray *et al*., 2012). Under warming temperatures, these pathogens may increasingly be expressed as disease. New pathogens, such as *B. exitiosa* may spread in UK shellfish (Longshaw *et al*., 2013).

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). 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 be increasingly high risk (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) 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. 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 the application of modelling techniques to plankton.

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).

Food safety and zoonosis

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. Runoff from agricultural areas under such events may also cause zoonotic contamination. Vibrio includes several zoonotic species that may increase their range and abundance under warming temperatures (Bresnan *et al*., 2020).

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.

Limits to sites availability

Sea-level rise may remove some shellfish production sites, but could produce new ones, it could also damage shore-based facilities.

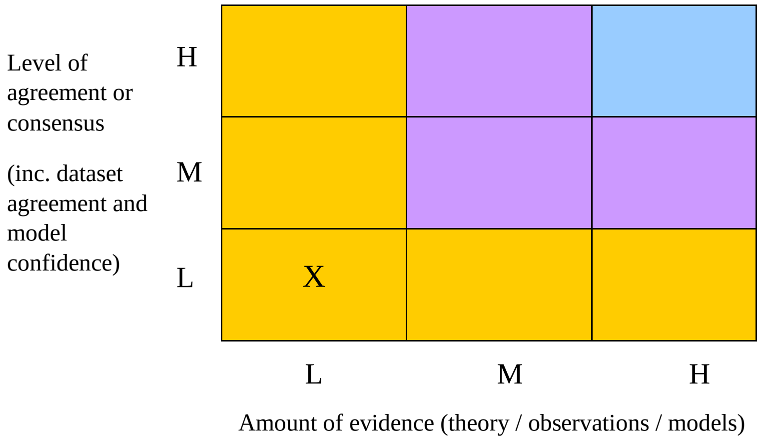
Storms may increase under rising temperatures, however, their impact on UK aquaculture is uncertain because the trajectories may also shift (Wolf *et al*., 2020). Storms are associated with structural damage to aquaculture facilities and resultant escapes (Jackson *et al*., 2015). Future offshore farms may be more exposed but will be designed to tolerate storms. 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?



Level of agreement or consensus

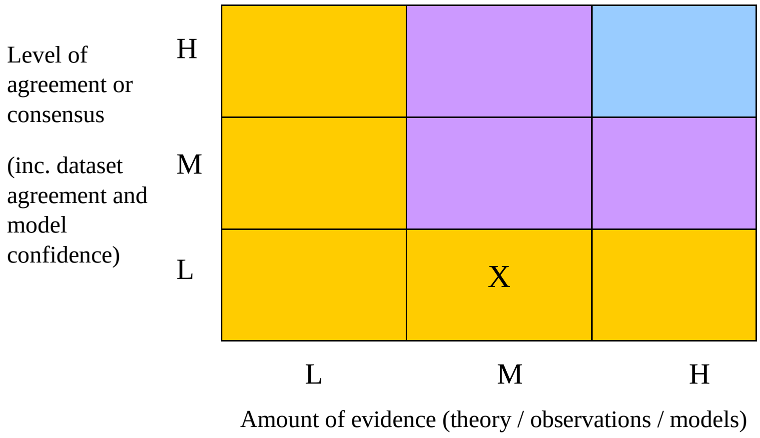
(inc. dataset agreement and model confidence)

	L	M	H
H	🟨	🟪	🟦
M	🟨	🟪	🟪
L	🟨 X	🟨	🟨

Amount of evidence (theory / observations / models)

We have statistical evidence 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 still low as only a few factors link to climate change, as opposed to seasonality and there is a need for more concrete evidence, but are at the boundary between low and moderate confidence as evidence has increased since Collins *et al*. 2020. However, 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 further 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.

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). Climate changes themselves are uncertain, for example, UK coastal waters display greater variability than the overall NE Atlantic region (Tinker and Howes, 2020) and species may have the capacity to adapt to 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 technological fixes, while growth rates are likely to increase, so the net impacts 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 CHALLENGES AND EMERGING ISSUES

- Understanding synergies between different pathogens and environmental drivers in fish health's response to climate changes
- 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.

REFERENCES

Albrektsen, S., Kortet, R., Skov, R.V., Ytteborg, E., Gitlesen, S., Kleinegris, D. *et al*., (2022) Future feed resources in sustainable salmonid production: a review. Reviews in Aquaculture. https://doi.org/10.1111/raq.12673

Arzul, I., Gagane, B., Bond, C., Chollet, B., Morga, B., Ferrand, S., Robert, M. and Renault, T. (2009) Effects of temperature and salinity on the survival of *Bonamia ostreae*, a parasite infecting flat oysters. Diseases of Aquatic Organisms, 85, 67–75.

Ashton, E.C., Guist, S., Roberts, D. and Sigwart, J.D. (2020) Effects of environmental factors and husbandry practices on summer mortality events in the cultivated Pacific oyster *Crassostrea gigas* in the North of Ireland. Journal of Shellfish Research, 39, 13-20.

Besson, M. Vandeputte, M., van Arendonk, J.A.M., Aubind, J., de Boer, I.J.M., Quillet. E. and Komen. H. (2016) Influence of water temperature on the economic value of growth rate in fish farming: The case of sea bass (*Dicentrarchus labrax*) cage farming in the Mediterranean. Aquaculture, 46, 47–55.

BiGGAR Economics. (2020) Estimation of the wider economic impacts of the aquaculture sector in Scotland. A report to Marine Scotland, 53pp.

Björnsson, B. and Tryggvadóttir, S.V. (1996) Effects of size on optimal temperature for growth and growth efficiency of immature Atlantic halibut (*Hippoglossus hippoglossus* L.). Aquaculture, 142, 33–42.

Bloecher, N., Powell, M., Hytterød, S., Gjessing, M., Wiik-Nielsen, J., Mohammad, S.N., Johansen, J., Hansen, H., Floerl, O. and Gjevre, A-G. (2018) Effects of cnidarian biofouling on salmon gill health and development of amoebic gill disease. PLoS ONE, 13(7), e0199842.

Borelage A.S., Ashby A., Herrero, A., Reeves, A., Gunn G.J. and Rodger, H.D. (2020) Epidemiology of marine gill diseases in Atlantic salmon (Salmo salar) aquaculture: a review. Reviews in Aquaculture 12, 2140-2159

Bosch-Belmara M., Milisenda G., Basso L., Doyle T.K., Leone A. and Piraino S. (2021) Jellyfish Impacts on Marine Aquaculture and Fisheries. Reviews in Fisheries Science & Aquaculture 29, 242-259. https://doi.org/10.1080/23308249.2020.1806201

Bresnan, E., Baker-Austin, C., Campos, C.J.A, Davidson, K., Edwards, M., Hall, A., McKinney, A. and Turner, A.D. (2020) Impacts of climate change on human health, HABs and bathing waters, relevant to the coastal and marine environment around the UK. MCCIP Science Review 2020, 521–545.

Brooker, A.J., Skern-Mauritzen, R. and Bron, J.E. (2018) Production, mortality, and infectivity of planktonic larval sea lice, Lepeophtheirus salmonis (Krøyer, 1837): current knowledge and implications for epidemiological modelling. ICES Journal of Marine Science, 75, 1214–1234.

Campos, C.J.A., Kershaw, S.R. and Lee, R.J. (2013) Environmental influences on faecal indicator organisms in coastal waters and their accumulation in bivalve shellfish. Estuaries and Coasts, 36, 834–853.

Capuzzo, E. (2022). Seaweed Industries and Products in the UK: A Brief Review. In: Ranga Rao, A. and Ravishankar, G.A. (eds) Sustainable Global Resources of Seaweeds Volume 1. Springer, Cham. https://doi.org/10.1007/978-3-030-91955-9_14

Christianen, M.J.A., Lengkeek, W., Bergsma, J.H., Coolen, J.W.P., Didderen, K., Dorenbosch, M. *et al*. (2018) Return of the native facilitated by the invasive? Population composition, substrate preferences and epibenthic species richness of a recently discovered shellfish reef with native European flat oysters (*Ostrea edulis*) in the North Sea. Marine Biology Research, 14, 590–597.

Clinton, M., Ferrier, D.E., Martin, S.A. and Brierley, A.S. (2021) Impacts of jellyfish on marine cage aquaculture: an overview of existing knowledge and the challenges to finfish health. ICES Journal of Marine Science, 78, 1557-1573.

Collingridge, K., van der Molen, J. and Pitois, S. (2014) Modelling risk areas in the North Sea for blooms of the invasive comb jelly *Mnemiopsis leidyi* A. Agassiz, 1865. Aquatic Invasions, 9, 21-36.

Collins C., Hall M., Fordyce M.J. and White P. (2019) Survival and growth in vitro of *Paramoeba perurans* populations cultured under different salinities and temperatures. Protist, 170, 153–167.

Collins, C., Bresnan, E., Brown, L., Falconer, L., Guilder, J., Jones, L., Kennerley, A., Malham, S., Murray A. and Stanley, M. (2020) Impacts of climate change on aquaculture. MCCIP Science Review 2020, 482–520.

Cottier-Cook E.J., Beveridge, C., Bishop, J.D.D., Brodie, J., Clark, P.F., Epstein G., Jenkins, S.R., Johns D.G., Loxton J., MacLeod, A., Maggs, C., Minchin D., , Mineur F., Sewell J. and Wood C.A. (2017) Non-native species. MCCIP Science Review 2017, 47-61

Cottier-Cook, E., Minchin, D., Giesler, R., Graham, J., Mogg, A.M.O., Sayer, M.D.J. and Matejusova, I. (2019) Biosecurity implications of the highly invasive carpet sea-squirt *Didemnum vexillum* Kott, 2002 for a protected area of global significance. Management of Biological Invasions, 10, 311–323.

Crozier, L.G. and Hutchings, J.A. (2014) Plastic and evolutionary responses to climate change in fish. Evolutionary Applications, 7, 68–87.

Davidson, K., Miller, P., Wilding, T.A., Shutler, J., Bresnan, E., Kennington, K. and Swan, S. (2009) A large and prolonged bloom of *Karenia mikimotoi* in Scottish waters in 2006. Harmful Algae, 8, 349–361.

Dickey, G., Preziosi, B.M., Clark, C.T. and Bowden, T.J. (2018) The impact of ocean acidification on the byssal threads of the blue mussel (*Mytilus edulis*). PLoS ONE, 13(10), e0205908.

Edwards, M., Atkinson A., Bresnan E., Hélaouët P., Ostle C., Pitois S. and Widdicombe C. (2020) Plankton and Jellyfish. MCCIP Science Review 2020, 322–353.

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, 77, 1793–1817.

Erkinharju, T., Dalmo, R.A., Hansen, M. and Seternes, T. (2020) Cleaner fish in aquaculture: a review on diseases and vaccination. Reviews in Aquaculture, 13, 189-237.

Fast, M.D. and Davlin, S. (2020) Lepeophtheirosis (*Lepeophtheirus salmonis* In P.T.K. Woo, J.-A. Leong and K. Buchmann (eds) Climate Change and Infectious Fish Diseases. CABI, Wallingford, UK, p 471-498

Falconer, L., Hjøllo, S.S., Telfer, T.C., McAdam, B.J., Hermansen, Ø. and Ytteborg, E. (2020) The importance of calibrating climate change projects to local conditions at aquaculture sites. Aquaculture, 514, 734487.

Falconer, L., Telfer, T.C., Garrett, A., Hermansen, Ø., Mikkelsen, E., Hjøllo, S.S., McAdam, B.J. and Ytteborg, E. (2022) Insight into real-world complexities is required to enable effective response from the aquaculture sector to climate change. PLOS Climate, 1(3): e0000017.

FAO (2022). Fishery and Aquaculture Statistics. Global aquaculture production 1950-2020 (FishStatJ). In: FAO Fisheries and Aquaculture Division [online]. Rome. Updated 2022. www.fao.org/fishery/statistics/software/fishstatj/en

Ferreira, J.G., Hawkins, A.J.S., Monteiro, P., Moore, H., Edwards, A., Goven, R., Lourenco, P., Mellor, A., Nunes, J.P., Ramos, L., Sequeiro, A. and Strong J. (2007) SMILE – Sustainable Mariculture in Northern Irish Lough Ecosystems: Assessment of carrying capacity for environmentally sustainable shellfish culture in Carlingford Lough, Strangford Lough, Belfast Lough, Larne Lough and Lough Foyle. Institute of Marine Research.

Filgueira, R., Guyondet, T., Comeau, L.C. and Tremblay, R. (2016) Bivalve aquaculture-environment interactions in the context of climate change. Global Change Biology, 2, 3901–3913.

Fitridge, I., Dempster, T., Guenther, J. and de Nys, R. (2012) The impact and control of biofouling in marine aquaculture: a review. Biofouling, 28(7), 649–669.

Fletcher, L.M., Forrest, B.M., and Bell J.J. (2013) Impacts of the invasive ascidian *Didemnum vexillum* on green-lipped mussel *Perna canaliculus* aquaculture in New Zealand. Aquaculture Environment Interactions 4, 17-30.

Frölicher, T.L., Fisher, E., M., and Gruber N. (2018) Marine heatwaves under global warming. Nature, 560, 360-364.

Garrett, A., Burton, C., Cocker, L., Smith, J., Berrill, I., Falconer, L., Telfer, T., McAdam, B. and Pinnegar, J. (2021) Understanding and responding to climate change in the UK seafood industry: Climate change risk adaptation in aquaculture sourced seafood. A Seafish report to the UK Government under the Climate Change Reporting Power, 104pp.

Gazeau, F., Quiblier, C., Jansen, J.M., Gattuso, J-P., Middelburg, J.J. and Heip, C.H.R. (2007) Impact of elevated CO_2 on shellfish calcification. Geophysical Research Letters, 34, L07603, doi:10.1029/2006GL028554

Gilbey, J. Sampayo J., Cauwelier E., Malcolm I., Millidine K., Jackson F., and Morris D.J. (2021) A national assessment of the influence of farmed salmon escapes on the genetic integrity of wild Scottish Atlantic salmon populations. Scottish Marine and Freshwater Science, 12 (12).

Gimenez, I., Waldbusser, G.G. and Hales, B. (2018) Ocean acidification stress index for shellfish (OASIS): Linking Pacific oyster larval survival and exposure to variable carbonate chemistry regimes. Elementa: Science of the Anthropocene, 6, 1–18.

Gobler, C.J., Doherty, O.M., Hattenrath-Lehmanna, T., Griffith, A.W., Kanga, Y. and Litaker, R.W. (2017) Ocean warming since 1982 has expanded the niche of toxic algal blooms in the North Atlantic and North Pacific oceans. PNAS, 114, 4975–4980.

Goulden, M., (2018). Portland Harbour– A High Level Review of Aquaculture Opportunities. Portland-Port. Co. UK.

Guyondet, T., Comeau, L.A., Bacher, C., Grant, J., Rosland, R., Sonier R. and Filgueira, R. (2015) Climate change influences carrying capacity in a coastal embayment dedicated to shellfish aquaculture. Estuaries and Coasts, 38, 1593–1618.

Hall L.M and Murray A.G. (2018) Describing temporal change in adult female *Lepeophtheirus salmonis* abundance on Scottish farmed Atlantic salmon at the national and regional levels. Aquaculture 489, 148-153.

Handeland, S.O., Imsland, A.K. and Stefansson, S.O. (2008) The effect of temperature and fish size on growth, feed intake, food conversion efficiency and stomach evacuation rate of Atlantic salmon post-smolts. Aquaculture, 283, 36–42.

Harrison, J., Nelson, K., Morcrette, H., Morcrette, C., Preston, J., Helmer, L., Titball, R.W., Butler, C.S. and Wagley, S. (2022) The increased prevalence of Vibrio species and the first reporting of *Vibrio jasicida* and *Vibrio rotiferianus* at UK shellfish sites. Water Research, 211, 117942.

Hastings, R.A., Rutterford, L.A., Freer, J.J., Collins, R.A., Simpson, S.D. and Genner, M.J. (2020) Climate Change Drives Poleward Increases and Equatorward Declines in Marine Species. Current Biology, 30, 1572-1577.

Hernroth, B. and Baden, S. (2018) Alteration of host-pathogen interactions in the wake of climate change – Increasing risk for shellfish associated infections? Environmental Research, 161, 245–438.

Humphreys, M.P., Artioli, Y., Bakker, D.C.E., Hartman, S.E., León, P., Wakelin, S., Walsham. P. and Williamson, P. (2020) Air–sea CO2 exchange and ocean acidification in UK seas and adjacent waters. MCCIP Science Review 2020, 54–75.

Jackson, D., Drumm, A., McEvoy, S., Jensen, Ø., Mendiola, D., Gabiña, G., Borg, J.A., Papageorgiou, N., Karakassis, Y. and Black, K.D. (2015) A pan-European valuation of the extent, causes and cost of escape events from sea cage fish farming. Aquaculture, 436, 21–26.

Kashulin A., Seredkina N. and Sorum H. (2017) Cold-water vibriosis. The current status of knowledge. Journal of Fish Diseases, 40, 119-126.

Kennerley, A., Lorenzoni, I., Luisetti, T., Wood, L.E. and Taylor, N.G.H. (2021). Mapping habitats for the suitability of jellyfish blooms around the UK and Ireland. Hydrobiologia, 848(7), 1535-1552.

King N.G., Wilmes, S.B., Smyth D., Tinker J., Robins P.E., Thorpe J., Jones, L. and Malham, S.K. (2021) Climate change accelerates range expansion for the invasive non-native species, the Pacific oyster *Crassostrea gigas*. ICES Journal of Marine Science, 78, 70-81.

Lee, J.E., Zoh, K.D. and Ko, G.P. (2008) Inactivation and UV Disinfection of Murine Norovirus with TiO_2 under Various Environmental Conditions. Applied Environmental Microbiology, 74, 2111–2117.

Lemasson, A.J., Fletcher, S., Hall-Spencer, J.M. and Knights, A.M. (2017) Linking the biological impacts of ocean acidification on oysters to changes in ecosystem services: a review. Journal of Experimental Marine Biology and Ecology, 492, 49–62.

Longshaw, M., Stone, D.M., Wood, G., Green, M.J. and White, P. (2013) Detection of *Bonamia exitiosa* (Haplosporidia) in European flat oysters *Ostrea edulis* cultivated in mainland Britain. Diseases of Aquatic Organisms, 106, 173–179.

Luisetti, T., Kennerly, A. and Lorenzoni, I. (2018) Jellyfish bloom impacts on human welfare: what do we know is happening vs what do we think is happening. In Engaging Marine Scientists and Fishers to Share Knowledge and Perceptions – Early Lessons. CIESM Monograph 50 [Briand, F. (ed)] CIESM Publisher, Monaco and Paris, pp. 181–186.

Mangi S.C., Lee J., Pinnegar J.K., Law R.J., Tyllianakis E., Birchenough S.N.R. (2018) The economic impacts of ocean acidification on shellfish fisheries and aquaculture in the United Kingdom. Environmental Science Policy, 86, 95–105.

Met Office (2022) UK Climate Projections UKCP. https://www.metoffice.gov.uk/research/approach/collaboration/ukcp

Michalek, K., Vendrami, D.L.J., Bekaert, M., Green, D.H., Last, K.S., Telesca, L., Wilding, T.A. and Hoffman, J.I. (2021) *Mytilus trossulus* introgression and consequences for shell traits in longline cultivated mussels. Evolutionary Applications, 14, 1830-1843.

Mock, T.S., Francis, D.S., Jago, M.K., Miles, P.C., Glencross, B.D., Smullen, R.P., Keast, R.S.J. and Turchini, G.M. (2021). Seasonal effects on growth and product quality in Atlantic salmon fed diets containing terrestrial oils as assessed by a long-term, on-farm growth trial. Aquaculture Nutrition, 27, 477-490.

Moriarty M., Murray A.G., Berx B., Christie, A.J., Munro, L.A. and Wallace, I.S. (2020) Modelling temperature and fish biomass data to predict annual Scottish farmed salmon, *Salmo salar* L., losses: Development of an early warning tool. Preventive Veterinary Medicine, 178, 104985

Munro, L.A. (2021) The Scottish Fish Farm Production Survey 2020. The Scottish Government, Edinburgh.

Munro, L.A. (2022) The Scottish Shellfish Farm Production Survey 2021. The Scottish Government, Edinburgh.

Murray, A.G., Marcos-Lopez, M., Collet, B. and Munro, L.A. (2012) A review of the risk posed to Scottish mollusc aquaculture from Bonamia, Marteilia and oyster herpesvirus. Aquaculture, 370–371, 7–13.

Noguera, P., Olsen, A.B., Hoare, J., Lie, K.I., Marcos-López, M., Poppe T.T, and Rodger H. (2019) Complex gill disorder (CGD): A histopathology workshop report. Bulletin of the European Association of Fish Pathologists 39, 172-176

Oliveira V.H.S., Dean K.R., Qviller L., Kirkeby C. and Bang Jensen B. (2021) Factors associated with baseline mortality in Norwegian Atlantic salmon farming. Scientific Reports, 11, 14702.

Oidtmann, B., Dixon, P., Way, K., Joiner, C. and Bayley, A.E. (2017) Risk of waterborne virus spread – review of survival of relevant fish and crustacean viruses in the aquatic environment and implications for control measures. Reviews in Aquaculture, 641–669.

Overton, K., Dempster T., Oppedal, F., Kristiansen, T.S., Gismervik, K. and Stein, L.H. (2019) Salmon lice treatments and salmon mortality in Norwegian aquaculture: a review. Reviews in Aquaculture, 11, 1398–1417.

Peeler, E.J., Reese, R.A., Cheslett D.L., Geoghegan, F., Power, A. and Thrush, M.A. (2012) Investigation of mortality in Pacific oysters associated with Osterid herpesevirus-1 μVar in the Republic of Ireland. Preventative Veterinary Medicine, 105, 136-143

Roberts, S.D. and Powell, M.D. (2005) The viscosity and glycoprotein biochemistry of salmonid mucus varies with species, salinity and the presence of amoebic gill disease. Journal of Comparative Physiology B, 175, 1–11.

Rodgers, C., Arzul, I., Carrsco, N. and Furones Nozal, D. (2018) A literature review as an aid to identify strategies for mitigating ostreid herpesvirus 1 in *Crassostrea gigas* hatchery and nursery systems. Reviews in Aquaculture,11(3), 565–585. https://doi.org/10.1111/raq.12246

Sánchez-Lazo, C. and Martínez-Pita, I. (2012) Effect of temperature on survival, growth and development of *Mytilus galloprovincialis* larvae. Aquaculture Research, 43, 1127–1133.

Shephard, S., MacIntyre, C. and Gargan, P. (2016) Aquaculture and environmental drivers of salmon lice infestation and body condition in seatrout. Aquaculture Environment Interactions, 8, 597–610.

Shi, W., Zhao, X., Han, Y., Che, Z., Chai, X. and Liu, G. (2016) Ocean acidification increases cadmium accumulation in marine bivalves: a potential threat to seafood safety. Scientific Reports, 6, 20197. doi: 10.1038/srep20197

Sokołowska, J. and Nowak, B. (2020) Amoebiosis (*Neoparamoeba perurans*) In P.T.K. Woo, J.A. Leong and K. Buchmann (eds) Climate change and infectious fish diseases. CABI, Wallingford, UK, pp. 303-318.

Spillman, C.M. and Hobday, A.J. (2014) Dynamical seasonal forecasts to aid salmon farm management in a climate hotspot. Climate Risk Management, 1, 25–38.

Thorvaldsen, T., Holmen, I.M. and Moe, H.K. (2015) The escape of fish from Norwegian fish farms: causes, risks and the influence of organisational aspects. Marine Policy, 55, 33–38.

Tinker, J.P. and Howes, E.L. (2020) The impacts of climate change on temperature (air and sea), relevant to the coastal and marine environment around the UK. MCCIP Science Review 2020, 1–32.

Tort, L. (2011) Stress and immune modulation in fish. Developmental and Comparative Immunology, 35, 1366–1375.

Townhill, B.L., Tinker, J., Jones, M., Pitois, S., Creach, V., Simpson, S.D., Dye, S., Bear, E. and Pinnegar, J. (2018) Harmful algal blooms and climate change: exploring future distribution changes, ICES Journal of Marine Science, 75, 1882–1893.

Van West, P. (2006) *Saprolegnia parasitica*, an oomycete pathogen with a fishy appetite: new challenges for an old problem. Mycologist, 20, 99–104.

Vikeså, V., Nankervis, L. and Hevrøy, E.M. (2016) Appetite, metabolism and growth regulation in Atlantic salmon (*Salmo salar* L.) exposed to hypoxia at elevated seawater temperature. Aquaculture Research, 48(8), 1–16.

Wallace, I.S., McKay, P. and Murray, A.G. (2017) A historical review of the key bacterial and viral pathogens of Scottish wild fish. Journal of Fish Diseases, 40, 1741–1756.

Whyte, C., Swann, S. and Davidson, K. (2014) Changing wind patterns linked to unusually high Dinophysis blooms around the Shetland Islands, Scotland. Harmful Algae, 39, 365–373.

Wolf, J., Woolf D. and Bricheno L. (2020) Impact of climate change on storms and waves relevant to the coastal environment around the UK. MCCIP Science Review 2020, 132-157.

Woo, P.T.K., Leong, J.-A. and Buchmann, K. (2020) Climate change and infectious fish diseases. CABI, Wallingford, UK.

Wood, L.E., Silva, T.A., Heal, R., Kennerley, A., Stebbing, P., Fernand, L. and Tidbury, H.J. (2021). Unaided dispersal risk of *Magallana gigas* into and around the UK: combining particle tracking modelling and environmental suitability scoring. Biological Invasions, 23,1719-1738.