The impacts of climate change on fisheries, relevant to the coastal and marine environment around the UK

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EXECUTIVE SUMMARY

- Recent changes in Atlantic mackerel distribution, and consequences for fisheries quota allocation have been linked to several possible factors, including warmer seas, changes in food availability and a density-dependent expansion of the stock.
- In the past few years, both commercial and recreational fishers have reported seeing large numbers of Atlantic bluefin tuna off the British Isles. It is thought that this has been partially influenced by changing climatic conditions.
- It can be incredibly difficult to attribute with confidence an observed change in the distribution or productivity of fish species to long-term climate change, especially when many other drivers are known to influence populations (e.g. fishing pressure, habitat modification, short-term climate variability etc.).
- The past 25 years have witnessed a significant decline in primary productivity of the North Sea, which has been associated with an overall decline in the recruitment of key commercial fish stocks.
- Cod and sole spawning has advanced earlier in the northern and central North Sea over the past 30 years by 2.4 and 1.5 weeks per decade respectively, linked to changing seawater temperatures.
- A study using temperature-dependent population models, has suggested that the maximum sustainable yield of exploited populations decreased globally by 4.1% from 1930 to 2010, with five ecoregions experiencing losses of 15 to 35%. Notably, populations in the North Sea and Celtic–Biscay shelf (i.e. around the British Isles) were among the most negatively impacted worldwide.
- Long-term changes in the frequency and magnitude of storms could pose a direct risk to UK fisheries, but future storm projections are highly uncertain. Storms can disrupt fishing effort, present a physical danger to fishers, their vessels and gear, as well as lead to financial hardship in fishing communities.

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- Major advances have been made regarding the ability to provide future projections for climate change impacts on fish and fisheries. In particular, scientists have started to provide 'forecasts' for some species at the seasonal to decadal time horizon.

1. INTRODUCTION

Fishing remains one of the most important maritime activities in the United Kingdom (UK). In 2017, UK fishing vessels landed 724,000 tonnes of fish and shellfish, accruing a revenue of around £980 million (MMO, 2018). The UK industry now employs around 11,692 fishermen, compared to 12,934 in 2006. There has been a similar decrease in the number of UK fishing vessels over this period – declining from 6752 in 2006 to 6148 in 2017. The recent contraction in the UK fishing industry has been a result of deliberate interventions to control fishing pressure and to ensure sustainable exploitation of European fish stocks, but to some extent also reflects the underlying influence of climatic factors on larvae recruitment to the fishery and growth, which determine the level of fishing that can be sustained by fish populations, given the prevailing environmental conditions.

The various impacts of climate change on fisheries in the United Kingdom were last reviewed in detail as part of the 10-year MCCIP retrospective report card in 2017 (see Pinnegar *et al*., 2017) but also in the North Atlantic chapter of the recent FAO report on *'Impacts of Climate Change on Fisheries and Aquaculture'* (see Peck and Pinnegar, 2018). Hence, much of the material included here is similar to that reported previously. However, a novel development has been the emergence of a yearly 'watching brief' report produced by Seafish (together with Cefas) that aims to communicate new scientific evidence as well as industry observations of climate change impacts concerning wild-capture fisheries and climate change in the UK. This watching brief report has now been through three full iterations most recently in September 2019 (see https://www.seafish.org/article/climate-change-adaptation) and these short documents provide a useful narrative of industry perspectives as well as scientific insights. Additionally, in June 2019, the UK Parliamentary Office of Science and Technology (POST) published a special 'POST-Note' on climate change and fisheries (see Stewart and Wentworth, 2019). This short document summarises the impacts of ocean warming, acidification, deoxygenation and storms, and explores how fisheries may adapt.

As part of this 2020 MCCIP assessment, a separate supporting document has been prepared on climate change consequences for 'Fish' (see Wright *et al*. 2020). Clearly there is substantial overlap between the 'Fish' and 'Fisheries' supporting documents, but in general the 'Fisheries' document has tended to focus on datasets derived from the commercial fishing industry or modelling focussed on understanding fisheries consequences. By contrast, the 'Fish' document primarily draws on fishery-independent survey datasets; it considers fundamental aspects of fish biology, physiology and life history and it does not consider impacts on shellfish. Notably, in the 'Fisheries' MCCIP document, the topic of observed or predicted changes in fish growth is not considered in any detail, even though it is acknowledged that there have been several high-profile publications, relevant to fisheries in the United Kingdom over the past few years (e.g. Baudron *et al*., 2014; Hunter *et al*., 2016). Changes in fish growth and the widely cited 'temperature-size rule' are however, discussed in detail in the 'Fish' report. Baudron *et al*. (2014) showed that over a 40-year period, six of eight commercial fish species in the North Sea underwent concomitant reductions in asymptotic body size and that shrinking body sizes have impacted fisheries yield.

Similarly, in a new paper published in 2019, Free *et al*. (2019) used temperature-dependent population models to measure the influence of warming on the productivity of 235 populations of commercial marine fish in 38 ecoregions. Some populations responded significantly positively (9 populations) and others responded significantly negatively (19 populations) to warming. Hindcasts indicate that the maximum sustainable yield of the evaluated populations decreased by 4.1% from 1930 to 2010, with five ecoregions experiencing losses of 15 to 35%. Notably, populations in the North Sea and Celtic–Biscay shelf (i.e. around the British Isles) were among the most negatively impacted worldwide. The authors found that exploitation history and temperature change interacted to determine the vulnerability of populations to warming. Populations that had experienced intense and prolonged overfishing were more likely to be negatively influenced by warming, especially when they had also experienced rapid warming (>0.2°C per decade).

2. WHAT IS ALREADY HAPPENING?

Effects on distribution

One of the themes that has repeatedly been raised in MCCIP reports over the past 10 years has been observed shifts in the distribution of species, including commercial fish. Following publication of the ground-breaking work by Perry *et al*. in 2005 (now cited more than 2400 times), many studies have been published that have confirmed shifts in distribution around the UK. These have included observational studies that have made use of scientific survey datasets (e.g. Dulvy *et al*., 2008; Simpson *et al*., 2011; Montero-Serra *et al*., 2015), but also studies that have examined data from commercial fisheries and demonstrated shifts in catch-per-unit-effort (e.g. Engelhard *et al*., 2011, 2014). More recently, Moyes and Magurran (2018) reported marked temporal changes in the dominance structure of marine-fish assemblages over the past three decades to the east and west of Scotland.

In 2016, ICES received a specific request for advice from the EU Commission to investigate long-term distribution shifts of key commercial fish stocks in relation to management areas and national jurisdictions. A report was prepared (ICES, 2016), and all species were found to have exhibited some changes in their distribution over the past 20–30 years, apart from Greenland halibut (*Reinhardtius hippoglossoides*), Norway pout (*Trisopterus esmarkii*) and spurdog (*Squalus acanthias*) for which no evidence was found. The main drivers of the distribution shifts were environmental conditions (mainly temperature) for all species, followed by density-dependent habitat selection (7 species), geographical attachment (6 species), species interactions (4 species), demographic structure (3 species), and spatial dependency (2 species). Eight species (anchovy (*Engraulis encrasicolus*), cod (*Gadus morhua*), hake (*Merluccius merluccius*), herring (*Clupea harengus*), Atlantic mackerel, plaice (*Pleuronectes platessa*), horse mackerel (*Trachurus trachurus*), and common sole (*Solea solea*)) have shifted their distribution in relation to Total Allowable Catch (TAC) management boundaries since 1985. Of these, the greatest shifts occurred for hake and Atlantic mackerel. In addition, several species were identified as ‘big movers’: Anchovy (northward shift in the North Sea), anglerfish (regional changes in the North Sea), blue whiting (increase in the North Sea and west of Scotland), cod (northward shift), hake (expansion in the North Sea), herring (changes across different TAC management areas), mackerel (major changes across north-east Atlantic), megrim (regional changes in the North Sea, Bay of Biscay and Celtic Sea), and plaice (increase in North Sea and Baltic Sea, changes across different TAC management areas). In the ICES advice issued to the EU Commission (in March 2017) it was stated that,

“Future changes in distribution are likely, but given the complexity of the mechanisms affecting the spatial distribution of fish stocks, predicting those changes with precision and accuracy is not possible. It is reasonable to assume that these changes will challenge some assumptions underlying the current management of Northeast Atlantic fisheries. Continued monitoring of the spatial distributions of fish stocks is essential to support future management.”

A particular focus in recent years has been the apparent westward and north-westward spread of Atlantic mackerel into Icelandic and Faroese waters, with consequences for fisheries quota allocation and governance. In October 2009, North Sea mackerel appeared to have moved away from the Norwegian Sector and Norwegian vessels attempted to follow the fish westwards resulting in disagreements over permissible catches by Norwegian boats in Scottish (EU) waters (see *Fishing News*, 9th October 2009). Shortly after this, Iceland and the Faroe Islands unilaterally claimed quota for mackerel (146,000 and 150,000 tonnes, respectively, in 2011; or 46% of total catches), since the species had suddenly attained high abundance in their territorial waters for the first time (see Figure 1). These events have been related to climatic influences (Hughes *et al*., 2014; Olafsdottir *et al*., 2019) and prompted difficult political negotiations that lasted for a further five years. A partial resolution to the long-standing political dispute regarding mackerel quotas in the North-East Atlantic (NEA) was brokered on 12 March 2014. A five-year arrangement was reached between the EU, the Faroe Islands and Norway (but not Iceland). Since 2013 the scientific evidence-base with regard to Atlantic mackerel, Scotland’s most valuable fishery, has increased considerably and we are now better able to describe the drivers behind this recent phenomenon and the consequences for fisheries in more detail.

After spawning, which typically takes place off north-west Scotland from February to July, mackerel migrate to their feeding grounds. Until the mid-2000s, these feeding grounds were mostly limited to the northern part of the North Sea and the Norwegian Sea, but in 2006 mackerel was first observed in significant amounts east of Iceland as by-catch in the Norwegian spring-spawning herring fishery and a large directed mackerel fishery grew to exploit the expanding population. The recent changes in mackerel distribution have been linked to several possible factors, including warmer seas, changes in food availability and a density-dependent expansion of the stock (ICES, 2013). Hughes *et al*., (2014) suggested that Sea-Surface Temperature (SST) had a significant positive association with the observed northward and westward movement of mackerel, equivalent to a displacement of 37.7 km per °C (based on spring mean SST for the region). During that period mackerel distribution range increased three-fold and the centre-of-distribution shifted westwards by 1650 km and northwards by 400 km (Olafsdottir *et al*., 2019). However, the association with climatic indices is not straightforward (Hughes *et al*., 2015). A comprehensive study of mackerel records by Astthorsson *et al*., (2012) highlighted 2007 as the year when distribution first started to change, but found that there were warmer years before 2007, so a simple temperature mechanism does not seem likely. Hughes *et al.* (2015) detected a significant climate effect on the depth of area fished, where mackerel were generally caught in areas of greater depth during positive Atlantic Multidecadal Oscillation (AMO) years. In addition, the AMO appeared to have a non-linear relationship with the spatial extent of mackerel catches, with an increased total fishing area in positive AMO years. Generalised additive models showed that both mackerel occurrence and density were positively related to location, ambient temperature, mesozooplankton density and Spawning Stock Biomass (SSB), explaining 47% and 32% of deviance, respectively (Olafsdottir *et al*., 2019).

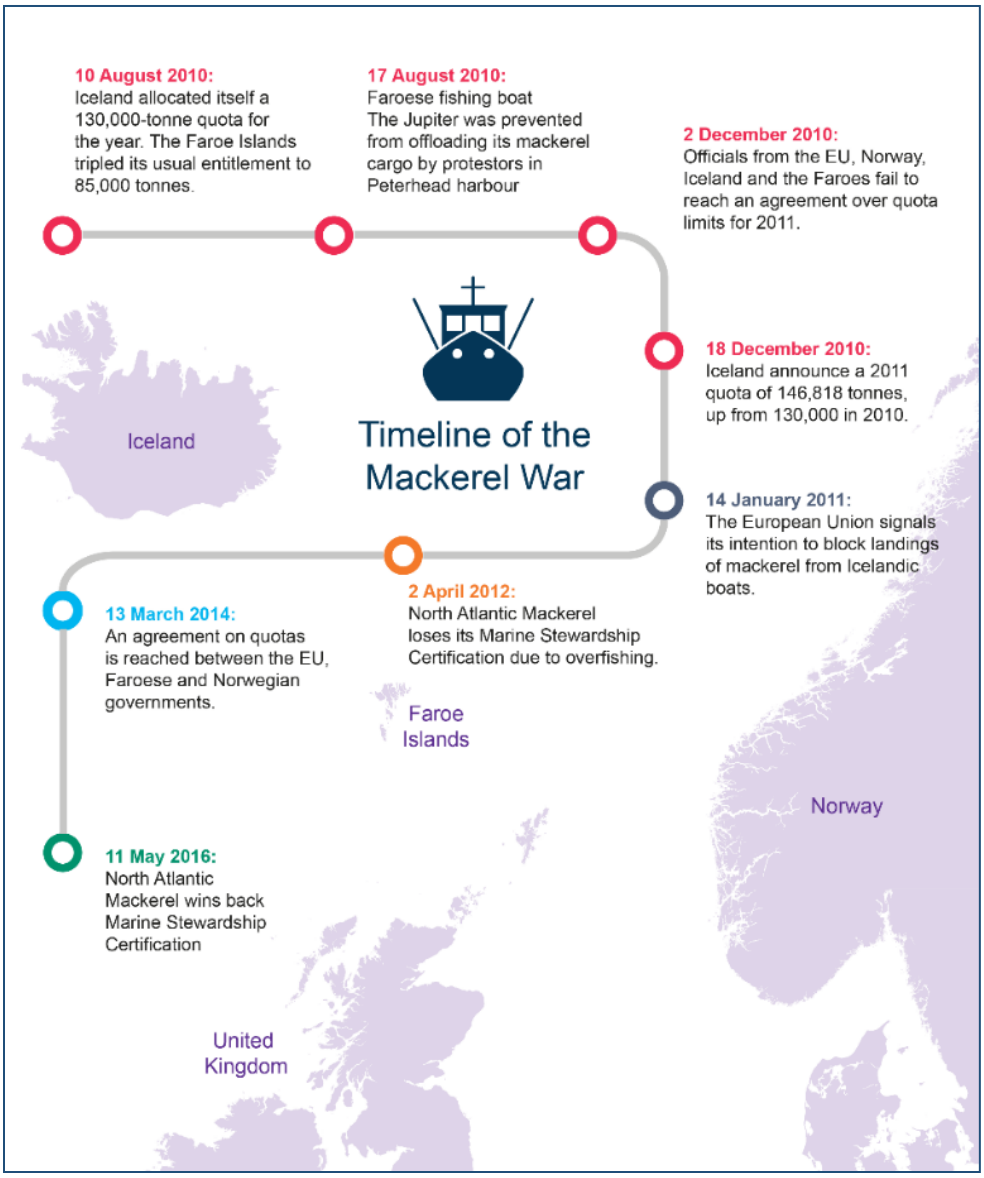


Figure 1: Summary of key events during the 'Mackerel War'. https://digitalpublications.parliament.scot/ResearchBriefings/Report/2018/4/25/Mackerel#Case-Study---The-Mackerel-War-

In recent years, both commercial and recreational fishers have reported seeing large numbers of Atlantic bluefin tuna *Thunnus thynnus*, especially off Devon and Cornwall, but also in the North Sea. Historically this species had been present throughout much of the North-East Atlantic, including around the British Isles where it had previously been a target of commercial fisheries from Norway and France and a UK sport fishery based in Yorkshire (Bennema, 2018). Bluefin tuna largely disappeared from UK waters in the 1970s when the yearly migration of large individuals to northern waters seemed to have ceased. However, tuna have now been reported as far north as Iceland and Greenland, possibly shifting their distribution in response to the expansion of mackerel (a major prey item), which has been at least partly influenced by changing climatic conditions (MacKenzie *et al*., 2014). Since 2008, the International Commission for the Conservation of Atlantic Tunas (ICCAT) has granted a small but rapidly increasing quota share to Norway and Iceland (52.48 and 43.71 tonnes respectively in 2017, rising to 200 and 140 tonnes by 2020) in recognition of the growing abundance of this species in northern waters. In January 2019, Faillettaz *et al*. published a paper that suggested that the reappearance of bluefin tuna in northern European waters can be explained by patterns of hydroclimatic variability and in particular the AMO. To reach their conclusion, the scientists examined the changing abundance and distribution of bluefin tuna in the Atlantic Ocean over the last 200 years. It should be noted that the UK has not been allocated a share of the total EU bluefin tuna quota, having never previously had a commercial fishery and therefore a 'track record' of harvesting this species. Currently, the Marine Management Organisation (MMO) guidance states that:

"[commercial] *Vessels must not target bluefin tuna and if caught accidentally they must be returned to the sea, alive and unharmed to the greatest extent possible. Sea anglers must not target bluefin tuna, any caught as a by-catch when targeting other species must be released immediately and not landed or brought onto the boat".*

Another persistent feature of MCCIP reports over the past 10 years has been the suggestion of increasing cephalopod (squid, cuttlefish and octopus) populations and resulting fisheries, with the often repeated statement that: "more boats are now trawling for squid than the region's traditional target species, such as haddock and cod," (originally from Hastie *et al*., 2009). Since 2013, a number of high-profile research papers have been published that support this claim. Most notably, Doubleday *et al*. (2016) assembled global time–series data of cephalopod catch rates (catch per unit of fishing or sampling effort) and demonstrated that cephalopod populations have increased worldwide over the last six decades; a result that seems to be related to patterns of surface warming and is remarkably consistent across a highly diverse set of cephalopod taxa. A more-detailed analysis by van der Kooij *et al*. (2016) extracted squid catches from a unique 35-year time–series study of bottom-trawl survey data in the North Sea (1980–2014), collected during late summer (August–September). Changes in distribution and abundance were compared with key climatic variables. Squid distribution across the North Sea increased over the 35-year time–series. Significantly positive relationships were found between this increase and climate variables for each of the dominant individual taxa studied, and also when all species were combined. *Loligo* expanded southwards from a predominantly north-easterly distribution, compared to northward expansions by *Alloteuthis* and the Ommastrephidae from their core distributions in the southern and central North Sea, respectively. A recent study by Oesterwind *et al.* (in press) highlighted increased abundance of broadtail shortfin squid *Illex coindetii* in the southern North Sea and provided evidence of a new spawning area, based on fishery survey datasets. The UK trade newspaper *Fishing News* included a special feature on expanding summer squid fisheries in the Moray Firth on 14th January 2016. This article stated that:

"It is probably fair to say that none of the trawlers fishing squid in the Moray Firth at the time of this trip were doing so out of choice. Rather, their presence was directly associated with the necessity to maintain some form of income when restrictions were preventing them from engaging in their preferred fisheries." Also that: *"The need to purchase customised squid trawls means that gearing-up for a fishery that usually lasts for just two months* [each year], *and sometimes considerably less, requires considerable initial outlay."*

Effects on stock recruitment

A major focus of previous MCCIP reports has been the impact of climate on fish recruitment (i.e. the number of juvenile fish reaching an age or size whereby they can be caught by the fishery). In recent years several publications have appeared that provide insights of relevance to UK commercial species. For example, Akimova *et al*. (2016) investigated the relation between North Sea hydrography (temperature and salinity) and fish stock variables (recruitment, spawning stock biomass and pre-recruitment survival index) for nine commercially important fishes using spatially resolved cross-correlation analysis. The results confirmed previously demonstrated negative correlations between temperature and recruitment of cod and plaice and identified regions exhibiting the most significant correlations (German Bight for plaice, and north-western North Sea for cod). They also revealed a positive correlation between herring spawning stock biomass and temperature in the Orkney–Shetland area, as well as a negative correlation between sole pre-recruitment survival and temperature in the German Bight.

Capuzzo *et al*. (2018) reported a significant decline in primary production in the North Sea, thought to be influenced by sea-surface warming and reduced riverine nutrient inputs. In turn, significant correlations were found between observed changes in primary production and the dynamics of higher trophic levels including (small) copepods and a standardised index of fish recruitment, averaged over seven stocks of high commercial significance (cod, haddock (*Melanogrammus aeglefinnus*), whiting (*Merlangius merlangus*), Norway pout, herring, sprat (*Sprattus sprattus*) and sandeel (*Ammodytes marinus*)).

Estrella-Martinez *et al*. (2019) provided annually resolved time–series of recruitment strength in North Sea herring over the past 455 years, based on relationships between recruitment and phytoplankton productivity, and making use of stable isotope measurements from ocean quahog (*Arctica islandica*) shells. The reconstruction suggests that there were five extended episodes of low recruitment levels before the 20th Century and that each of these was associated with poor feeding conditions. These findings are supported by contemporaneous, somewhat piecemeal, documentary evidence on herring catches.

According to the most-recent stock assessment reports for cod, populations around the UK were heavily overfished in the early-mid part of the first decade of the 21st century, when they were at their lowest ever recorded value. However, since this period, fishing mortality has been significantly reduced through vessel-decommissioning schemes and statutory effort controls. Spawning stock biomass in the North Sea has recovered to a level (118,387 tonnes in 2018) above its precautionary reference limit, but this recovery has been much slower than originally anticipated and there has been little recovery elsewhere. In the Irish and Celtic Seas, as well as the west of Scotland, cod stocks are still at low levels, despite the very dramatic and deliberate reduction in fishing mortality. It has been stated that this is largely a reflection of continued poor recruitment in all UK cod stocks, at least partially related to prevailing climatic conditions since the mid-1990s (e.g. Sguotti *et al*. 2019). Winter *et al*. (2019) provided a mechanism for this (a potential ‘Allee effect’) and suggested that a fishing moratorium is only sufficient for recovery when SST rise remains within 2°C and fishing is restricted over 15 years. If SST rises beyond 2°C, even immediate banning of fishing is not sufficient anymore to guarantee recovery. On the other hand, Brander (2018) warned against overemphasising the role of climate. He noted that the average SST for the North Sea over the period 2000–2015 increased by >1°C relative to the 1961–1990 baseline and, contrary to the earlier projection of Drinkwater (2005), the cod stock doubled in biomass rather than declining.

Effects on phenology

Another common theme that has been covered repeatedly in MCCIP fisheries’ reports over the past 10 years has been ‘phenology’, i.e. changes in the timing of natural events such as fish spawning date, migration patterns, hatching of larvae, etc. Fincham *et al.* (2013) examined the date of peak spawning for seven sole stocks based on market sampling data in England and the Netherlands. Four of seven stocks were shown to have exhibited a significant long-term trend towards earlier spawning (including the eastern-central North Sea, southern North Sea and Eastern English Channel) at a rate of 1.5 weeks per decade since 1970. A clear seasonal shift to earlier appearance of fish larvae has been described for southern North Sea cod and many other species (Greve *et al.*, 2005). In the English Channel, earlier spawning following warmer temperatures has been observed in summer-spawning species, for example mackerel and horse mackerel (Genner *et al.*, 2010). In contrast, species that spawn in spring tend to spawn later following warmer winters, including lemon sole *Microstomus kitt* and pollack *Pollachius pollachius* (Genner *et al.*, 2010).

McQueen and Marshall (2017) examined inter-annual variation in the timing of Atlantic cod spawning, as estimated by calculating an annual Peak Roe Month (PRM) from records of roe landings spanning the last three decades in the northern North Sea, central North Sea and Irish Sea. A trend towards earlier PRM was found in all three regions, with estimates of shifts in PRM ranging from 0.9 to 2.4 weeks per decade. Temperatures experienced by cod during early vitellogenesis were found to correlate negatively with PRM, suggesting that rising sea temperatures may have contributed to this apparent shift in spawning phenology. Other authors have demonstrated a difference of several weeks in spawning time between different sub-populations of cod (i.e. ‘Viking’ versus ‘Shetland’ cod), and thus observed shifts in phenology might be linked to the relative abundance or targeting of different sub-stocks, rather than climatic influences on individual populations (Gonzalez-Irusta and Wright, 2016). Neuheimer *et al*. (2018) used novel metrics of thermal time (similar to ‘degree days’) and a model of temperature-dependent ‘Stage Durations’ (SDs) to establish potential match-mismatch between the appearance of first-feeding cod larvae and their prey across the species' distribution range (~40° to 80°N). Spawning dates in cod varied by more than 86 days across the species’ range (including populations on both sides of the Atlantic), largely driven by SST and it is suggested that this flexibility allows cod to adapt to prevailing conditions, given that prey animals are also governed by the same environmental signals in a very similar way. It is suggested that the potential for decoupling of predator and prey timing is highest for cold water populations of cod, rather than warmer-water populations, such as those around the British Isles (Neuheimer *et al.*, 2018).

Heat waves, cold snaps and extreme events

Over the past few years considerable attention has been dedicated towards understanding and characterising ‘marine heat waves’ and their sometimes devastating consequences for commercial fisheries (e.g. Hobday *et al*., 2016; Frölicher and Laufkötter 2018). Oliver *et al*. (2018) suggest that from 1925 to 2016, global-average marine heatwave frequency and duration increased by 34% and 17%, respectively, resulting in an overall 54% increase in annual marine heatwave days globally. The frequency and duration of marine heat waves are projected to continue to increase, including in the large marine ecosystems, such as around the British Isles (Frölicher *et al*., 2018). Specifically, marine heat waves in northern Europe would be expected to negatively impact cold-water species such as cod and wolffish *Anarhichas lupus*, By contrast, ‘cold snaps’ (unusual periods of cold weather) are projected to occur less frequently in the future around the British Isles (Stryhal and Huth, 2019) and this could benefit warm-water species such as sole. Both heat waves and cold snaps have been implicated in observed mass-mortality events affecting cockles *Cerastoderma edule* (see Burdon *et al.* 2014).

During February 2018, massive numbers of starfish, crab, mussels and lobsters were washed up on the North Sea coast of the UK, following freezing weather and storms. Animals were piled up along the Holderness coast in Yorkshire and similar mass mortality events were reported in Kent and Norfolk. This followed a sudden 3°C drop in seawater temperature between 26th February and 4th March. Beginning on 22 February 2018, Great Britain and Ireland were affected by a cold snap, dubbed the 'Beast from the East' by the media and officially named Anticyclone Hartmut, which brought widespread unusually low temperatures and heavy snowfall to large areas. All the organisms piled up on the shores were dead, except some commercial-sized lobsters (see Figure 2). The Yorkshire Wildlife Trust worked alongside local fishers to rescue the surviving lobsters. An estimated 25,000 lobsters were transported to merchants' tanks in Bridlington. The aim was to put the lobsters back in the sea when the weather improved (on 5th March). Such 'cold-snap' events have become relatively rare in recent years, given that winters have tended toward being warmer (on average) than was the case in the past (Hurst 2007). Previous cold-snap events such as the 'big freeze' in 1963 witnessed large-scale fish die-offs, especially of warm-water species such as sole (Woodhead, 1964; Hurst 2007), and they remind us that, even though temperatures are generally warming around the UK, cold periods will still occur. On the whole, however, 2018 has been identified as the 7th warmest year on record for the UK despite the very cold conditions experienced in February.

Figure 2: Rescue operation for live lobsters washed up on the coast of Yorkshire following a sudden 3°C drop in seawater temperature, 4th March 2018. (Photos: Rodney Forster.)

Effects of ocean acidification and low oxygen

Over the past few years, hundreds of papers have been published focussing on the impact of Ocean Acidification (OA) on marine organisms (Browman, 2016). However, there is still a lack of conclusive evidence as to what the possible consequences for commercial fish and shellfish might be and, consequently, the impacts on fisheries and aquaculture are largely unknown. Opinions voiced in the literature range from complete catastrophe for global fisheries (e.g. Colt and Knapp, 2016) to very modest impacts.

Mangi *et al*. (2018) provided a review of relevant (2005–2016) laboratory experiments conducted on commercial shellfish species (mainly crustaceans and molluscs) with a particular focus on those of interest in the UK. This review only considered studies that simulated pH changes of less than 0.4 pH units, as this was considered a realistic pH scenario for the year 2100 around the British Isles. A total of 11 studies were included in this analysis following the methodology adopted by Ramajo *et al*. (2016) and Kroeker *et al*. (2013). The authors divided the species into molluscs and crustaceans, as the various meta-analyses that have been completed in recent years by Kroeker *et al*. (2013), Hendriks *et al*. (2010) and Kroeker *et al*. (2010) have all indicated that crustaceans (crabs, lobsters and shrimps) are more robust to simulated pH changes than molluscs (bivalves and gastropods). A log-transformed Response Ratio (LnRR) was calculated, which is the ratio of the mean effect in the acidification treatment to the mean effect in a control group. A LnRR of zero is interpreted as the experimental treatment having no effect on the response variable, while a positive value indicates a positive effect and a negative value indicates a negative effect. The effect size at different pH values were subsequently used to calculate anticipated financial losses in 2100 (see below).

Responses in fin-fish are particularly uncertain. Although several studies have noted that early life stages (eggs and young larvae) of fish may be sensitive to the direct effect of OA (e.g. Franke and Clemmesen, 2011; Frommel *et al*., 2012), the results appear to depend on the fish species and habitat of the stock (e.g. Pimentel *et al*., 2016). Rather confusingly, negative impacts of OA on larval growth, development, metabolism and survival have all been documented, but so have positive, indirect food web impacts of OA on survival and growth (Sswat *et al*., 2017).

Reduced oxygen concentrations in marine waters have been cited as a major cause for concern globally (Diaz and Rosenberg, 2008) and there is evidence that areas of low oxygen saturation have started to proliferate in the North Sea (Queste *et al*., 2012). Whether or not these changes are a result of long-term climate change remains unclear, and it is also unknown whether such changes will impact on commercial fish and their fisheries (Townhill *et al*., 2017a). A study by Townhill *et al*. published in 2017 (Townhill *et al*., 2017b), examined the potential impact of reducing oxygen concentrations in the North Sea on commercial fish stocks. Oxygen availability is key in determining habitat suitability for marine fish. As a result of climate change, low oxygen conditions are predicted to occur more frequently and over a greater geographic extent in the future, although not to the minima of previous decades (caused by eutrophication). To assess the potential effects of climate-induced low oxygen on fisheries, critical thresholds derived from laboratory experiments on five commercial fish species were integrated with hind-cast and future oxygen projections from a hydrodynamic-biogeochemical model. By using this approach, changes in habitat suitability from the 1970s to 2100 were identified. In the North Sea, the current extent of low oxygen areas is smaller than was the case during the 1970s. Oxygen levels are expected to decrease again in the coming century due to climate change. In affected areas and years, intermediate oxygen levels could have impacts in late summer on swimming, growth, ingestion and metabolic scope of some commercial fish (Townhill *et al*. 2017b).

3. WHAT COULD HAPPEN IN THE FUTURE?

In the past few years, major advances have been made with regard to the ability to provide future projections for climate change impacts on fish and fisheries. This progress has been made on two separate fronts: (1) providing forecasts at the seasonal to decadal time horizon, and (2) providing long-term projections of species distribution, fish stock productivity and hence consequences for fishing fleets and the economy.

Studies using coupled atmosphere–ocean models and empirical statistical models have begun to demonstrate the potential for climate and therefore fisheries 'forecasts' on near-term to decadal time scales, particularly in the North Atlantic region (Payne *et al*. 2017). Hazeleger *et al*. (2013), skilfully predicted variability associated with the Atlantic Multidecadal Oscillation (AMO) 2–9 years ahead and Matei *et al*. (2012) demonstrated that the SST variations of the North Atlantic and Mediterranean Sea can be skilfully predicted up to a decade ahead, with the North Atlantic subpolar gyre region standing out as the location with the highest predictability on a global scale.

The ICES Working Group on Seasonal-to-Decadal Prediction of Marine Ecosystems (WGS2D) is a group that aims to provide predictions on timescales from seasons to decades in order to support real-time fisheries management in Europe (ICES, 2018). Several 'products' from this group are potentially of use to fisheries in the UK. In June 2017, WGS2D issued its first 'forecast' for blue whiting *Micromesistius poutassou* spawning habitat in the North Atlantic (subsequent forecasts were issued in August 2018 and January 2019). Forecast skill was assessed using historical data independent of those used in model development. The skill based on persistence is significant for forecast lead-times up to 2–3 years. Similar short-term forecasts have also been issued for bluefin tuna feeding habitat in the North Atlantic and for sandeel *Ammodytes marinus* recruitment in the North Sea (issued 20-09-2019, valid through to 01-04-2020.), for example:

"Forecasts for all individual stocks suggest a low probability (5% to 25%) of a strong year class, with a high probability (between 45% and 65%) of these year classes being in the lower third of the historically observed recruitment." (http://www.fishforecasts.dtu.dk/forecasts.)

On a longer timescale, a UK study by Fernandes *et al*. (2017) made use of available observational, experimental, and modelling approaches to quantify potential impacts of OA and warming on future fisheries catches, as well as revenues and employment in the UK fishing industry. Across all scenarios, bivalve species were suggested to be more affected than the fish species. Overall, losses in revenue were estimated between 1–21% in the short term (2020–2050), with England and Scotland being the most negatively impacted region in absolute terms and Wales and North Ireland in relative terms. Losses in total employment (fisheries and associated industries) may reach approximately 3–20% during 2020–2050, with the >10 m fleet and associated industries bearing the majority of the losses. Only the >10 m fishing fleet in Scotland showed average positive impacts, but those too were lost after 2050. The main driver of the projected decreases was suggested to be increases in temperature (+0.5–3.3°C), which exacerbate the impact of decreases in primary production (10–30%) in UK fishing waters. The inclusion of an effect of OA on the carbon uptake of primary producers (phytoplankton) had very little impact on the projections of potential fish and shellfish catches (<1%).

Applying a Net Present Value (NPV) and Partial Equilibrium (PE) approach, Mangi *et al*. (2018) estimated both direct and economy-wide economic losses to shellfish production in the UK as a result of ocean acidification by 2100. Estimates using the NPV method showed that the direct potential losses due to reduced shellfish production could range from 14% to 28% of fishery NPV by 2100. This equates to annual economic losses of between £3 and £6 billion of the UK's GDP at 2013 levels, under a medium- and high-emission scenario. Results using the PE model showed the total loss to the UK economy from both shellfish production and shellfish consumption, ranging from £23–£88 million. In addition, there are regional variations due to different patterns of shellfish wild-capture fisheries and aquaculture practiced in the devolved nations, and the sensitivities of species to OA. Overall, Wales was suggested to be the most heavily impacted devolved nation, losing between 30–59% of total shellfish NPV largely because of the importance of mollusc fisheries. Predicted losses for other devolved nations are less, e.g. for England 16–33%, Scotland 10–21% and Northern Ireland 16–32% of NPV, largely because wild-capture fisheries and aquaculture are more reliant on crustaceans (especially *Nephrops norvegicus*) rather than molluscs, and crustaceans are known to be more robust (Styf *et al*., 2013).

Narita and Rehdanz (2017) attempted to perform a national and sub-national assessment of the economic impact of OA on mollusc production in Europe, using two scenarios of biological sensitivity based on Kroeker *et al*. (2013), i.e. the value of calcification loss (40%, the largest effect size) and the value of growth loss (17%, the smallest effect size). Highest levels of overall impact were found in the countries with the largest current shellfish production, such as France, Italy and Spain. Impacts were also examined in the UK, the Channel Islands and the Isle of Man, with annual economic losses by 2100 expected to amount to US$ 97.1 million, US$ 1 million and US$ 12.7 million respectively under a worst-case scenario, mostly due to impacts on scallop fisheries.

A major uncertainty with regard to future projections for UK fisheries is the lack of clear consensus as to whether primary production (phytoplankton) will increase or decrease in the waters around the British Isles. Net primary production is a key driver of many ecosystem models. Variants of the bioclimate envelope approach (Cheung *et al*., 2011, 2013) suggest a reduction in maximum fisheries catch potential by up to 30% in the North Sea by 2050, relative to 2000 under a medium-high emissions scenario. In contrast, using a size-structured food web model Blanchard *et al*. (2012) predicted a 24% increase in potential catch for the UK, assuming the same underlying climate scenario. Possible reasons for the discrepancy seem to stem from different underlying projections for changes in net primary production that drove the two contrasting biogeochemical models. The model used by Cheung *et al*. (2011) anticipated a decrease in net primary production available for fish while the one used by Blanchard *et al*. (2012) projected an increase. Most-recent studies (e.g. Jones *et al*., 2015; Fernandes *et al*., 2017) (see above) have used outputs from down-scaled regional models that anticipate a decline in net primary production. Consequently, these studies also suggest an overall decline in the net present value of fisheries in the UK. Jones *et al*. (2015) used outputs from two different Earth system models (GFDL ESM2.1 and Medusa), both of which suggested declines in primary production for the North-east Atlantic and this agrees with recent observational data reported by Capuzzo *et al*. (2018).

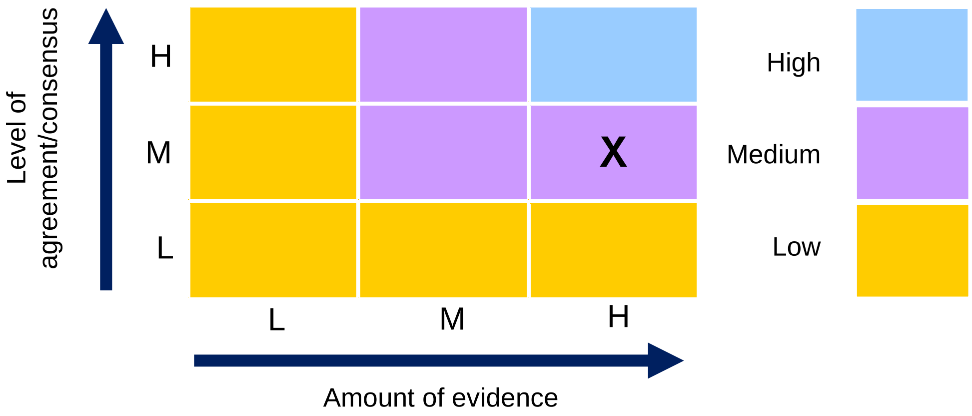
Rutterford *et al*. (2015) used fish survey data, together with generalised additive models (GAMs), to predict trends in the future distribution of species in the North Sea and concluded that fish species over the next 50 years will be strongly constrained by availability of suitable habitat, especially in terms of preferred depths. Shallow-water flatfish species may be particularly impacted, since if forced northwards by warming seas, suitable habitat will be greatly constrained, leading to a requirement for rapid ecological niche shifts, or else population declines. Jones *et al*. (2015) used similar models and suggested that the total maximum catch potential is projected to decrease within the UK Exclusive Economic Zone (EEZ) by the 2050s, resulting in a 10% decrease in net present value, assuming a ‘medium-high’ emission scenario. Despite the variation in predictions from alternative model formulations, the direction of change in NPV proved to be robust to model choice. This study highlights many of the key factors influencing future profitability of UK fisheries and the importance of enhancing adaptive capacity (Jones *et al*., 2015).

Serpetti *et al*. (2017), used an Ecopath with Ecosim (EwE) food-web model to explore direct and indirect impacts of both fishing and warming temperatures on species biomass and fisheries catches off the west coast of Scotland. This model implementation incorporated thermal tolerances of species and was applied across four IPCC climate-change scenarios as well as differing fisheries management regimes (Serpetti *et al*., 2017). The capability to incorporate information about optimum, minimum and maximum temperature tolerances is a relatively recent feature of EwE (introduced in 2016). Cod and herring, with low optimum temperatures, were sensitive to rising temperature and strongly declined by 2060 under all the climate projections. Under the 'MSY + low emissions' scenario, cod biomass increased by the end of the century associated with the lower temperatures of this climate scenario. Haddock biomass was more resilient to warming maintaining constant biomass under the 'MSY + low emissions scenario, but a large decline in other projections. Saithe is also more eurythermal than all the other gadoids and declined only under the 'MSY + high emissions' scenario. Whiting biomass remained stable under the 'MSY + low emissions scenario, but showed a strong increase under the other projections.

4. CONFIDENCE ASSESSMENT

In general, there is more information about climate-change impacts on the fishing industry than any other UK maritime sector or commodity. Fish resources (especially those in the North Sea) have been intensively studied for more than 100 years and authors have been discussing links to climate and weather since 1914 (Hjort, 1914). However, despite this rapidly growing evidence base (documented in successive MCCIP reports) over the past 10 years, there is still considerable uncertainty about 'attribution', given that some of the changes observed in distribution or productivity of fish stocks are likely to have only been partially driven by climate change and partially driven by other factors, such as changes in fishing pressure or habitat modification. Brander (2018) has warned against over-emphasising the role of climate change, and some widely reported storylines about consequences for fish and fisheries (for example the projected expansion of seabass around the UK and the decline of cod) are now having to be re-thought. A good example of the contentious nature of this debate relates to the management of Atlantic mackerel. Scientists disagree strongly about whether or not the stock has migrated/shifted westwards towards Iceland or simply expanded its range, and whether or not any changes are a result of climate change. Similarly, the recent expansion of bluefin tuna has been linked to long-term climate change, but also short-term climate variability and recovery from previously much higher levels of fishing pressure. Despite hundreds of new papers over the past 10 years, opinions regarding the impacts of OA range from wholesale degradation of marine ecosystems and fisheries to negligible impacts with minimal economic consequences (Hendriks *et al*., 2010; Kroeker *et al*., 2010). As such the amount of available evidence is judged as being 'high', but the level of agreement and consensus is still judged as being 'medium'. Consequently, the overall assessment has not changed from the 2013 MCCIP Report Card (see the three top priority challenges reported below).

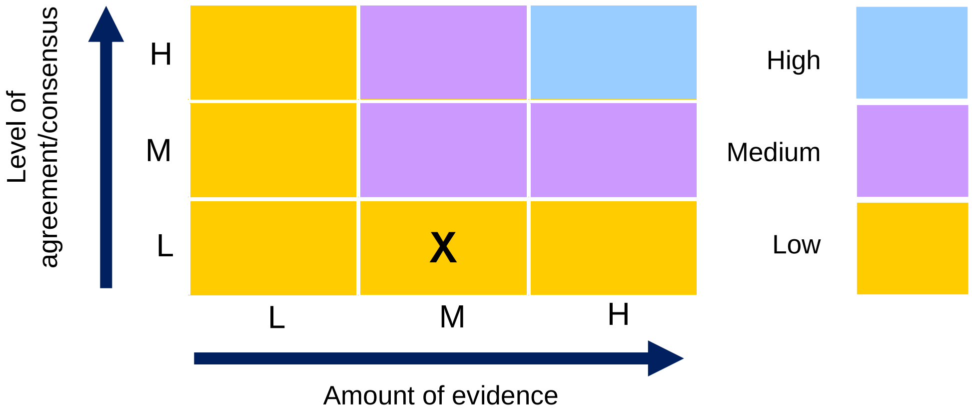
What is already happening?



Similarly, with regard to understanding what might happen in the future, the evidence-base has strengthened significantly. Many new modelling studies have appeared in recent years, and these have considered not only the likely impacts on fish and shellfish species, but also consequences for individual fishing fleets and local economies. However, these studies are heavily constrained by the available information coming from downscaled biogeochemical models, and in particular assumptions about the future trajectory of primary production around the UK. Completely contradictory outputs have been obtained from lower food-web models, and this has resulted in contradictory projections for fishery yield and fish distribution. In addition, different biological models have yielded very different projected outputs for the same species (see Jones *et al*., 2015), and so an approach that is gaining ground is to use an 'ensemble' of different models, in the hope that robust projections of responses will emerge overall.

With regard to OA, the validity of assumptions contained within recent modelling studies (for example Fernandes *et al*., 2017; Narita and Rehdanz, 2017; Mangi *et al*., 2018) can be considered somewhat 'heroic', given the often contradictory responses yielded for closely related taxa in laboratory experiments. This being said, the various meta-analyses that have been completed by Kroeker *et al*. (2013), Hendriks *et al*. (2010) and Kroeker *et al*. (2010) have all indicated that crustaceans (crabs, lobsters and shrimps) are more robust to simulated pH changes than are molluscs (bivalves and gastropods). As a result, the level of confidence has not changed from that stated in the 2013 Annual Report Card, i.e. a medium amount of evidence and low consensus.

What could happen in the future?



5. KEY CHALLENGES AND EMERGING ISSUES

Key challenges

The three top priority challenges which need to be addressed to provide better advice to fisheries stakeholders, can be summarised as: (1) attribution, (2) understanding storminess, and (3) devising suitable adaptation options.

As stated above, it can be incredibly difficult to attribute with any confidence an observed change in the distribution or productivity of fish species to long-term climate change, especially when many other drivers are known to influence populations (e.g. fishing pressure, habitat modification, short-term climate variability etc.) and therefore dependent fisheries. Several widely reported stories, such as the westward expansion of mackerel in recent years, and the slow recovery of cod stocks, are not ‘clear-cut’ and there are many competing explanations for the phenomena observed (sometimes not related to climate at all). Detection and attribution of climate change effects are critical if we are to devise appropriate adaptation actions going forward. In the context of fisheries management, a common approach (as enshrined in the UK National Adaptation Plan) has been to reduce other pressures such as overfishing, in order to build resilience in fish populations so that they are better able to cope with climate stresses in the foreseeable future. Fishing pressure and climate change interact, such that overfishing can cause fish populations to become more vulnerable to short-term natural climate variability (e.g. Ottersen *et al.*, 2006) by making such populations less able to ‘buffer’ against the effects of the occasional poor year classes. Conversely, long-term climate change can make stocks more vulnerable to fishing, by reducing the overall productivity of the stock, such that the same level of fishing pressure might not be sustained, or stocks expected to recover to, levels observed in the past (Winter *et al.*, 2019; Vert-pre *et al.*, 2013).

Changing storminess poses a direct risk to fisheries: storms disrupt fishing effort and pose a physical danger to fishers, their vessels and gear, as well as to fishing communities and their infrastructure. Although ocean warming may alter the potential fish catch over the next 50 to 100 years, changing storminess has the potential to cause more-immediate and catastrophic impacts (Sainsbury *et al*., 2018). Fishing remains the most dangerous occupation in the UK: the fatal accident rate is 115 times higher than that in the general workforce and much of this is related to operating in poor weather conditions (Roberts *et al*., 2010). Uncertainty in projections of past and future storminess from global and regional climate models remains high as a result of widespread variation in analytical methods, poor historical observational data, and the challenge of distinguishing externally forced climate changes from natural internal climate variability. At present, confidence in the wind and storm projections from Global Climate Models (GCMs) and down-scaled Regional Climate Models (RCMs) is relatively low, with some models suggesting that north-west Europe will experience fewer (though more intense) storms in the future, whereas other models suggest an increase in storm frequency. Assessing the vulnerability of fisheries to changing storminess is essential for prioritising limited adaptation resources and informing adaptation strategies.

In a 2015 report published by Seafish (Garrett *et al*., 2015), it was suggested,

"…*taking action to adapt to* [long term] *climate change is not presently a priority for the majority of industry contributors. Industry* [instead], *highlight the effect of near term events – severe storms affecting ports in Fraserburgh and Peterhead and in the South West, stormy conditions affecting crew safety, flooding of processing units, changing distribution of species for example.*"

Recent efforts have focussed on the storms that occurred during winter 2013–14, which meteorologists from the UK Met Office have suggested was the stormiest period in the 66-year record, due to unprecedented cyclone intensity and frequency (Matthews *et al*., 2014). The UK fishing industry was severely disrupted with severe damage to fishing boats and harbour facilities, especially in Devon and Cornwall (Andrew, 2014). A preliminary analysis was carried out of fishery disruption in south-west England using satellite-derived vessel monitoring data to characterise the relationship between weather variables (wave height, wind speed etc.) and behaviour of the fleet. Fishing effort was greatly curtailed when wind speed exceeded 10 m/second, and particularly so when winds exceeded 15 m/second (Cefas, unpublished data). Projections from climate modellers (e.g. Donat *et al*., 2011) suggest that the occurrence of extreme wind speeds in excess of 15 m/second will increase over the UK during the coming century and that therefore UK fisheries will likely face elevated levels of disruption in the future (see Sainsbury *et al*., 2018). Sainsbury *et al*. (2018) provided a 'research roadmap' to better understand the impact of changing storminess on global fisheries.

Climate change is affecting marine and coastal ecosystems throughout the North Atlantic, including commercial, recreational and subsistence fisheries. Climate adaptation actions are taken to either avoid (or minimise) or take advantage of climate change impacts, either by decreasing vulnerability or increasing resilience. Devising appropriate adaptation actions for this sector has proven challenging, given that there may be barriers to successful adaptation, including market failures, information barriers, and policy barriers whereby quota restrictions or international jurisdictions limit the adaptability of fishing fleets. Traditional fisheries management tools, such as restrictions on allowable catch, landing size, seasonal closures, gear restrictions, marine protected areas, essential fish habitat protection, and protection of spawning aggregations, are and will remain necessary (see Grafton, 2010) but may not be sufficient on their own to sustain fisheries in the face of the combined onslaught of climatic and non-climatic stressors in the future. A wide diversity of adaptation measures has been tested, applied and advocated in the North Atlantic and these are reviewed in two reports from the United States (Gregg *et al*., 2016) and the UK (Defra, 2013). Importantly, developing suitable climate change adaptation strategies also requires an understanding of the adaptive capacities of fleets to cope with and adapt to future impacts. While the UK fishing industry in general is considered to have a relatively high adaptive capacity (Defra, 2013; Garrett *et al*., 2015), differences within and across different fleets, sectors, fisheries and regions regarding their abilities to adapt exist, but current understanding within a UK context is limited. Such information is however needed to identify what adaptation options would be most effective, and allow the development of actions that are able to consider and reflect the differing needs and challenges.

Emerging issues

Marine recreational fishing is popular globally and benefits coastal economies and people's well-being. For some species, it represents a large component of fish landings. Climate change is anticipated to affect recreational fishing in many ways, creating opportunities and challenges (Townhill *et al*., 2019). Rising temperatures are expected to impact the availability of fish to recreational fishers, through changes in recruitment, growth and survival. Shifts in distribution are also expected, affecting the location where target species can be caught. Climate change also threatens the safety or attractiveness of fishing. Opportunities may be reduced owing to rougher conditions, and costs may be incurred if gear is lost or damaged in bad weather (Townhill *et al*., 2019). However, not all effects are expected to be negative. Where weather conditions change favourably, participation rates could increase, and desirable species may become available in new areas. Drawing on examples from the UK and Australia, Townhill *et al*. (2019) synthesized existing knowledge to develop a conceptual model (Figure 3) of climate-driven factors that could impact marine recreational fisheries, in terms of operations, participation and motivation.

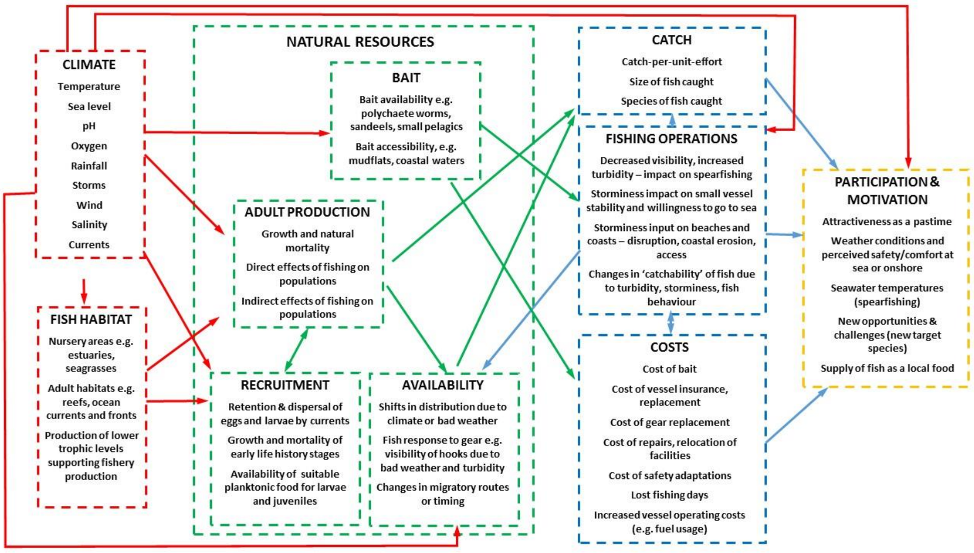


Figure 3: The pathways by which each aspect of recreational fishing can be affected by climate change, from the climate drivers, to changes in natural resources, catches, fishing operations, costs and fisher behaviour. (Reproduced from Townhill et al.*, 2019.)*

The Defra *Economics of Climate Resilience* report in 2013 (Defra 2013) identified that fisheries management and quota arrangements can severely constrain the ability of fishers to adapt to climate change. Under the EU Common Fisheries Policy, Total Allowable Catches (TACs) are shared between EU member nations through pre-agreed ‘relative stability’ arrangements. These arrangements were based on the member state’s catches during a historical reference period (1973 to 1978) and give each state a fixed percentage share of the total stock in perpetuity (Morin, 2000). Since the late 1970s, climate change has shifted the geographical distribution of many commercial species so that in many instances national shares no longer coincide with geographic proximity. To be truly ‘adaptive’ to distribution shifts would require adaptive management and governance structures that allow access and allocations to be based on updated information that reflects current, and future prevailing conditions, and places less emphasis on historical track record (Pinsky *et al*., 2018).

A particular focus in recent years has been on the concept of ‘zonal attachment’ (Hannesson, *et al*., 2013), i.e. the spatial distribution of the stock over time and over the various life-history stages in relation to EEZ boundaries. Future negotiations will depend on increased cooperation and collaboration between countries, but as seen in previous examples such as the ‘mackerel wars’ (Figure 1), considerable conflict among countries can arise. With the UK’s imminent departure from the EU Common Fisheries Policy, together with continued shifts in species distributions, negotiations will probably be very difficult (Phillipson and Symes, 2018; Shepherd and Horwood, 2019). It seems likely that the intricacies of fish distribution patterns (past, present and future) will become a major issue for debate over the next few years.

The ‘EU landing obligation’ (discard ban) was introduced between 2015 and 2019 for all commercial fisheries species under TACs, or under minimum landing sizes. The obligation stipulates that once the least plentiful quota species in a mixed fishery is exhausted, the whole fishery must cease operation. Baudron and Fernandez (2015) have argued that many commercial fish stocks are beginning to recover under more-sustainable exploitation regimes, in some cases, also as a result of favourable climatic conditions. For example northern hake (*Merluccius merluccius*), a warm-water species, has recolonised the northern North Sea from which they had largely been absent for over 50 years (Baudron and Fernandes, 2015; Staby *et al*., 2018). These shifts in distribution, whether driven by climate change or not, have implications for the management of other stocks. Notably, if discards are banned under the ‘EU landing obligation’, the relatively low quota for hake in the region could be a limiting factor (a ‘choke stock’) that may potentially result in the premature closure of the entire demersal mixed fishery, jeopardizing livelihoods of commercial fishermen, especially in Scotland (Baudron and Fernandes, 2015). In addition, Cormon *et al*. (2016) have suggested that this shift in hake distribution could impact local food-webs, as hake are voracious predators.

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