MARINE CLIMATE CHANGE IMPACTS PARTNERSHIP: SCIENCE REVIEW
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Impacts of climate change on aquaculture

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EXECUTIVE SUMMARY

There is little existing evidence of impacts on aquaculture that can be attributed to climate change. Several effects have been observed that could be related to a changing climate such as increased shellfish contamination, harmful plankton events and the establishment of non-native species, but it is not clear that a changing ocean climate is responsible for these effects. Given the current predictions, climate change is unlikely to have a significant effect on Scottish mariculture over the next decade. However, within the next 50 years or more, the forecast changes are likely to result in noticeable effects. Sea-level rise may reduce coastal habitat suitable for bivalve cultivation in the south of the region (where Scottish mariculture is undertaken). Rising average water temperatures will result in faster growth rates for some species (e.g. Atlantic salmon, mussels and oysters) but prolonged periods of warmer summer temperatures may cause thermal stress, particularly for cold water species (e.g. cod and Atlantic halibut) and intertidal shellfish (oysters). However, warmer waters may provide opportunities to culture new species, or species that are currently economically marginal in UK waters.

Diseases of cultured fish and shellfish including bacterial, viral, parasitic and fungal diseases, will be affected by a changing thermal regime, but in a largely unpredictable manner. However, under conditions of thermal stress, cultured species are likely to be more susceptible to disease and warmer conditions may allow the establishment of exotic diseases, while diseases such as cold water vibriosis, may become much rarer. Sea lice are likely to remain a problem in salmon culture and rising temperatures will extend their season and may increase infective pressure, requiring more treatments. Increased storminess (higher frequency of strong wind speeds) predicted for certain seasons in some regions will increase the risk of escapes through equipment failure and may necessitate site relocation or changes to equipment design, making a move to offshore finfish culture more difficult.

Ocean acidifaction may have detrimental effects on mollusc spat-fall, making natural seeding of mollusc farms less efficient. Rising water temperatures may exacerbate the establishment of invasive species to higher latitudes potentially bringing increased costs to deal with fouling organisms or harm to stock.

The forecast warmer waters with calmer, drier summer months will have an effect on planktonic communities, although this will be difficult to predict in detail. There may be an increase in the frequency of harmful algal and jellyfish blooms, potentially causing more fish kills and closures of shellfish harvesting areas, but the forecast reduction in summer precipitation may benefit classification of shellfish growing areas. Increased temperatures and more abundant plankton could also enhance early spawning success and spat fall of cultured shellfish species, to the benefit of the shellfish industry.

FULL REVIEW

Marine aquaculture takes place in Regions 1-7 of UK waters. The majority (over 99%) of marine fin fish aquaculture is based in the Scottish waters of Regions 1, 5, 6 and 7. Shellfish are cultured in all of the seven regions with coastline using a wide variety of methods. Using the latest available data (Cefas pers.comm. and Ireland 2009; BIM, 2009) total UK and Ireland production was 172740 tonnes of finfish (0% England, <1% Wales, 92% Scotland, <1% N Ireland, 7.3% Ireland) and 60,626 tonnes of shellfish (6.5% England, 13.8% Wales, 12.0% Scotland, 12.7% N Ireland, 55% Ireland). The dominant species currently produced are Atlantic salmon, mussels and oysters. In England and Wales, mariculture is primarily focused on the culture of oysters and mussels, with some effort being put into the rearing of species such as lobsters. To date, there has been little published research or consensus opinion on the effects of climate change on UK mariculture. However, much can be inferred from the published literature on the effects of environmental variables on cultured species. Although the impacts suggested below are made predominately with respect to the Scottish aquaculture industry, many of the impacts may also be relevant for aquaculture based in other UK coastal waters.

Ocean climate change in mariculture areas

Scottish aquaculture in the marine environment (mariculture) is concentrated around the west coast of mainland Scotland and the Western and Northern Isles (Regions 1, 5, 6, 7). In England and Wales, culture of oysters and mussels mainly takes place along the southern coast of England and around the southern and northern coastline of Wales (Regions 2, 3, 4, 5). Significant shellfish production also occurs in the sea loughs of Northern Ireland (Regions 5 and 6). Predictions of climate variables in these areas taken from the UKCIP published forecasts on http://www.ukcip.org.uk/wordpress/wp-content/PDFs/UKCIP02_briefing.pdf were used to derive the subsequent predictions of effects on aquaculture. The following points relating to the predicted climate change in the key Scottish mariculture areas were used as the basis for predicting effects on mariculture:

All areas around the UK where aquaculture activity is practised are predicted to experience rises in annual and seasonal mean sea-surface temperatures of up to 2.5 – 3.5°C by 2098 (as modelled and in comparison to 1961-1990 values). Over the same timescales, the summer precipitation is predicted to decrease (0-10% by 2020 and 10-30% by 2080 taken from earlier predictions, http://www.ukcip.org.uk/wordpress/wp-content/PDFs/UKCIP02_briefing.pdf).

1. WHAT IS ALREADY HAPPENING?

There are currently no observed overt significant impacts on the UK aquaculture industry that have been conclusively shown to result from climate change. However, there are some changes in the sector that could be related to a changing climate. For example increases in the incidence of norovirus associated with bivalve shellfish that could be associated with increases in precipitation, run-off and sewerage overflow and the establishment of feral non-native populations of Pacific oysters in Northern Irish sea loughs which could be related to increases in water temperature allowing successful reproduction of cultured stock.

2. WHAT COULD HAPPEN?

Sea level rise. Low confidence

Predicted rises in sea level are most likely to impact on the south of the UK where rises are least likely to be offset by uplift (Shennan *et al*., 2006; Callaway *et al*., 2012; Horsburgh and Lowe, 2013). This may result in loss of coastal habitat important for aquaculture such as intertidal soft sediments (oysters) and shallow sedimentary habitats (managed mussel beds). These are the predominant aquaculture types in use in this region. Retreating coastlines may not be mitigated by sedimentary deposition restoring the lost coastal habitat due to a lack of sediment supply thereby increasing the vulnerability of the habitat to further coastal erosion (Orford and Pethick, 2006). In addition coastal developments and defences provide a hard barrier to retreating habitats potentially creating coastal 'squeeze' (Crooks, 2004) as sea levels rise in the south of the UK (Callaway *et al*., 2012).

Direct effects of temperature increase. Medium confidence

An increase of 2°C may well adversely affect some species currently being farmed in Scotland as the thermal optima for the animal's physiology may be exceeded for long periods of time during the summer months. Aquaculture of species such as Atlantic cod and Atlantic halibut may not be possible in the south of the country or be limited to areas of deep-water up-welling where the water is cooler than normal. Salmonid species are more tolerant of higher temperatures (Cano and Nicieza, 2006; Galbreath *et al* 2006; Goniea *et al*., 2006; Larsson and Berglund, 2006; Reddin *et al*., 2006; Tackle *et al*., 2006) than Atlantic cod (Claireaux *et al*., 1995; Levesque *et al*., 2005; Neat and Righton, 2006) and Atlantic halibut (Bjornsson and Tryggvadottir, 1996; Aune *et al*., 1997; Imsland *et al*., 2000; Hurst *et al*., 2005) but higher peak temperature in the summer months, which may well be of longer duration than present could cause issues with thermal stress and potentially make some sheltered, warmer sites unsuitable for those species during the summer months. Increasing temperatures would also restrict the southward expansion of salmon farming development as temperatures rise above the optimum range (13-17°C). In the short to medium term however site suitability and availability will be the dominant factor affecting the range of salmon cultivation.

Optimal temperatures for on-growing large cod are generally low (approximately 7°C; Neat and Righton, 2006) and although rising temperatures in Scottish waters may have some benefit to the growth rates of juveniles, growth rates of adults are likely to suffer.

Growth rates of shellfish species (mussels and oysters) are dependent on temperature and the continued availability of the planktonic food supply. It is recognised that mussel populations around the UK comprise three species of *Mytilus* that are able to hybridise, and therefore, it is possible that they will be able to tolerate the expected wider temperature fluctuations. Intertidal shellfish, notably Pacific oyster (*Crassostrea gigas*), are currently susceptible to occasional mortality events during prolonged periods of hot weather. These would be likely to increase in frequency under warmer conditions. This species of oyster is not endemic to the UK and our current thermal regime is not optimal for spawning and natural recruitment from cultured stocks to establish wild populations. Under conditions of increased temperature, this may change.

A predictive modelling study of farmed shellfish growth under temperature regimes of +1°C and +4°C in Northern Irish waters (Strangford Lough) as part of the SMILE (Sustainable Mariculture in Lough Ecosystems) project suggests that production of mussels would decrease by 10% and 50% under +1°C and +4°C scenarios respectively. Oysters, due to their differing physiology, were predicted to experience much less growth limitation under the same scenarios (Ferreira *et al*., 2008).

Broodstock of some species (e.g. Atlantic halibut, Arctic charr) require low winter temperatures (3 months <6°C) for egg maturation. Production of high quality ova could require increased energy costs and capital expenditure associated with temperature control of broodstock and the availability of suitable broodstock sites may be restricted in the future. In fact the survival of viable populations of wild Arctic charr in the region could be threatened.

Opportunies for new species. Low confidence.

Warmer water conditions could, potentially, allow new species to be cultured (Bergh *et al.*, 2007) in the region where the current temperature maximums and minimums are marginal for the species, such as sea bass, sea bream, turbot, hake, scombriforms (e.g. blue fin tuna), nori, ormer and Manilla clams. Although it should be recognised that other barriers to species diversification (e.g. economic) may prevent these opportunities being realised.

Diseases of fish and shellfish. Low confidence.

From a disease point of view an increase in temperature can have many effects. Bacterial, viral and fungal disease will, in general, have shorter generation times. It is possible that some diseases, which transmit above a minimum temperature, will increase in prevalence. Not all effects on disease will be detrimental. For example the seasonal window of infectivity of some serious infectious conditions such as Viral Haemorrhagic Septicaemia Virus (VHSV) or the freshwater viral disease Infectious Pancreatic Necrosis Virus (IPNV) could be shortened, whilst others that require a minimum temperature to cause clinical symptoms and transmission, such as Bacterial Kidney Disease (BKD) in freshwater salmonids, could be lengthened. However, as most fish are poikilothermic their physiology is largely governed by the temperature of their surrounding environment and warmer water will mean the immune system of these animals will function more effectively in preventing the establishment of infections (up to the thermal optimum of the animal; Bowden *et al.*, 2007). It is therefore possible that clinical infections will not increase as fewer infections become established in the host. Once the thermal optimum is exceeded, then the function of the immune system will decline and physiological stress and oxygen depletion (warmer water holds less oxygen in solution than cold water) may well lead to disease and welfare issues.

Some viral infections can only occur between narrow temperature ranges, often 10-12°C (Bricknell *et al.*, 2006a), usually during spring and autumn. Under warmer conditions this temperature window may decrease in the spring (and occur earlier in the year) as more rapid warming of water occurs in spring. Conversely if cooling of the environment is delayed during the autumn this temperature window may become extended and occur later in the year. Additionally, warmer water conditions may allow the establishment of exotic diseases, which are currently excluded as the climate is too cool to permit transmission. Beneficially, diseases that occur under cool environments, e.g. cold water vibriosis, may become much rarer if the ecosystem is not cold enough for their biology.

If shellfish experience super-optimal thermal conditions (as will be more likely, particularly for intertidally cultivated species, given the predicted changes in temperature for the regions where they are cultivated) they may be more susceptible to bacterial, viral and parasitic infections.

By their nature it is difficult to understand the response of diseases of unknown aetiology to increase in temperature. Some may become established in the UK, new ones may develop as a result of the warmer conditions while others that occur under cooler water regimes may decline.

Bacterial infections

As a rule of thumb as temperature increases the generation time of bacteria decreases (Duguid *et al.*, 1978) so under higher temperature regimes most bacterial infections would be predicted to progress faster once the host was infected, however, as mentioned above, assuming the animal is not at its thermal limit the fishes immune system will be operating more effectively and may well overcome the infection (Le Morvan *et al.*, 1996; Eggset *et al.*, 1997a; Lillehaug, 1997; Van Muiswinkel and Wiegertjes, 1997).

Under a rising temperature regime some bacterial diseases of fish, such as *Moritella viscose* (Benediktsdottir *et al.*, 2000; Coyne *et al.*, 2006) and cold water vibriosis (Nordmo *et al.*, 1997; Nordmo and Ramstad, 1999; Steine *et al.*, 2001), may decline in abundance as these diseases are characteristically seen in winter under cold water conditions and the new warmer environment may well adversely affect these bacteria. *Aeromonas salmonicida* and BKD, however, tend to occur under rising temperature regimes and during the summer months (Roberts, 1976; Rose *et al.*, 1989; Eggset *et al.*, 1997b; Jonsdottir *et al.*, 1998; Nordmo and Ramstad, 1999; Piganelli *et al.*, 1999; Lillehaug *et al.*, 2000; Nagai and Lida, 2002; Jacobson *et al.*, 2003; Bruno, 2004; Hirvela-Koski *et al.*, 2006). If the environment warms by 2°C then it is possible that diseases such as these will occur earlier in the year (as the spring will be warmer and earlier) and the period in which these diseases are common may well be extended, increasing the infectious pressure of these pathogens in the environment. Warmer conditions may also favour currently rare bacterial infections such as *Mycobacterium marinum* and *Mycobacterium chelonae*, allowing these pathogens to extend its range further north. Indeed, it appears *M. marinum* has become endemic in some populations of striped bass in the wild and in culture under rising temperature regimes in Chesapeake Bay (Matsche *et al.*, 2010; Gauthier *et al.*, 2011).

Increased water temperatures could also increase the risk of vibriosis infections of shellfish. Recent studies in the Mediterranean have shown a link between vibrio infections, seasonality and temperature (Vezzulli *et al.*, 2010). Changes in precipitation (increases in winter in the north) could also influence bacterial loading to the coastal environment where fish and shellfish farms are situated. This could increase the rate of infection.

Viral diseases

Viruses effectively hijack the host's cells to replicate and the rate of replication is governed by the animal's physiology (Duguid *et al.*, 1978). As most fish are poikilothermic (Bond, 1996) their physiology is largely governed by the temperature of their surrounding environment and warmer water will mean the animals will have a faster metabolism, which in turn could lead to increased viral replication within the host. It is worth pointing out again that, assuming the animal is not at its thermal limit, the fishes' immune system will be operating more effectively and may well overcome the infection as described above.

Some viruses can only infect their host during a very narrow temperature window (usually 10-12^{o}C for most viruses currently of interest in Scotland (Jarp *et al*., 1996; Stangeland *et al*., 1996; Bowden *et al*., 2002; Kollner *et al*., 2002; Bowden, 2003; Einer-Jensen *et al*., 2004; Park and Reno, 2005; Skall *et al*., 2005a,b; Bricknell *et al*., 2006a) so an increased temperature regime may shorten this window as spring warming of water may well be increased reducing the period when infection can take place. Conversely cooling of the aquatic environment in autumn may be slower and the autumn infectious window may well increase in duration. This may result in a change in the seasonal distribution of diseases and it may well allow the pathogens to encounter new hosts as their duration in the aquatic environment is different from today. For example an increased infectious window in the autumn may mean that autumn migrating fish such as the critically endangered smelt may encounter pathogens that it does not normally meet.

Parasitic diseases

As parasites of fish and shellfish often have very complex life cycles involving many intermediate hosts, understanding how climate change would affect parasite abundance and the incidence of infection is more difficult to predict. Some parasites will become rare or disappear from Scottish waters because their physiology is not suitable to the warmer environment or their intermediate and final hosts decline in numbers as the environment changes, migrate further north to cooler waters (Clark *et al*., 2003; Drinkwater, 2005; Rose, 2005) or the parasites thermal limits are exceeded (Boxaspen, 1997; Boxaspen and Naess, 2000). However other parasites will become more abundant as their definitive host and intermediate hosts colonise the new environment or, as Scottish waters warm up, the environment will be able to support new parasitic organisms, which are currently at or below their thermal minimum, and they would be able to survive and colonise new hosts in the warmer ecosystem. For example *Caligus curtis*, currently rare in Scottish waters, may effectively extend their range further north, especially if susceptible fish hosts can over-winter or establish viable populations.

It is easier to predict the response of parasites with direct life cycles, such as sea lice (*Lepeophtheirus salmonis*) to changing environmental parameters. It would be expected that a 2^{o}C increase in water temperature will decrease the life cycle by approximately 2 days and permit more generations in a season (Heuch *et al*., 1995; Boxaspen, 1997; Boxaspen and Naess, 2000), potentially increasing the infective pressure of this parasite in Scotland. However, the time the copepodid stage remains infectious will also decrease from about 10 days under current climatic conditions to around 8 days under the warmer regime suggested here (Johnson and Albright, 1991a,b). During the over-wintering period more copepodid and mobile stages may survive allowing a more rapid establishment of infection each spring. Currently *L. salmonis* has a population boom in early May and declines in numbers in late October (Pike and Wadsworth, 2000). Under a warmer regime with warmer springtime temperatures the spring lice bloom may occur earlier in the year and the autumn decline push into November or even December. Such an extended season would undoubtedly lead to more clinical interventions to control lice as well as increased lice infective pressure within the environment.

Salinity changes resulting from perturbed precipitation could also affect sea lice. At salinity values <29 ppt lice survival is compromised (Bricknell *et al*., 2006b), which might suggest potential for increased infection rates in estuaries, Scottish lochs and Irish loughs where reduced precipitation could decrease the low salinity influence around this value in the surface waters of these transitional environments.

Fungal disease

Like bacteria, as temperature increases the generation time of fungal organisms decreases so that, under higher temperature regimes, most fungal infections would be predicted to progress faster once the host was infected. However, as mentioned above, assuming the animal is not at its thermal limit, the fishes' immune system will be operating more effectively and may well overcome the infection.

Saprolegnia is one disease that could cause concern in a warming environment. Currently this disease occurs each spring and causes major welfare issues with parr and smolts often necessitating clinical intervention and treatment with antifungal drugs. Under warmer conditions it is feasible that *Saprolegnia* would occur earlier in the year and progress faster in infected fish (Howe and Stehly, 1998; Howe *et al*., 1998; Quiniou *et al*., 1998; De Canales *et al*., 2001; Lategan *et al*., 2004; Udomkusonsri and Noga, 2005; Gieseker *et al*., 2006) and the autumn decline in the disease would occur later in the year.

Fungal diseases exotic to Scotland becoming established is a potential concern especially as the trade in tropical ornamental fish (including goldfish, which are often cultured under warm water regimes in the Middle and Far East, China and USA) may be a source of introduction of the exotic fish fungi into the country.

Wind and Storminess. Low confidence.

The UKCIP predictions for wind speeds are very uncertain. It is predicted that winter depressions will become more frequent, with deeper lows. However it is difficult to clearly predict regional effects. Based on UKCIP forecasts, some areas are predicted to experience an increase (up to 10%) in the 20 year return period daily mean speeds in some seasons (e.g. west coast of Scotland in autumn/winter and Orkney/Shetland in summer). Also in general across the North-East Atlantic storm events have intensified and this increase is predicted by some authors to continue (Leckebusch *et al*., 2006). An increase in the frequency of stormy conditions, will have significance for the integrity of aquaculture structures and increase the risk of escapes. If the finfish sector wishes to expand significantly it is likely to have to consider moving to more exposed offshore locations in the near future. It is in these environments that the greatest engineering challenges will be faced, with infrastructure subjected to substantial wave stress. This is likely to exacerbate the forecast effects of storminess on the sector. Mussel farms are particularly vulnerable to damage by storms (Dankers, 1995) while infrastructure damage to finfish farms can result in significant losses of fish with potential environmental and economic impacts (Taylor and Kelly, 2010). It is not clear whether changes in fish farm escapes where data exist (Scotland) are related to changes in weather patterns and more comprehensive monitoring would be required to assess this across the UK and Ireland. There is some evidence (Overstreet, 2007) that extreme weather events can harm and reduce parasite populations which may have some subsequent beneficial effects for fish health or reduced economic costs of parasitic treatments. Mean daily wind speeds with two-year return periods are predicted to decline over much of the West coast of Scotland during summer months. These calmer conditions are likely to have effects on planktonic communities with potential knock-on effects for stock health.

Rainfall, salinity and run-off. Low confidence.

UKCIP predictions indicate a likely increase in winter precipitation and a decrease in summer precipitation in the north of the region where aquaculture is predominantly located. Increased run-off could result in increased flow rates and turbidity in estuarine environments where bivalve aquaculture is often located. These potential winter effects could result in damage to equipment, loss of stock and increased contamination of shellfish with bacteria and viruses from sewerage overflows and run-off from land where livestock faecal material is present. Subsequent impacts on shellfish classification (determined according to the presence of enteric bacteria) could result in increased costs of depuration of shellfish to make them safe for consumption or increased risks of, for example, norovirus infection in consumers.

Conversely in summer months reduced impacts on shellfish contamination from enteric bacteria and viruses is possible. Reduced freshwater inputs could also reduce estuarine mixing which has been shown to be related to the incidence of harmful algal toxins in shellfish, such as diarrhetic shellfish poisoning (DSP) in Portugal (Vale and de M. Sampayo, 2003).

Ocean acidification. Low confidence.

Future changes in ocean carbonate chemistry are difficult to predict with any certainty and the effects of this are hard to elucidate given the difficulties associated with monitoring long term biological responses to very small changes in experimental conditions. However, it is predicted that the effects of ocean acidification will be more pronounced in the highly productive coastal regions where aquaculture is located. Under lower pH conditions one of the predicted effects is disruption of the shell laying processes of early life history stages of shelled molluscs (Raven *et al*., 2005). During shell development initial soluble calcium carbonate structures will be vulnerable under conditions of lower pH before the more stable and insoluble aragonite and calcite shells are formed. Thus there may be some effects on planktonic, larval and early settled stages of cultured bivalve molluscs. It is currently unclear whether predicted acidification will impact on the natural spat supply and settlement relied upon by the majority of mussel farming operations in the UK and Ireland.

Macroalgae. Low confidence.

Macroalgae cultivation in the UK and Ireland is currently in its infancy, but has significant interest and growth potential to supply both niche dietary and pharmaceutical markets as well as large scale cultivation for biofuels. Significant cultivation is likely to have to take place in offshore environments (where space is available) where physical infrastructure will be susceptible to the same issues from increased storminess as the finfish sector.

Macroalgal growth rates are dependent on nutrient concentrations. Forecast climate change scenarios, where changes in precipitation may bring varied nutrient loadings to nearshore environments, will have consequent effects on macroalgal productivity. Variability in nutrient loading as might be expected under conditions of more variable precipitation, will also favour invasive short-lived algal species rather than the longer lived kelp species normally considered for cultivation.

Kelp cover has been shown to be sensitive to environmental conditions such as increased temperature and precipitation as has been demonstrated in Southern California (Grove *et al*., 2002).

Increased stratification, caused by higher temperatures and lower wind speeds is also likely to reduce kelp growth and impact on production as nutrient supply to surface waters is restricted by stratification.

The greatest influence on the future of macroalgae farming in the UK and Ireland, however, is going to be technological and the availability of suitable locations rather than changes in ocean climate. Climate change, however, is likely to change the composition of species suitable for cultivation locally and increase the difficulties associated with offshore cultivation techniques.

Non-native species. Low confidence.

Marine non-native invasive species are already causing significant economic impacts in the UK and Ireland. Some studies suggest that the rate of invasions is likely to increase under climate change and increasing temperature regimes (Byers *et al*., 2002; Stachowicz *et al*., 2002). There is currently little evidence of impact on aquaculture from non-native species in the UK and Ireland. However, examples from beyond the region suggest climate change could increase the rate of invasions, particularly in marine habitats at higher latitudes (Reid *et al*., 2009; Ruiz and Hewitt, 2009) as species ranges expand further north.

Impacts on the aquaculture industry are most likely from fouling organisms such as tunicates (e.g. *Didemnum vexillum*) which has already impacted mussel beds and marinas and could impact on aquaculture infrastructure or service vessels. The potential impact of these species is significant and they are already present close to aquaculture facilities in the region. Their progression could be enhanced by climate change, and greater knowledge regarding the current distribution is needed along with improved monitoring to detect progression or the occurrence of new species.

Populations of feral *Crassostrea gigas*, introduced for aquaculture purposes in the 1970s, are establishing in Northern Irish sea loughs. Initial assessments assumed that environmental conditions would not allow the *in-situ* reproduction of this species, but initial reports of the establishment of feral populations outside aquaculture sites were received in the 1990s. Since then feral populations have been observed established throughout the northern basin of Strangford Lough raising concerns over the potential for significant habitat changes to occur. The frequency distribution of the local feral populations suggested that recruitment was not occurring every year and initial attempts to cull the feral populations were undertaken. Although not conclusively a result of climate change, the potential impact of rising temperatures is the subject of further study (Guy and Roberts, 2010).

Harmful planktonic events. Low confidence.

Climate change is having a complex effect on planktonic communities. Several studies have associated rising surface temperatures with an increase in the relative abundance of flagellates and dinoflagellates (compared to diatoms), e.g. in the NE Atlantic (Edwards *et al*., 2006), North Sea (Edwards and Richardson 2004), Baltic Sea (Wasmund *et al*., 1998) and Norwegian coast (Saetre *et al*., 2003). Hinder *et al*. (2012) have associated increases in wind speed and changes in direction with an increase in the relative abundance of diatoms in the continuous plankton recorder dataset. Both of these taxonomic groups contain potentially toxic or nuisance species that can be responsible for stress or kills of cultured finfish or result in harvesting closures for shellfish growing waters. There are many complicating factors and for the regions where Scottish aquaculture is concentrated there are no accurate predictions for the future trends in the occurrence of such harmful algal blooms (HABs). Changes in precipitation will affect the salinity of coastal waters as well as the stratification of water columns and the availability of nutrients for phytoplankton growth. Changes in nutrient ratios caused by reduced summer rainfall could result in silica limitation, a factor known to increase the toxicity of some diatom species (Youlian *et al*., 1998). In addition the zooplankton communities which graze on phytoplankton communities have also been observed to be changing and the effect temperature changes will have on this grazing rate and subsequently on potential harmful phytoplankton communities is very complex and hard to predict. Changes in sea water alkalinity as a result of a modified carbonate chemistry could also be detrimental to algal growth (Hansen, 2002).

Jellyfish have also been shown to increase in abundance in association with climate change (as well as overfishing) (Lynam *et al*., 2011). There has been an increase in the abundance of warmer water species at higher latitudes where vulnerable finfish are predominantly cultivated, for example *Pelagia noctiluca* which can cause pathology in the gills of salmon and kill entire stocks (Doyle *et al*., 2008). Jellyfish are a comparatively poorly monitored species and it will be difficult to determine whether climate change is affecting their abundance and distribution without improved monitoring in place.

It is possible that the future hydrodynamic regime will favour a different planktonic community to the present. It is possible that species currently absent or rare in Scottish waters may become established and new toxic / nuisance species may pose problems for aquaculturists. The phenology (temporal patterns of occurrence) of planktonic species are also likely to be altered (Edwards and Richardson, 2004), with effects on the timing and efficacy of shellfish spat fall.

3. KNOWLEDGE GAPS

a. The extent to which sea-level rise and associated coastal habitat loss (including areas suitable for intertidal mollusc culture) will be offset by coastline morphology reformation.

b. The potential relationship between fish farm escapes and changing frequency of storm events.

c. The likely effects of ocean acidification on early life stages of bivalves and implications for shellfish farm spat-fall.

d. Monitoring for the potential spread of non-native species.

e. Impacts of climate change on the environmental impacts of aquaculture – e.g. assimilative capacity of receiving water bodies.

f. Update of epidemiological risk assessments on aquaculture pathogens to account for climate change factors

g. Improved monitoring of jellyfish to be able to determine the impact of climate change on this aquaculture risk

h. Improved centralised monitoring of potentially affected aquaculture parameters such as spat-fall, growth of stock, storm damage, fouling rates etc.

These knowledge gaps have been expanded from the last report card in response to identification of further issues in recently published literature.

4. SOCIO-ECONOMIC IMPACTS

a. Potential increased costs to industry associated with infrastructure damage from storm events and associated loss of stock.

b. Potential increased costs associated with shellfish depuration or increased consumer health risk from shellfish with bacterial and viral contamination following increased run-off, sewerage overflow and bacterial loading to estuarine systems.

c. Improved return on production efficiency resulting from increased growth rates associated with some species under changed hydrographic conditions.

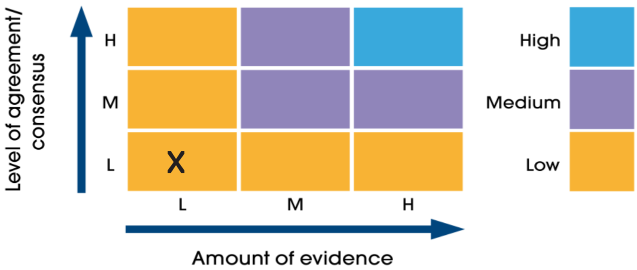
d. Industry and insurance costs associated with loss of stock from more frequent harmful planktonic events.

e. Costs associated with clearing fouling invasive organisms whose spread may be exacerbated by climate change.

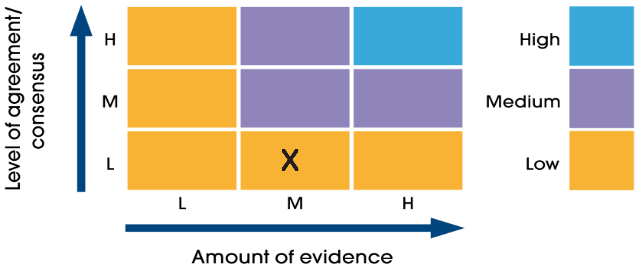
f. Increased costs relating to intervention for disease control.

5. CONFIDENCE ASSESSMENT

What is already happening?



What could happen?



There are no reports that the authors are aware of that present robust evidence that climate change is already affecting the UK aquaculture industry, only observations of effects that could be attributable to climate change effects. The number of theoretical ptredictions of effects in the literature are increasing but vary considerably regionally.

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